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Technical Note

1970-43

Airborne Severe Storm Surveillance

J. W. Meyer,
Editor

Volume II Reports of Working Panels

2 November 1971

Prepared for the Advanced Research Projects Agency
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Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

AIRBORNE SEVERE STORM SURVEILLANCE
VOLUME II. REPORTS OF WORKING PANELS

Report to the
Advanced Research Projects Agency
of a Summer Study
3 through 28 August 1970

J. W. MEYER, Editor

Division 4

TECHNICAL NOTE 1970-43
VOLUME II

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FOREWORD

This volume contains the reports of the Airborne Severe Storm Surveillance Summer Study working panels. These reports represent more detailed discussions in support of both their findings and their recommendations. The panels were made up principally of full-time participants. Three panels enjoyed the support of a part-time member. The affiliations and full addresses of all panel members can be found in Appendix I of Volume I, page 43.

Dr. James W. Meyer

Dr. Melvin A. Herlin

Editors

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

REPORTS OF WORKING PANELS

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SECTION I

REPORT OF THE CONTEMPORARY OPERATIONS PANEL

C. J. Callahan, Chairman

Lt. Col. Foster A. Post

Major William V. Yelton

Airborne Severe Storm Surveillance Summer Study

August 1970

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I. SUMMARY

A. Background

The Department of Commerce (DoC) holds the statutory responsibility for providing warnings of severe weather to the general public of the United States. As used in this paper, severe weather is defined as the results of (1) tropical hurricanes or storms, and (2) East Coast winter snow storms. As an essential source of data for the preparation of these warnings, the DoC has requested aircraft weather reconnaissance from the Air Force and Navy, elements of the Department of Defense (DoD). This use of operational military and naval aircraft began in the World War II period and is soundly rooted in economics and logic. It is extremely costly to purchase, maintain, and operate an extensive fleet of operational aircraft dedicated solely to the reconnaissance role, and the necessary aircraft, crews, and facilities are already in existence within the DoD.

As a corollary, however, it would also be illogical for DoD aircraft to be assigned to a permanent research role, in which flight schedules vacillate with research requirements, aircraft configurations are subject to modification as new instruments are installed to measure various parameters, and where the civil (research) interest is dominant. Hence, the DoC possesses a much smaller number of aircraft to meet the research requirements of the nation.

The years have thus seen the evolution of a DoD capability for airborne operational reconnaissance missions and a parallel but nonduplicatory emergence of a limited DoC fleet intended for research purposes. Under certain situations, established by political considerations, the DoC fleet can assume an operational role, e. g. , when flights are required over Cuba. In addition, this capability can be employed in those rare instances when military aircraft are occupied with other tasks.

This example of DoC-DoD cooperation is far from new; for twenty-five years, annual conferences attended by representatives of the agencies have been held in which explicit procedures for probing tropical cyclones, instrumentation, and communications have been outlined. In the case of East Coast winter storms, cooperation is of more recent vintage; the DoC requested (and received) DoD support initially in the winter of 1969-1970.

The early bilateral hurricane conferences and the more recent meetings on East Coast winter storms have been expanded and formalized under the auspices of the Federal Coordinator for Meteorological Services and Supporting Research, a position established in late 1963. Reporting to the Federal Committee, a group of agency representatives on the under-secretary level, the Federal Coordinator has established a substructure where specifics of plans for aerial weather reconnaissance are worked out annually for operations in hurricanes and East Coast storms.

Figure I-1 shows this organization to and including the working group level responsible for preparing draft plans in the specific areas under study in this report.

At this point in time, no DoC requirements for operational reconnaissance of severe local storms (e. g. , mid-west tornadoes) have been levied on the DoD.

As of August 1970, the membership on the various groups of interest is given as follows:

Table I-1: Federal Committee

Table I-2: ICSM

Table I-3: SC/BMS

Membership of the working groups is identical, viz:

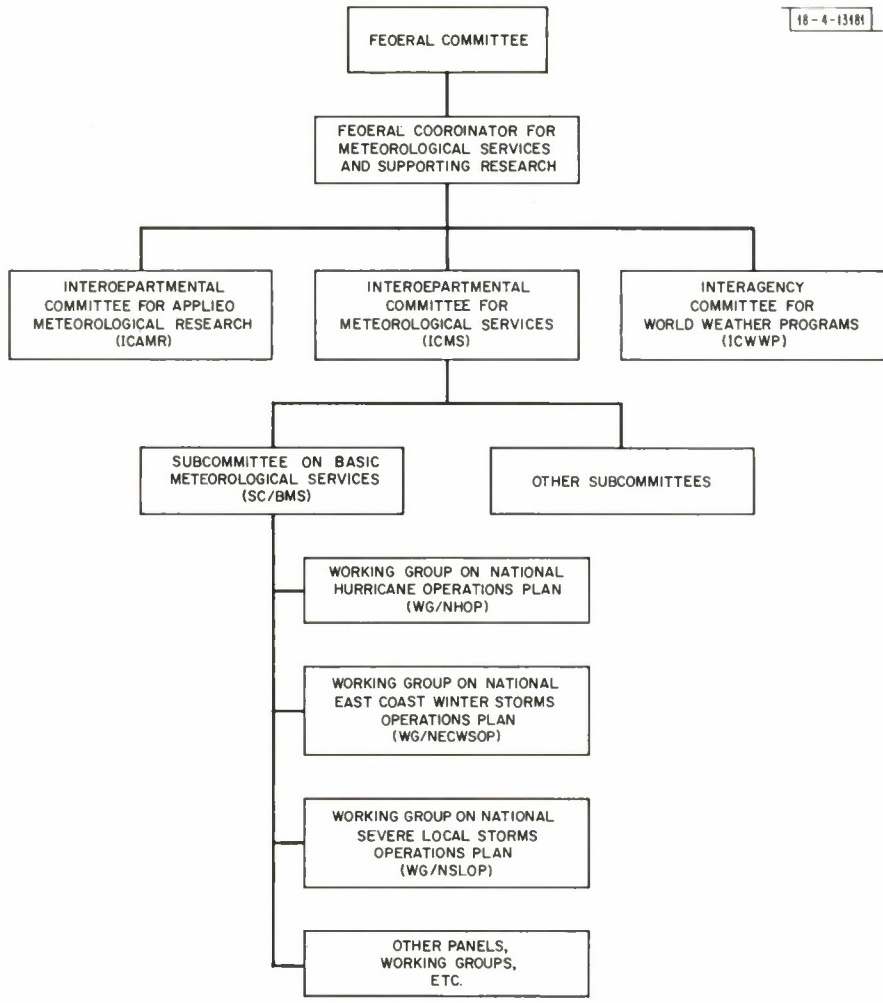


Fig. I-1. Committee and working group organization for coordination of Federal efforts in meteorology.

TABLE I-1
 FEDERAL COMMITTEE FOR METEOROLOGICAL SERVICES AND
 SUPPORTING RESEARCH

<u>AGENCY</u>	<u>MEMBER</u>	<u>ALTERNATE</u>
Atomic Energy Commission	Dr. Rudolf Engelmann Fallout Studies Branch Div. of Biology & Medicine Atomic Energy Comm. Washington, D. C. 20545	
Department of Agriculture	Mr. T. W. Edminster Deputy Administrator, ARS Agricultural Research Service, Room 324A Dept. of Agriculture Washington, D. C. 20250	Mr. David M. Hershfield Soil & Water Conservation Research Div. Dept. of Agriculture Washington, D. C. 20250
Department of Commerce	Dr. Myron Tribus, Chmn Ass't Secretary for Science & Technology Dept. of Commerce Washington, D. C. 20230 Col. C. E. Roache (Sec'y) Deputy Ass't Administrator for Environmental Sys. Room 817, Building 5, NOAA 6010 Executive Blvd. Rockville, Md. 20352	
Department of Defense	Dr. Donald M. MacArthur Deputy Director, Research & Technology DDR&E, OSD, Rm. 3H144 Dept. of Defense Washington, D. C. 20301	Brig. Gen. R. F. Long, USAF Special Assistant for En- vironmental Services Joint Chiefs of Staff Dept. of Defense Washington, D. C. 20301
Department of HEW	Dr. J. A. Lieberman Asst. Admin. for R&D, Consumer Protection & Environmental Health Service Dept. of HEW (Room 6113) 200 C Street, NW Washington, D. C. 20204	Dr. John H. Ludwig Assoc. Commissioner for Control Tech., R & D Air Pollution Control Agency Boston Center Tower, #2 801 N. Randolph Street Arlington, Va. 22203
Department of Interior	Dr. Donald B. Dunlop Science Advisor Office of the Secretary Dept. of the Interior Washington, D. C. 20240	Dr. William Thurston Asst. to Science Advisor Room 5200 Dept. of the Interior Washington, D. C. 20240
Department of State	Mr. Herman Pollack, Dir. International Scientific and Technological Affairs Dept. of State Washington, D. C. 20520	Dr. Robert T. Webber Deputy Dir, Office of Space & Environmental Science Affairs Dept. of State Washington, D. C. 20520

Department of Transportation	R. Adm. R. E. Hammond Room 2224 Coast Guard Building 1300 E Street, NW Washington, D. C.	Mr. Victor W. Kowalczyk Chief, Weather Staff (AT-40) Room 422A (FAA) 800 Independence Ave., SW Washington, D. C. 20553
National Aeronautics & Space Administration	Dr. Homer E. Newell. Assoc. Admin. (AA) NASA Washington, D. C. 20546	Dr. Morris Tepper, Deputy Dir. Space Applications Programs, & Dir. of Meteorology NASA Washington, D. C. 20546
National Communications System	Mr. Clifford D. May, Jr. Deputy Manager National Communications System Washington, D. C. 20305	Mr. G. M. Blencoe, Asst. Mgr. National Communications System Washington, D. C. 20305
National Science Foundation	Dr. Edward Todd, Exec. Asst. to Deputy Asst. Dir. for Research Room 320 National Science Foundation 1800 G Street, NW Washington, D. C. 20550	Dr. Fred D. White, Head Atmospheric Sciences Div. of Environmental Sciences National Science Foundation Washington, D. C. 20550
Bureau of the Budget (OBSERVER)	Mr. David Lawhead Budget Examiner Bureau of the Budget Exec. Office Building Room 463 Washington, D. C. 20503	

TABLE I-2

INTERDEPARTMENTAL COMMITTEE FOR METEOROLOGICAL SERVICES

<u>AGENCY</u>	<u>MEMBER</u>	<u>ALTERNATE</u>
Department of Commerce NOAA	Dr. C. E. Jensen, Chairman Chief, Fed. Plans & Coord. Div. AE1, Room 818, Bldg. 5 6010 Executive Boulevard Rockville, Md. 20852	
Department of Agriculture	Mr. Talcott W. Edminster Deputy Administrator Agricultural Research Service Dept. of Agriculture Washington, D. C. 20250	Mr. David M. Hershfield Soil & Water Conservation Research Div. Agricultural Research Service Dept. of Agriculture Rte 1, Plant Industry Station Beltsville, Md. 20705
Department of Commerce	Dr. George P. Cressman Dir., Weather Bureau Rm. 1401, Gramax Bldg. 8060 13th Street Silver Spring, Md. 20910	Dr. K. R. Johannessen Assoc. Dir., Meteorological Ops. Room 1410, Gramax Building 8060 13th Street Silver Spring, Md. 20910
Department of Defense	Col. J. R. Anderson DDO/Environmental Services Joint Chiefs of Staff Pentagon, Rm. 1B671 Washington, D. C. 20301	Lt. Col. E. V. Cooke, Jr. DDO/Environmental Services Joint Chiefs of Staff Pentagon, Room 1B672 Washington, D. C. 20301
Department of the Interior (OBSERVER)	Dr. Donald Dunlop Science Adviser Office of the Secretary Dept. of the Interior Washington, D. C. 20240	Mr. James L. Kerr Div. of General Engineering Code 211, Bureau of Reclamation Dept. of the Interior Washington, D. C. 20240
Department of State	Dr. Robert T. Webber Office of Space & Environ- mental Science Affairs New State Building Room 7820, Code SCI Department of State Washington, D. C. 20520	Dr. E. G. Kovach Office of International Scientific & Technological Affairs Room 4218, New State Bldg. Department of State Washington, D. C. 20520
Department of Transportation (Coast Guard)	Capt. R. P. Dinsmore, Chf. Marine Sciences Division Room 7315 U. S. Coast Guard HQ 400 Seventh St., SW Washington, D. C. 20591	Cdr. Richard Morse Marine Sciences Division Room 7311 U. S. Coast Guard HQ 400 Seventh St., SW Washington, D. C. 20591
Bureau of the Budget (OBSERVER)	Mr. David Lawhead Office of Management & Budget, Room 463 Executive Office Building Washington, D. C. 20503	

Federal Aviation Administration	Mr. William N. Flenner Acting Dir. , Air Traffic Service (AT-1)Rm. 400E Federal Aviation Admin. 800 Independence Ave, SW Washington, D. C. 20553	Mr. Victor Kowalczyk Air Traffic Service, AT-40 Rm 413, Fed. Aviation Admin. 800 Independence Ave. , SW Washington, D. C. 20553
National Aeronautics & Space Administration	Dr. Morris Tepper, Dir. Meteorological Programs Div. Office of Space Science & Applications NASA 400 Maryland Ave. , NW Washington, D. C. 20546	Mr. Louis B. C. Fong, Asst. Dir. , Space Applications Programs Office of Space Science & Applications NASA, FOB-6, Rm 5H062 Washington, D. C. 20546
Department of COMMERCE (NOAA)	Col. E. J. Cartwright, Secy AE1, Rm. 818, Bldg. 5 6010 Executive Blvd. Rockville, Md. 20852	
National Communications System	Mr. Paul J. Cahan Defense Communications Agency (NCS) Navy Dept. Service Ctr. 8th & South Court House Road Arlington, Va. 22204	Mr. J. J. Caso Defense Communications Agcy (NCS) Navy Dept. Service Ctr. 8th & South Court House Rd. Arlington, Va. 22204

TABLE I-3

SUBCOMMITTEE ON BASIC METEOROLOGICAL SERVICES (SC/BMS)

Department of Commerce	Dr. K. R. Johannessen Chairman Weather Bureau Room 1410, Gramax Bldg. 8060 13th Street Silver Spring, Md. 20910	Dr. Harry Foltz Weather Bureau, Rm 1416 Gramax Building 8060 13th Street Silver Spring, Md. 20910
Department of Agriculture	Mr. K. M. Kent, Chief Hydrology Branch Dept. of Agriculture South Bldg, Rm. 5250 Washington, D. C. 20250	Mr. David M. Hershfield Soil & Water Conservation Research Div. Agricultural Research Service Dept. of Agriculture Rte 1, Plant Industry Station Beltsville, Md. 20705
Department of Defense	Lt. Col. E. V. Cooke DDO/Environmental Services Joint Chiefs of Staff Pentagon, Rm 1B672 Washington, D. C. 20301	Cdr. F. J. Schatzle DDO/Environmental Services Joint Chiefs of Staff Pentagon, Rm. 1B672 Washington, D. C. 20301
Federal Aviation Administration	Mr. Thomas Speakmon AT-40, Room 413A Federal Aviation Admin. 800 Independence Ave., SW Washington, D. C. 20553	
National Aeronautics & Space Administration	Mr. Louis B. C. Fong Office of Space Science & Applications Code SAA, Room 5H062 NASA 400 Maryland Ave., SW Washington, D. C. 20546	Mr. Robert E. Turner Aerospace Environment Div. Marshall Space Flight Center NASA (Attn: R-AERO-Y) Huntsville, Ala. 35812
Department of Commerce NOAA	Mr. C. J. Callahan Federal Plans & Co- ordination Div. AE1, Room 818, Bldg. 5 6010 Executive Blvd. Rockville, Md. 20852	
Department of Transportation (Coast Guard)	Cdr. Richard M. Morse Marine Sciences Div. Coast Guard Hqtrs. Room 7311 400 Seventh St., S. W. Washington, D. C. 20591	

Mr. Samuel O. Grimm, Jr., DoC Chairman
 Lt. Col. Ernest V. Cooke, JCS, DoD
 Mr. Thomas Speakmon, DoT
 Mr. Cornelius J. Callahan, DoC, Exec. Secretary

Each working group has a dual responsibility:

- 1) To arrange for an annual meeting of representatives of the interested agencies. A factual report of agency effort in the area of interest during the past year is the first product; and
- 2) To prepare a draft version of the plan for the coming year. This is a second product.

The reports are forwarded to SC/BMS and ICMS, where they are noted. The draft plans are sent to SC/BMS, where they are reviewed and forwarded to ICMS for approval. Publication is arranged by the Federal Coordinator after the plans have been reviewed at his level, and the substance of the plans is then directive on the agencies involved. Federal Committee members are provided copies of the plans, and general distribution is then made by the working group chairman to a list provided by each agency.

B. The Organization of Contributing Agencies

The operational reconnaissance missions are flown by aircraft of the Air Force, the Navy, and the National Oceanic Atmospheric Administration (NOAA), formerly the Environmental Science Services Administration. The command and control structure varies, as do the types of aircraft used; the coordination aspects, through which the organizations are tasked for specific missions, are established through the National Plans. This section will outline the organizational structure within each of the three services and list the numbers and types of aircraft assigned.

In summary, the total resources in the current airborne reconnaissance fleet are given in the table which follows.

TABLE I-4
 AIRCRAFT RECONNAISSANCE RESOURCES

Service	Type of Aircraft	Aircraft
Air Force	WC-130A	3
	WC-130B/E	22
	WC-135B	10
	RB-57C	6
	RB-57F	19
	AF Total	60
Navy	WC-121	19
	Navy Total	19
RFF*	DC-6A/B	2
	RB-57A	1
	WC-130B	1**
	RFF Total	4

Summary: AF 60; Navy 19; RFF 4; TOTAL 83

* Research Flight Facility.
 ** Replaced DC-4. Instrumentations being transferred from DC-4 to WC-130.

1. Air Force

The organizational structure of the Air Force reconnaissance units is shown in Fig. I-2, with the current complement of aircraft indicated.

2. Navy

While the Air Force chain of command to its reconnaissance aircraft is relatively direct, a more complex arrangement exists in the Navy because of its overall structure. The Navy organization of its reconnaissance units is given in Fig. I-3.

In addition to the command structure given above, the Navy reconnaissance squadrons fulfill requirements which can be diagrammed. Functions of each squadron in this respect are given in Fig. I-4.

As a matter of information, the personnel strength of VW-4, based at the Naval Air Station, Jacksonville, is 65 officers and 385 enlisted men. Each aircrew consists of 21 personnel.

3. NOAA Research Flight Facility (RFF)

The RFF is a component of the NOAA. Its organization can be diagrammed as shown in Fig. I-5.

C. Aircraft Characteristics Tabulations

Performance data for the aircraft used in weather reconnaissance are tabulated below.

	AF WC-130	AF WC-135	AF RB-57F	Navy WC-121	NOAA DC-6	NOAA RB-57A
Max. Alt. Ft.	30,000	40,000	60,000+	18,500	22,000	43,000
True Airspeed, KTS	294	411	410	210	240	420
Range, N.M.	3,500	6,500	2,050	2,750	2,600	1,900
Time (Hrs:Min)	12:25	16:30	5:00	14:30	12:00	4:50
No. Crew Members	6	7	2	17-22	7	2

D. Meteorological Sensors and Equipment Tabulations

1. Altitude

There are two types of altitude-measuring equipment aboard the reconnaissance fleet. Pressure altimeters and radar altimeters are both used. There is little commonality, as indicated in Table I-5.

2. Temperature Sensors

These sensors are used on the reconnaissance fleet to obtain temperatures at the flight level, at the sea surface, and below the sea surface. Characteristics are given in Table I-6.

3. Humidity Sensors

Two types of humidity sensors are used in the reconnaissance fleet, as well as a particle size device. Details are given in Table I-7.

4. Wind Measuring Equipment

At present, flight-level winds are measured by four types of equipment. There is no current capability for measuring winds below the aircraft other than by visual observation of the state of the sea. Details are given in Table I-8.

5. Sondes

Dropsondes are used to obtain pressure, temperature, and humidity below the aircraft at specified levels. Three types are used: the T-6, the Bendix T-13, and the Honeywell T-13. Details are given in Table I-9.

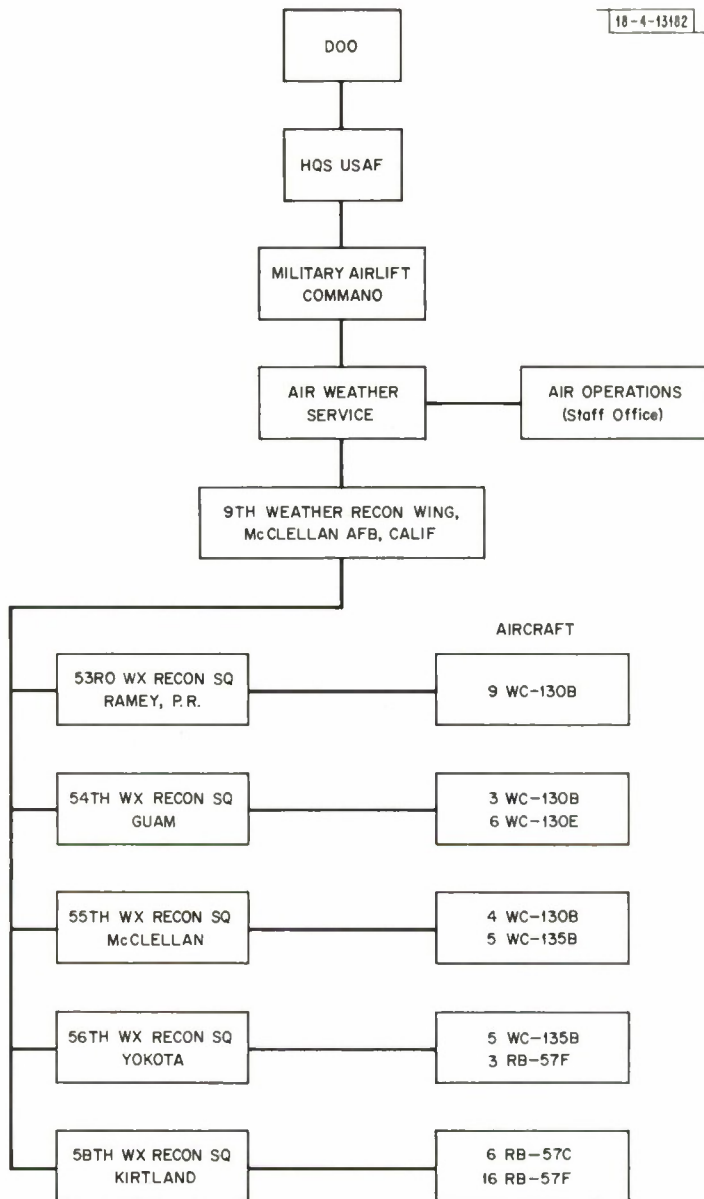
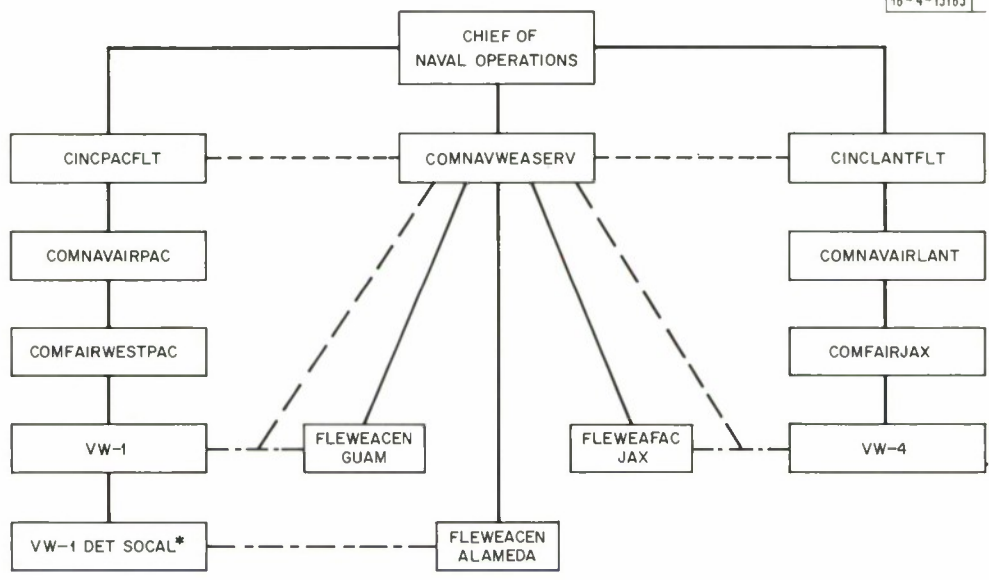


Fig. I-2. Air Force reconnaissance organization.



----- NAVAL WEATHER SERVICE REQUIREMENTS
 - - - - - LIAISON
 TECHNICAL GUIDANCE

	JACKSONVILLE	ALAMEDA	AGANA, GUAM
AIRCRAFT	VW-1	VW-1 SOCAL	VW-4
WC-121N	6	2	11

*SOCAL = SOUTHERN CALIFORNIA

Fig. I-3. Navy administrative chain of command, reconnaissance squadrons.

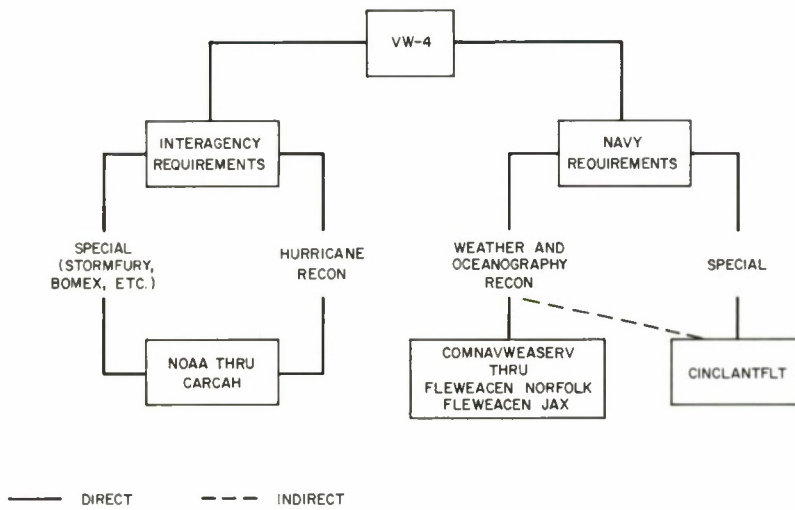
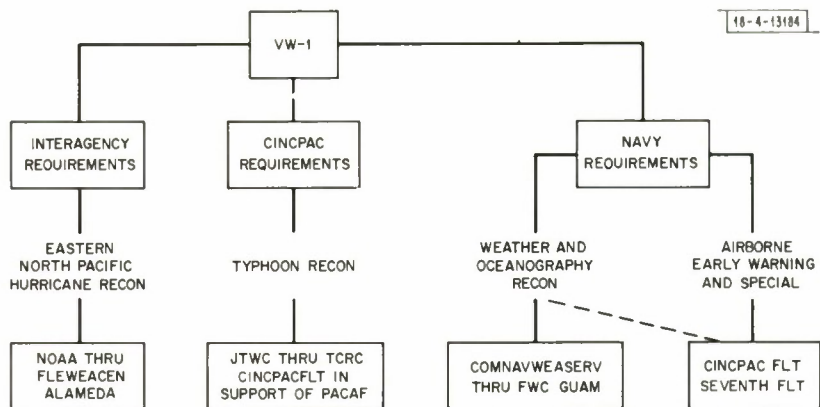
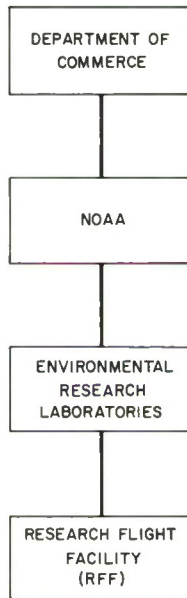


Fig. I-4. Navy reconnaissance squadron requirements.



AIRCRAFT: 2 DC-6 A/B
1 RB-57A
1 DC-4
1 WC-130B*

*WC-130B WILL REPLACE DC-4 IN OCTOBER 1970

Fig. I-5. RFF organizational structure.

TABLE I-5
 ALTITUDE MEASURING DEVICES

	Air Force		Navy	NOAA
	WC-130	WC-135	WC-121	DC-6
1. Pressure Type	MA-1	MA-1	FA-112	555TI
Range	0-50K'	0-50K'	0-20K'	1050-50MB
Accuracy	50' + 0.25% alt.	50' + 0.25% alt.	±0.5MB	±0.5MB
Performance	fair (airspeed sensitive)	fair (airspeed sensitive)	good	good
2. Radar Type	APN-42A	APN-42A	<u>SCR-718</u> APN-159	APN-159
Range	0-50K'	0-50K'	0-10K'	0-10K'
Accuracy	20' + .025% alt.	20' + .025% alt.	50' + .25% alt.	8' or 1%
Performance	poor*	poor*	good	good
Error at 10K' (T.O., rms)	±106'	±106'	±77'	±77'

* Air Force has been notified that the APN-42A needs emergency remedial action.

NOTE: Strip recorders for pressure altitude and radar altitude will be installed on the WC-130 fleet as a part of the Phase II modification.

TABLE I-6
TEMPERATURE SENSORS

	Air Force		Navy	NOAA
	WC-130	WC-135	WC-121	DC-6
1. <u>Flight Level</u>				
Type	Rosemount 102*	Rosemount ML-598	Vortex	Vortex AMQ-8
Range	-85° to +50°C	-85° to +50°C	-40 to +50°C	-80 to +50°C
Accuracy	±1°C	±1°C	±0.5°C	±1.0°C
Performance	good	good	good	good
2. <u>Sea Surface</u>				
Type	**		PRT-4A	IR
Accuracy			±1°C	+10 to +110°F ±2°F (est)
Performance			fair to 1500'	
3. <u>Subsurface</u>				
Type			SSQ-36	
Depth			1000'	
Accuracy			±1°C	
Performance			Excellent	

* The Rosemount ML-598 will replace the Rosemount 102 in Phase 1 of the WC-130 modification.

** A Barnes Sea Surface Temperature Indicator (Model PRT-5) is scheduled for installation in Phase 2 of the WC-130 modification.

NOTE: A strip recorder for temperatures will be installed in the WC-130's as a part of Phase 2 modifications.

TABLE 1-7
HUMIDITY SENSORS

	Air Force		Navy	NOAA	
	WC-130	WC-135	WC-121	DC-6	
1. <u>Humidity/Dewpoint</u>	*				
Type	None	None	Cambridge Sys- tems 137-C3	IR Hygrometer	Cambridge Systems
Range			-54° to +50°C	0-20 gm/m ³	-50° to +50°C
Accuracy			±1°C	±5%	
Performance			FAIR Slow response, saturates in rain	GOOD	FAIR
2. <u>Liquid Water Content</u>	None	None	None	Johnson-Williams	
Range				0-6 gm/m ³	
Accuracy				±30% cst	
3. <u>Particle Size</u>	None	None	None	Two R&D samples and nuclei counter	
Range					
Accuracy					

* A Cambridge Systems Optical and Point Hygrometer (model 137-C3-SCT-MR) is scheduled for installation in Phase II modification of the WC-130 fleet.

Note: A strip recorder for dewpoints will be installed as a part of the Phase II modification on the WC-130 fleet.

TABLE I- 8
FLIGHT LEVEL WIND MEASUREMENTS

	Air Force		Navy	NOAA
	WC-130	WC-135	WC-121	DC-6
1. <u>Compass-Type</u>	N-1	N-1		N-1
Accuracy	$\pm 2^\circ$	$\pm 2^\circ$		$\pm 0.2^\circ$
Performance	Good	Good		Good
2. <u>Airspeed-Type</u>	M-1A	M-5	AX-606	A-2
Accuracy	± 5 kts	± 8 kts		± 5 kts
Performance	Fair	Fair		Good
3. <u>Doppler Radar-Type</u>	APN-147	APN-147	APN-153	APN-82
Ground speed				70-700 kts
Range	70-1000 kts	70-1000 kts		± 2.1 kts
Accuracy	± 5 kts	± 5 kts		
4. <u>DRIFT</u>				
Range	$\pm 40^\circ$	$\pm 40^\circ$	$\pm 60^\circ$	$\pm 45^\circ$
Accuracy	$\pm 0.25^\circ$	$\pm 0.25^\circ$	$\pm 1^\circ$	$\pm 0.15^\circ$
Performance		Good, except over moving targets		
T. O. Wind Error (rms)	3° /kts	3° /7kts	Unk	3 kts < 15 kts 2 % > 15 kts

Note: Strip recorders for wind direction and speed will be installed as part of the Phase II modification of the WC-130 fleet.

TABLE I-9
DROPSONDES

	Bendix T-13	T-6	Honeywell T-13
1. <u>Temperature Range</u>	-90° to +40°C	-60° to +40°C	-90°C to +40°C
Accuracy	±1.2°C	±1.2°C	±1.2°C
Sampling Interval	120'	Continuous, every other 20 mb	120'
Response speed	Fair-slow recovery at launch	Good	
Performance	Fair	Fair	
2. <u>Pressure Accuracy</u>	± 6.0 mb	± 6.0 mb	± 3.0 mb
Sampling Interval	240'	650'	240'
Performance	Pressure reversals and skips during drop	Long extrapolation at sea level	New sensor ±2 mb
3. <u>Humidity Accuracy</u>		7% RH for 1 cycle only. Then undefined every other 20 mb continuous	
Sampling Interval	120'		120'
Response Speed		2 sec at 40°C to 2 min at -40°C	
Performance		Poor - washes out deteriorates in atmosphere, very slow response.	
4. <u>Sond Fall Rate (F/M)</u>	5000'	1500' (after 6 sec free fall)	5000'
5. <u>Cost</u>	\$165	\$71	\$150
6. <u>Failure Rate</u>	14%	27%	
7. <u>Overall Performance</u>	Fair - Quality control problem	Fair	
8. <u>Future Potential</u>	Fair	Poor	

Note: In Phase I of the WC-130 modification program, a Hewlett-Packard dropsonde system will be installed, with the capability to use the AN/AMT-13 instrument. While the desired accuracy for the dropsonde is ±2 mb, the present limits are ±6 mb.

In Phase II of the WC-130 modification program a Hewlett-Packard Desk Calculator (Model 9100B) will be installed to expedite data reduction: this is particularly applicable to preparing the dropsonde message.

6. Weather Radars

Weather radars on current aircraft are adaptations of ground-based equipment. Table I-10 shows the current instrumentation.

TABLE I-10
WEATHER RADARS

Scope	Air Force	Navy	NOAA
PPI*	AN/APN-59B (3 cm)	AN/APS-20E (10 cm)	DC-6's AN/APS-20E (10 cm) Collins WP-101 (5-6 cm)
RHI**	None	AN/APS-45 (3 cm)	Bendix RDR-ID (3.2 cm)

* PPI - Plan Position Indicator

** RHI - Range/Height Indicator

E. Operating Costs

Operating costs are generally computed in dollars per hour. However, it is extremely difficult to provide comparative costs because of the various accounting procedures. Furthermore, the Air Force uses four different methods to arrive at the value of aircraft.

1. Trade-In Value

This is the saving if the airframe is deleted from the inventory. It includes direct savings such as total maintenance support, equipment, petroleum/oil/lubrication (POL), spare parts, flight and supporting personnel pay, travel, and per diem. It also includes savings in such indirect items as associated reductions in base exchanges, commissaries, hospitals, recreation, and housing support, resulting from a decrease in operating personnel. Trade-in values for Air Force reconnaissance aircraft are estimated to be:

WC-130	\$1.6 million
WC-135	2.6 million
RB-57F	1.0 million
RB-57C	1.0 million

Similar data are not available on RFF and Navy WC-121 aircraft at this time.

2. Service Operating Cost

This is the cost per flying hour for each type of aircraft. It includes POL, maintenance (squadron, field, and depot level) and spare parts. It does not include aircrew pay or base support functions. This cost is tabulated as follows:

Service	Aircraft	Cost/Flying Hour	Service	Aircraft	Cost/Flying Hour
AF	WC-130	\$639	Navy	WC-121	\$110*
AF	WC-135	737	RFF	DC-6A/B	600
AF	RB-57F	821	RFF	RB-57A	482
AF	RB-57C	482	RFF	WC-130	651

* Navy estimate. Includes only fuel, oil, and maintenance support equipment. Does not include spares, parts, crew pay, travel costs, etc.

3. Air Weather Service Unit Operating Cost

Using the entire budget of the 9th WRWg and assuming the total of \$35 million was expended to produce the authorized flying hours, still another cost can be computed for the Air Force aircraft. This now includes aircrew pay, operational overhead, POL, AWS purchases, spares and equipment, and squadron maintenance. It does not include field or depot maintenance. With this basis:

<u>Type Aircraft</u>	<u>Cost/Flying Hour</u>
WC-130	\$598
WC-135	690
RB-57F	821
RB-57C	451
RFF (all aircraft)	550*

DoD Price

Another measure is the price the DoD would charge a non-DoD customer for each flying hour. This is specified in AFM 76-28.

<u>Type Aircraft</u>	<u>Cost/Flying Hour</u>
WC-130	\$929
WC-135	886

F. Measurements Summary

Measurements of meteorological parameters for operational purposes are made by reconnaissance aircraft as specified in the National Plans cited previously. Details are amplified in directives issued by the services involved. For research purposes, measurements are made by the RFF as specified by the requesting agencies.

In general, an internationally approved code form (called "RECCO" for "Reconnaissance") is used to record and report the observations. This is a digital code, approved by the World Meteorological Organization (WMO), which can be relayed as an input to computers operated by the services.

In addition to this basic digital information, further amplifying data are provided on tropical storms. This format is nationally approved. The basic RECCO code form is given in Appendix A additional data on tropical storms are provided as indicated in Appendix B.

Since parameters measured for research purposes vary with the type of research, a formalized procedure for recording and reporting these data is set up on an ad hoc basis. For example, cloud physics data are collected by RFF crews and can consist of liquid water content, icing information, nuclei count, and cloud descriptions.

G. System and Unit Improvements

1. Air Force

a. Air Force WC-130B aircraft are undergoing a three-phase modification and sensor update program (Project SEEK CLOUD) to improve total capability. Phase 1 is expected to be complete on 16 aircraft by November 1970. This work is being accomplished at Lockheed, Marietta, Georgia.

b. In this same period (ending in June 1970), the WC-135 fleet is scheduled for update of sensors and the installation of a single-shot dropsonde dispenser. Two of the

* This assumes that all 1031 hours flown by the RFF in 1970 cost the total budget of \$566,983.

ten aircraft involved under Project "SEEK STORM" (WC-130B's), with Phase I and II modifications complete, will receive new nose radars. These will be off-the-shelf RCA AVQ-30C, C-band radars, which will replace the current APN-59B (X-band) now installed. One of these two aircraft will be further modified by adding a side-looking antenna system at Sierra Research Corporation, Buffalo, New York. Features include a 6-foot parabolic disc, flush-mounted in the forward cargo door.

c. The major improvement program is called Airborne Weather Reconnaissance System (AWRS) and is also referred to as Project 5222. The contract definition phase has been completed by the Electronic Division of General Dynamics, San Diego, and Kaman Corporation of Bloomfield, Conn. The Source Selection Board of the Electronic Systems Division, Air Force Systems Command, has completed its work and has submitted recommendations to the office of the Secretary of Air Force for Research and Development. The Secretary has authorized funds for one prototype. Identification of the contractor and order for the prototype should be released by May of 1971. If the prototype proves itself, the system will be installed on twenty-two AF and one RFF WC-130s and ten AF WC-135s. As now envisioned, subsystems will be obtained for sensor, data processing, on-board display, and communications. The time frame to complete modification of the fleet is of the order of several years.

2. Navy

In 1969, the Naval Air Systems Command was directed to reconfigure a Lockheed P-3A anti-submarine warfare aircraft for weather reconnaissance. Meteorological equipment was obtained from a WC-121N. The end result of the contract with Lockheed-Burbank (signed June 30, 1970) will be an austere prototype WP-3A model, to be delivered to the Navy by October 15, 1970. Features will include:

- a. Installation of an APS-20 radar, set in a retractable pylon assembly in the bomb bay area;
- b. A reset of tilt limit switches for the forward APS-80 (X-band) radar to provide a 30° look above aircraft level, to obtain cloud height information;
- c. Provision of a second radar altimeter;
- d. Installation of meteorological sensors in the forward fuselage to minimize propeller effect;
- e. A flight meteorologist position at the port windows forward of the propellers. Readouts and displays of meteorological and navigational instruments will be available, as well as a thirty-channel recording system;
- f. Installation of various oceanographic sensors, with recorder and linkage to the thirty-channel system;
- g. Dropsonde capability.

3. NOAA - RFF

The RFF will receive one of the Air Force WC-130B's with Phase I and Phase II modification completed.

II. DETAILS

A. Present Hurricane Warning Service (HWS)

1. Description

Detection of hurricanes and timely warning against them has been the task of the Weather Bureau for nearly a century — since the Signal Corps issued a hurricane warning for the coast between Cape May, N. J. and New London, Conn. in 1873. The success of this operation is reflected in the steady decrease in hurricane deaths at a time when population in hurricane-affected areas has doubled and tripled. The present hurricane warning system, headquartered at NOAA's National Hurricane Center in Miami, Florida, is a smoothly operating warning establishment, supported by the experience and dedication of its personnel and the broad new technology that has become an integral feature in America's weather service.

Until the emergency begins, the National Hurricane Center is the visible portion of the Hurricane Warning Service. Then, the warning cycle illuminates the structure of the entire system. The National Hurricane Center is still the focus of action and still controls the total warning apparatus; it also acts as the National Hurricane Information Center, coordinating the flow of bulletins and advisories to the public. Some measure of the evolution of effectiveness in the hurricane warning system can be inferred from a comparison between the loss of human life suffered in the 1900 Galveston, Texas storm resulting in 6000 deaths, and the 255 deaths which resulted from the great Hurricane Camille of 1969. Emphasizing this difference is the fact that Camille was one of the most fearsome storms ever to strike the Continental United States. The increase in the timeliness and accuracy of hurricane predictions and warnings is an outgrowth of improved data collection, communication, and analysis.

2. Data Collection, Communication, and Analysis

NOAA's NWS, through the Director of the NHC, Miami, Fla (NHC-MIA); Meteorologist-in-Charge, Eastern Pacific Hurricane Center, San Francisco (EPHC-SFO); and Central Pacific Hurricane Center, Honolulu, Hawaii (CPHC-HNL) have the responsibility for providing tropical cyclone forecasts and attendant advice for the general public, marine, and aviation interests. These agencies also provide this information to the Armed Forces within their regions of responsibility. In order to provide these services, an extensive data-collection network has been established. Synoptic surface weather observations and upper air soundings from military weather stations, ships, and reconnaissance aircraft are collected by 100-word-per-minute teletype on the military COMET collecting and disseminating system (Fig.I-6). Data from NWS and FAA stations are collected via services "A" and "B" teletypewriter systems (Figs.I-7 and 8). Radar data from NWS stations along the coast forming the Radar Report and Warning Coordination (RAWARC) System are an additional source of information (Fig.I-9). Also, a network of volunteer observers called CHURN (Cooperative Hurricane Reporting Network) comprised of Coast Guard stations and private citizens, provides local information. Each CHURN station is linked to the nearest NWS for reporting purposes. Tidal information, as well as supplemental meteorological data, is furnished by NOAA's Coast and Geodetic Survey Stations. In addition to routine reports collected and analysed on a daily basis at NHC and other centers, when a tropical disturbance or suspect area has been spotted from satellite data, aerial reconnaissance, ship report, or the synoptic



Fig. I-6. COMET collecting and disseminating system.

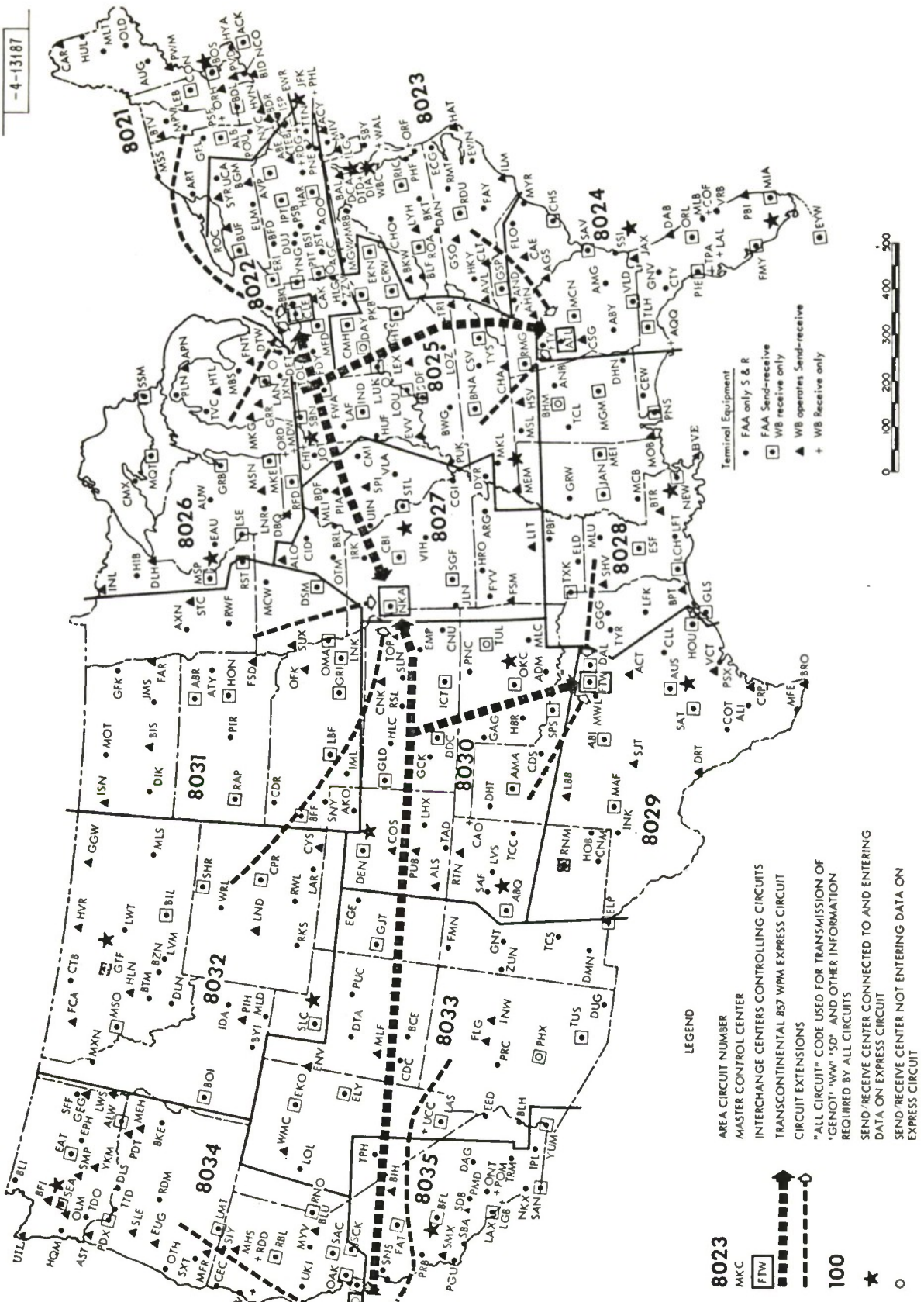
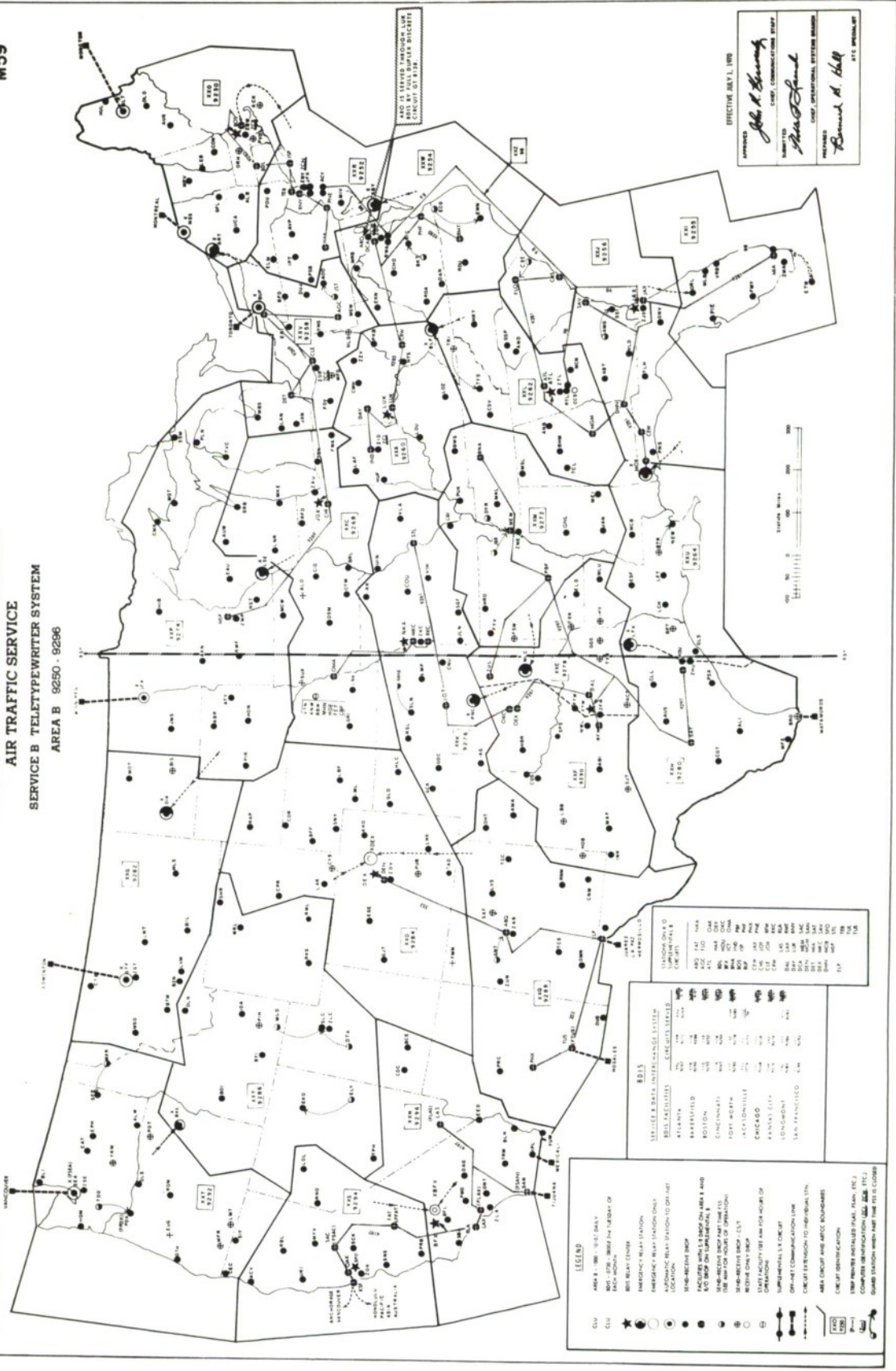


Fig. I-7. Service A teletypewriter system.

DEPARTMENT OF TRANSPORTATION
 FEDERAL AVIATION ADMINISTRATION
 AIR TRAFFIC SERVICE
 SERVICE B TELETYPEWRITER SYSTEM
 AREA B 9250 - 9296

M59

-4-13188



network, special reports are requested. These reports are of aircraft reconnaissance data collected by flying into the suspected storm area along a special flight path specified by the Director, NHC. This aerial surveillance continues until the storm dissipates or coasts in over land, where its remnants are tracked by land-based reporting stations. Parameters measured and reported by aerial reconnaissance include a horizontal observation, at flight level, of the winds, temperature, weather conditions, turbulence, dewpoint, height of the standard millibar level, and a summary of the cloud type, altitude, and coverage within the surrounding observation circle. In addition to data collected at flight level, vertical soundings of the atmosphere from the aircraft to the surface are made by dropsonde. Data telemetered back to the aircraft from the sonde includes temperature, humidity, and pressure height. Some data reduction and processing are required aboard the aircraft before the raw measurements can be transmitted in a usable format to NHC. Processing includes compressional correction applied to the total temperature to derive a correct ambient temperature value, installation and airspeed corrections applied to the pressure altimeter to compute ambient pressure, manual reduction of raw digital dropsonde data to arrive at a usable, correct atmospheric sounding, and other minor corrections applied to current "state-of-the-art" instrumentation. The format used universally to transmit reconnaissance data is the RECCO code, which consists of a series of five-digit numerical groups which can be transmitted easily by voice or radio teletype. Since the data are in coded form, however, some time is lost in data correction, manual reduction, and encoding aboard the aircraft prior to transmission. This varies from five minutes for a horizontal observation to as much as one hour for vertical dropsonde data from high altitudes. In addition to data in the RECCO code format, special reports are transmitted to NHC on the hurricane eye, or center, the vortex, and selected profiles from the center to the periphery of the storm. A systematic means of data relay has been devised to expedite aerial reconnaissance observations from the aircraft to the NHC. (See Communications.)

Because of its mobility, versatility, and response to centralized control and direction, the manned reconnaissance aircraft has become one of the primary data collection sources available to the hurricane forecaster. Due to differences in the instrumentation and capability of aircraft flown by each service, USAF, Navy, and RFF, altitudes flown and storm penetration techniques differ somewhat. However, data reported by all reconnaissance flights into tropical cyclones have been carefully standardized in the National Hurricane Operations Plan. Rapid, direct communication of hurricane observations is stressed in the Plan and should be made available immediately.

The coded data communicated to NHC receive a detailed analysis.

3. Prediction, Alerting, Warning, and Interpretation

The analysis used by NHC has been tailored to serve current prediction techniques. In conjunction with hand-produced analysis such as the three-hourly surface synoptic charts and the subjective techniques implied in its use, a more objective tool in the form of five numerical models is used, which is supplied with inputs from the observation network and run operationally to determine the path and intensity of the storm. These models are not sufficiently developed as yet to provide unique and highly accurate results. At this time, three models are run routinely (NHC-67, Dr. Sanders's, and HURRAN). The remaining two, of Navy origin, are run occasionally. The results of the model runs, together with subjective judgment

of the forecaster, determine the prognosis. Use of these techniques has reduced the mean 24-hour error to 110 nautical miles.

With mean prediction errors of this magnitude, it is essential to have both a good surveillance system and a timely alerting and warning system. To localize hurricane alerts and warnings for specific coastal areas, responsibility is distributed over the Miami Center and four other NWS offices, New Orleans, Washington, Boston, and San Juan. All offices are lined by normal NWS communications and by a special hurricane teletypewriter circuit. This is comprised of the coastal portion of the Weather Bureau RAWARC system, which focuses on hurricane warning activities from 1 June through 30 November, the nominal hurricane season.

These communication systems, plus those of the Office of Civil Defense, Federal Aviation Administration, and the Armed Forces, tie the hurricane forecasters to local governments, law enforcement agencies, and other emergency forces (e. g., Red Cross, Coast Guard) and to the public through mass media such as radio, TV, and the newspapers. This information flow is not one-way. Along the coastline from Brownsville, Texas to Portland, Maine, radar-equipped NWS stations feed information back to the NHC, in addition to their routine reports.

The basic hurricane alert message is called an advisory, a verbal description issued by teletype and other methods at six-hour intervals, describing the storm, its position and anticipated movement, and its prospective threat. When a tropical depression is found to include winds from 34 to 63 knots, it is called a tropical storm and receives a name. Advisories are numbered consecutively, and arrangements are made for intermediate messages when unexpected developments arise. Routine advisories are issued at 0400, 1000, 1600, and 2200 GMT.

As a storm approaches the coast, a "hurricane watch" announcement is included in the advisory. This is a first alert for emergency forces and the general public in prospective threatened areas. The watch is issued when the hurricane poses a significant but uncertain threat to a coastal area, or when a tropical storm threatening that area may intensify into a hurricane with winds over 64 knots.

A "hurricane warning" announcement is included in the advisory when a hurricane is expected to strike the coast within the next 24 hours. These warnings are transmitted to NWS forecast offices, where they are interpreted for local effects, such as coastal peculiarities in conjunction with tides or storm surges, and disseminated to the public served by that office. In many instances, communities have prepared advanced plans for action to be taken when a warning is received. Usually, these plans are formulated by a hurricane preparedness committee, consisting of civic leaders, the local civil defense director, law enforcement and disaster relief personnel, representatives of city utilities and news media, and representatives of State and Federal Governments, including a local NWS official.

The purpose of these plans is to minimize property damage and eliminate loss of life. Of course, not all property can be protected, but it has been found that the existence of a plan will materially aid in protecting human life.

4. Measurements

Aircraft measurements of meteorological elements for operational purposes are carried out by the U. S. Air Force (USAF), Navy, and NOAA's Research Flight Facility (RFF), according to service and data user needs. Procedures for making these measurements are formalized in Operating Procedure Directives developed and published by the individual services.

A standardized format in the form of the World Meteorological Organizations (WMO)

RECCO code has been adopted as the common vehicle for transmission and relay of in-flight meteorological data. This code has proven to be an excellent tool as a wide variety of parameters, under varying conditions, can be reported without changing the basic format of the code. (See Appendix A.) The code has lent itself well to computer processing and is accepted and used in its present form by computers at the National Meteorological Center, the Global Weather Central, and Fleet Weather Centrals.

In addition to RECCO-coded reports, reconnaissance aircraft collecting data in tropical storms transmit special reports of additional parameters which do not fall within the framework of the RECCO code. These reports carry detailed information on the eye or center position of tropical cyclones, vortex data, wind, pressure, and temperature profile data within the storm, and other vital information.

B. Severe Storm Types — Current Reconnaissance

1. Tropical Cyclones, Hurricanes, and Typhoons

For ease of analysis and internal consistency, the procedure for collecting and reporting data in tropical cyclones has been formalized in the National Hurricane Operations Plan (NHOP). This Plan is drafted by the Working Group (WG/NHOP) and published by the Federal Coordinator, NOAA. This document represents a coordinated effort by all agencies participating in storm reconnaissance and forecasting in the North Atlantic and Northeastern Pacific regions. Although the special flight patterns and reporting procedures are adhered to by each agency, differences exist between the services in storm penetration techniques and the details of the data collected. These differences are generated by the use of different types of aircraft, such as USAF's WC-130B and the Navy's WV-121, and the collection of additional weather elements for specific inter-service use, such as the Navy's requirement for sea surface information as observed from a low-level flight profile. The flight tracks are a special requirement levied for the 1970 season by the Director, NHC, to provide a standardized technique for the systematic measuring of parameters in those quadrants of the storm deemed to be of significance to the hurricane forecaster. The detailed, standardized procedures set forth in the NHOP represent a coordinated effort to systematically reconnoiter tropical cyclones, storms, and depressions, to measure those parameters possible within the capability of existing hardware, and to minimize differences introduced by variances in aircraft performance, aircrew experience, and instrumentation.

2. East Coast Winter Cyclones

On a somewhat lesser scale than in the tropical storms, airborne reconnaissance to measure weather parameters is being flown against the East Coast winter cyclones. These missions are flown during the winter and early spring along predetermined tracks off the Eastern Coast of the U. S. to provide adequate weather observations for prediction and, thus, provide timely warning of severe and crippling winter storms.

Specific tracks are required by the NWS through the NHC to the Chief, Aerial Reconnaissance Coordination, Atlantic Hurricanes (CARCAH), who in turn levies the requirement for a mission on the USAF or Navy. RFF aircraft are occasionally used as backup for DoD aircraft involved in these operations.

Horizontal weather parameters measured and observed include all elements listed in the RECCO Code (Appendix A). Additional cloud physics data is collected by RFF aircrews, when available, which consists of liquid-water content, total water content, icing detection, cloud construction, and nuclei count.

Vertical samplings of the atmosphere from the aircraft to the sea surface are obtained by dropsonde at 300- to 500-n. mi intervals, or as determined by the requesting agency. Parameters measured by dropsonde are temperature, humidity, and pressure profiles.

The details governing winter storm reconnaissance are contained in the National East Coast Winter Storms Operations Plan (in press), prepared by the Ad Hoc Committee of the Subcommittee on Basic Meteorological Services.

3. Tornadoes

Aerial reconnaissance on an operational basis is not being flown against tornadoes and severe local storms at this time, as no requirement for these services has been levied by severe local storm forecasting and warning agencies.

C. Research and Operational Measurements - (RFF)

The RFF originally was to be a research-oriented facility, but it can contribute operational measurements. Research programs supported by the RFF include the International Indian Ocean Expedition, Project Stormfury, EQUALANT, ECCRO, BOMEX, and many more.

Recent research supported by the RFF is presented in an article by Friedman and Callahan in Weatherwise (August 1970). Complete discussions on the measurement and recording capabilities, cloud physics, seeding, and special instrumentation available to the researcher with the RFF aircraft may be found in a technical report by Conrad, Connor, and Friedman (in press) (1970).

1. RFF Instrumentation

The instrumentation systems (sensors and recording systems) used for airborne hurricane research should represent the state of the art. Present systems in use, while providing reasonable accuracy and precision, are in many cases obsolescent, if not obsolete. Problems in obtaining replacement parts for maintaining such systems can and often do present acute difficulties.

Current systems requiring updating are:

- (1) AN/APN-82 Doppler radar system (which provides in-flight navigational and wind data);
- (2) Aircraft search and weather depiction radar systems;
- (3) Temperature measuring systems;
- (4) Moisture measuring systems;
- (5) Ambient pressure;
- (6) Absolute altitude measuring systems;
- (7) Specialized cloud physics instrumentation;
- (8) Vertical sounding instrumentation; and
- (9) Data-recording systems.

2. Characteristics, Promise, and Problems, RFF Instrumentation

Navigational accuracy could be improved with better Doppler radar equipment, supplemented with an independent system, e. g. , to provide position information in areas of poor or nonexistent LORAN coverage, and/or other navigational facilities. A better Doppler system would also improve in-flight Doppler "spot winds," perhaps to an accuracy and/or precision on the order of one knot. To obtain this accuracy, the Doppler system should be coupled with an inertial platform. In turbulent seas, a source of error with Doppler systems is the motion of the reflecting surface or spray, resulting in errors as large as the net transport of water below the aircraft. The inertial platform could correct the Doppler navigation and wind systems,

and would be essential to the RFF turbulence-measuring system.

Another example of measurement requirements is the analysis of the in-flow in a hurricane. If the wind direction is in error by only a few degrees, in-flow may be shown in an area where out-flow is actually taking place.

Radar systems now in use are a compromise with regard to maximum range, wavelength, weight, antenna size, and visual displays. RFF aircraft utilize 10-cm, 5.6-cm, and 3.2-cm radar systems. The 10-cm wavelength (APS-20E) is not materially attenuated by precipitation, and therefore, is a useful tool in hurricane work. The antenna used on the DC-6A/B aircraft, however, is too small for best performance. A larger antenna cannot be installed because of aircraft structural limitations. The system has poor resolution in both the horizontal and vertical planes. The APS-20E system provides only qualitative PPI data.

The 5.6-cm radar (WP-101) also provides only qualitative PPI data.

The 3.2-cm (RDR-1D) radar system is used on the DC-6A/B aircraft to provide data on the vertical distribution of "clouds" (RHI) in a plane perpendicular to the aircraft heading. Both quantitative (limited to height and distribution) and qualitative data has been obtained with this system.

The C-54 (DC-4) aircraft also has a 3-cm radar system with a standard PPI presentation. Qualitative data is obtained with it.

Clearly, to improve the radar data, radar calibration is essential to getting quantitative measurements.

All radar scopes are photographed on the RFF aircraft, and data documentation is satisfactory for qualitative data. However, additional (preferably automated) data documentation would be necessary for quantized data recording and analysis.

Temperature systems should have relatively fast response times, and should be accurate to the order of ± 0.5 c. Current temperature measurements are made with the AN/AMQ-8 (vortex) temperature-measuring system and the Rosemount total temperature-measuring system. (Data from the Rosemount system must be corrected for dynamic heating to obtain the ambient temperature.)

The vortex system may suffer from "wet-bulbing" in heavy precipitation. Its response time is 10 to 20 seconds, with an error of ± 1 c over the range -80c to + 50c.

The Rosemount system provides a faster response (20 msec to $1/e$ response) and an error of ± 1 c over the range -70c to +30c. Rosemount temperature data must be corrected for compressional effects (i. e., the total, not the ambient temperature, is measured directly by this system).

Clearly, it would be desirable to have a system that measures ambient temperature directly with the Rosemount response time, but does not suffer from wet-bulbing in heavy precipitation.

Moisture content information is gotten with an infrared hygrometer (IRH) — vapor density measurements — and a dew (frost)-point hygrometer. The IRH operates in the range 0 to 20 gm^{-3} or more, within 5 to 10% error, responding to a 90% change in from 0 to 10 seconds.

The dew (frost)-point hygrometer provides dew (frost)-point directly, has a response time of approximately 10 seconds and is within ± 2 c of values derived from IRH system data. There is an additional problem (heat sink). At very low humidities, a heat sink problem might increase the response time to 2 minutes. This does not appear to be important in hurricane

operations. Improvement of the IRH/dew (frost)-point systems and/or implementation of "state-of-the-art" systems for airborne use should be considered.

Ambient pressure data is provided by a Giannini pressure transducer with an error of ± 0.5 mb over the range of 1050 to 50 mb. A response rate of 10 mb/sec^{-1} is felt to be satisfactory.

The absolute (radar) altimeter system utilized at present operates at altitudes from 200 to 50,000 feet with an error of approximately $\pm 1\%$. The response time, 500 ft/sec^{-1} , is adequate for hurricane research. The major problems encountered with this system are lack of systems support, test, and maintenance facilities.

Cloud physics instrumentation provides information on drop-size distribution in the storm, liquid-water content, volume median drop size, number and distribution of cloud particles and nuclei, and other items. These highly specialized systems are not generally available commercially.

Cloud seeding can be done with RFF aircraft, but improved pyrotechnics and delivery are needed.

Vertical sounding data, that is, the vertical distribution of pressure, temperature, and humidity, is currently supplied with the AN/AMT-3 dropsonde system. This system should be updated with state-of-the-art equipment as soon as practicable.

Recording systems: The variety of individual preferences and logistic support requirements necessary to record data simultaneously from a representative number of different meteorological instruments makes it difficult to identify a "best" type of recording system to meet all research needs. Of the automatic devices currently available, the most widely used are the digital, oscillographic, and photographic recording systems.

Digital data recording systems (magnetic tape) offer the advantage of high-speed recording, in which the data are treated as numeric values and recorded at finite intervals of time (normally for hurricane flights, the recording rate of one complete sample per second is utilized). In this manner, the recorded information may be processed readily with compatible ground-based electronic data-processing systems.

Preliminary evaluation of the recorded data from the computer-printed record is not ordinarily feasible until manual or automatic plotting of the data is accomplished. Oscillograph or analog recording devices are therefore preferred by many because initial evaluation of the data may be performed directly. The oscillograph record provides one with a continuous analog record of selected parameters. However, data reduction preparatory to computer processing requires laborious and time-consuming conversion of the analog record to digital form.

Photographic data-recording systems using analog indicators are relatively simple and inexpensive. They are particularly adaptable to short-term projects for which the time and funds available preclude establishing more elaborate systems, and where the volume of data to be collected is small.

The RFF has established digital data-recording systems (magnetic tape) as its primary recording medium. Analog recording systems, including FM magnetic tape, oscillograph recorders, and photographic systems are also utilized. Therefore, the RFF is able to provide backup recording facilities for hurricane data, in addition to matching sensor resolution and response times to appropriate primary recording systems.

Further utilization of the FM magnetic tape system (used primarily for sensors with fast response times) is anticipated in the future. The capability for A- to -D conversion with the aircraft digital systems is also contemplated. A recently acquired digital system, currently installed on the C-54 aircraft, is being evaluated by the RFF. This concept will be the basis for the development of future digital and A/D systems.

D. Meteorological Sensor Calibration Program (Current Methods)

1. General

In precise measurement of altitude, two of the major difficulties that arise are, first, to sense the true static pressure from a rapidly moving aircraft, and second, to make an instrument which is accurate enough to indicate the pressure that has been sensed. Errors arising from the sensing problem are called "installation errors", and those arising from the indicating problem are called "instrument errors." Thus, the accuracy of the heights of pressure surfaces reported by Air Weather Service (AWS) reconnaissance aircraft, both flight-level and dropsonde, depends upon the accuracy of the radio altimeter and pressure altimeter systems used by the meteorologist. Since a relatively large error may be present in either system, the two systems have to be calibrated coincidentally. Any change in either system necessitates a recalibration. The instrument errors affecting the accuracy of the pressure altimeter are hysteresis, friction, zero-setting, readability, temperature, scale, and static-system leakage. The installation error is commonly called "the static source error." Each of these errors is explained and discussed in subsequent paragraphs. As pressure is usually one of the meteorologist's prime concerns, he must take a personal interest in the calibration and maintenance of the entire static pressure system. The confidence of ground weather personnel, in the validity of reconnaissance observations, is often won or lost by the accuracy of the pressure reports. In practice, calibration corrections are obtained for the total system, absolute altimeter and pressure altimeter combined, and applied to the pressure altimeter readings to simplify computation procedures.

2. Altimeter Errors

a. Hysteresis and Friction Errors: These errors result from sluggishness of the aneroid bellows and from friction in the transmission mechanism between the aneroid and the pointers. These errors can be reduced but not completely eliminated by tapping the altimeter before each reading. Maintaining constant cruising level for at least a half-hour before and during the reading of the altimeter further reduces the hysteresis error.

b. Zero-Setting Errors: Since altimeter zero-setting errors are of small magnitude, the setting in the barometric scale window may be changed to altimeter setting for purposes of ground-checking the pressure altimeter.

c. Readability: The instrument is graduated for every 20 ft. During flight, the altimeter is read to the nearest 10 ft. Care in reading will eliminate errors of parallax.

d. Ambient Temperature: The pressure instruments are normally checked (calibrated) at a temperature of approximately 20°C. Any variation in the instrument temperature during actual operation will introduce an error. Construction of the instrument compensates partly for this error, but the compensation will decrease with increasing height. During normal cruising with an operational cabin heating system, the temperature will seldom deviate more than 5°C. The error introduced is approximately ± 10 ft.

e. Scale or Instrument Error: The diaphragm deflection of the aneroids on the ideal altimeter should have a linear relation to the pressure change. Due to material imperfection and the construction itself, the diaphragm deflection is not the same at all heights for the same given change in atmospheric pressure. The magnitude of this error normally increases with height.

f. Static-System Leakage: Leaks in the pitot-static system lines will cause erroneous readings of pressure heights and indicated airspeed readings. The maintenance technical orders for each type of aircraft establish the frequency with which the checks for leaks are performed. However, additional checks for leaks in the static lines may be performed as required when leaks or water in the lines are suspected.

g. Installation Errors: The static pressure error is a defect of the source of static pressure, not of the instrument; it arises purely from the aerodynamics of the moving aircraft. For a given geometry of an aircraft, the error is a function of indicated airspeed, altitude, pressure altitude, and gross weight of the aircraft. The static pressure errors for many types of aircraft are determined during flight tests and recorded in the form of a flight data correction graph in Tech Orders. Generally, this is not the true correction for all individual aircraft, since the static pressure error of two apparently identical aircraft may be different. Each aircraft must be separately calibrated by flight calibration methods. Static pressure errors are especially prevalent in high-speed jet aircraft. A boundary layer with a slight vacuum is produced over the flush mounted static ports, causing a large-magnitude error in the pressure altimeter reading. This correction varies with airspeed and altitude. The variability of the correction renders it extremely difficult to include in single corrections, such as the historic correction, and is usually applied separately to the pressure altimeter reading.

E. Historical Calibration Method

1. Altimeters

This method is the primary method for calibrating altimeter systems on all AWS reconnaissance aircraft. Historical corrections are averages of the differences in standard pressure surface heights measured by an aircraft, as compared to selected radiosonde stations. The radiosonde heights are assumed to be correct and aircraft heights are corrected to agree with them. A minimum of three flights will be obtained before the averaged results will be published as the historical correction data. This historical data on each aircraft is averaged at least every two weeks and results published in linear feet. The primary instrument will be located at the meteorological officer's position, and the pilot's altimeter will be calibrated as a backup. To verify aircraft heights when the radiosonde station is more than ten miles from the aircraft calibration point, the following procedure is used:

Using the geostrophic wind equation:

$$V = \frac{-g}{2\Omega} \frac{D}{\sin \varphi n}$$

where

V = wind velocity in knots,

D = change in height in linear feet,

n = distance in n.mi between the RAOB station and calibration point,

φ = mid-latitude between the two points.

As g and Ω are constant, a K value can be found that is dependent only on the $\sin \phi$. This value can be substituted into the equation for any given latitude.

Therefore:

$$V = K \frac{D}{n} \quad \text{or} \quad D = \frac{n}{K} V$$

In addition to flight calibrations just described, a ground calibration is performed on each altimeter. With the current altimeter setting indicated on the instrument, the altimeter should read the field elevation plus the height of the altimeter above the runway.

2. Temperature Calibration

Rosemount total temperature systems are calibrated historically much the same as the altimeter systems. Temperature system at the navigator's position is usually used as a backup. Correction data is published along with the altimetry data.

F. Baseline Calibration of Dropsonde Instruments

Although a detailed discussion of the baseline calibration procedures can be found in operating manuals published by the various agencies using these instruments, the intent here is to present a general synopsis of the numerous steps taken to insure those accuracies obtainable with current sensors. In several cases, such as sea-level pressure and relative humidity, the degree of accuracy desired by the National Hurricane Center cannot be consistently attained by contemporary equipment.

Baselining includes calibrating the pressure, temperature, and relative humidity sensors, computing correction factors for these elements, and checking the sonde for proper operation. Preparation of data tapes to load correction and calibration data of the pressure sensor into the computer, checking the sonde's analog voltage references and transmitting frequency are also done during the baseline function.

To properly calibrate the sonde, a controlled atmosphere is required. This is supplied by the baseline calibration set, described in detail in AF T.O. 12M42 AMT 13-2, and a Tenny vacuum chamber. The test set is to check the temperature and humidity elements and resistance values. The vacuum chamber serves two purposes: (1) to exercise the pressure sensor under near actual atmospheric conditions, and (2) to calibrate resistance readings after the sonde has been run up and down through at least 10,000-ft pressure altitude. This verifies the proper functioning of the pressure sensor with altitude change.

After charging and baseline calibration sondes are stored in a low humidity temperature controlled area until used. Stocks are usually used within 15 days of baselining. Prior to ejection from the aircraft, the sonde is placed in the drop chamber and checked again immediately prior to the drop.

G. Other Flight Instruments

Standard flight instruments such as the Doppler Navigation System receive routine maintenance and calibration in accordance with individual maintenance T.O. specifications for each system.

H. Communications

The meteorological data collected on Atlantic and Caribbean hurricanes is relayed from the aircraft by HF voice transmission for immediate retransmission on the hurricane network, as depicted in Appendix E for the Air Force and Navy. Also depicted is the data usually transmitted by voice in the Eastern Pacific for the Air Force and the Navy. The WC-135's

and WV-121's have a 100-word-per-minute teletype capability that speeds transmissions when the circuit is operational. Western Pacific data is voice-transmitted to the nearest air/ground airways for retransmission to interested users, such as the Joint Typhoon Warning Center (JTWC) on Guam. Only meteorological parameters and clear text analysis summaries are sent, as there is no provision for sending real-time radar or camera coverage. VHF/UHF is not feasible due to line-of-sight limitations. Even HF use is difficult in and near the severe storms.

East Coast winter storm data is sent by HF voice via military air/ground stations to the weather monitor at Charleston Air Force Base for retransmission into the automated weather networks (civil and military).

I. Accomplished or Planned Improvements

1. Air Force

Air Force AWS WC-130's are presently undergoing a two-phase modification and sensor update program to improve total capability. Phase I (see below) will be completed on the sixteen B models by November 1970. All twenty-two aircraft will have both Phase I and Phase II (see below) complete by September 1971, with most of them ready for the storm season. An Airborne Weather Reconnaissance System (AWRS), called Project 5222 (see Appendix F) is now in the contract definition phase and is scheduled for implementation over the next few years. Funding phase points of this project will permit continuous update commensurate with the current state of the art. Two WC-130's are to receive a radar modification, replacing the nose radar (APN-59B) with an off-the-shelf RCA AVQ-30C. Additionally, Sierra Research will install a six-foot, flush-mounted, side-looking radar on one of the two AVQ-30 aircraft. All three radars are scheduled for test and evaluation only (see p. 25). The WC-135 fleet is scheduled for update of sensors and installation of a single-shot drop-sonde dispenser and humidity sensor.

2. Navy

The two Navy weather reconnaissance squadrons have been equipped with WV-121 aircraft since the mid-1950's. About 1967, support was becoming a problem and the Naval Air Systems Command (NASC) was directed to recommend a replacement weather reconnaissance aircraft. After comparative tests, the Lockheed P-3 was selected over the WC-130 and WC-121N. Within the Navy, a worldwide support capability for P-3 aircraft already existed, and this was an important factor in making the choice.

By 1969, funding was austere, and NASC was directed to proceed with the configuration of one P-3 aircraft. An early P-3A antisubmarine warfare aircraft has been made available, and meteorological equipment from a WC-121N is being relocated in the P-3 (Cf. p. 25).

3. RFF

Acquisition of a WC-130B and the implementation of a state-of-the art integrated data-acquisition system for the aircraft is planned for 1970-1971, with a follow-on program to take advantage of AWRS technology.

The updating of the present RFF aircraft complex and instrumentation systems, further study and data validation, commonality and standardization of systems and

techniques with other aviation facilities engaged in environmental research, are but a few of RFF's goals for the near future.

J. Air Force SEEK CLOUD Program

1. Phase I

Phase I consists of:

- (1) Installation of an APN-42A radar altimeter, in addition to the SCR-718;
- (2) Installation of a weather officer's work table and instrument console;
- (3) Installation of AN/AMQ-28 Rosemount total temperature measuring system;
- (4) Installation of an AN/AMQ-29 Hewlett-Packard dropsonde data recording system with the capability to use the AN/AMT-13 instrument. (Desired dropsonde pressure accuracy is ± 2 mb; present limits are ± 6 mb).
- (5) Installation of MA-1 Pressure Altimeter at ARWO (Airborne Reconnaissance Weather Office) position.
- (6) Installation of single-shot (AMT-13) dropsonde dispenser.

Most aircraft in the WC-130B fleet will have received Phase I and Phase II modifications by the 1971 hurricane season—all by September 1971.

2. Phase II

Phase II consists of:

- (1) Installation of a Cambridge Systems Optical Dew Point Hygrometer, Model 137-C3-SCT-MR;
- (2) Installation of a Barnes sea-surface temperature indicator, Model PRT-5, 9 1/2 to 11-1/2 micron range;
- (3) Installation of a Hewlett-Packard desk calculator, Model 9100B, to expedite dropsonde* data reduction;
- (4) Installation of strip-chart recorders for:
 - Wind direction and speed,
 - Dew Point,
 - Temperature,
 - Pressure altitude and radar altitude,
 - Sea-surface Temperature,

3. Phase III

Phase III will consist of:

- (1) Installation of a Rosemount Model 102 temperature probe (for temperature reference for central air data computer);

* Provides recording capability as sensor signals become available. SEEK CLOUD Phase II provides for recording total temperature, dew point, radar altitude, and sea-surface temperature. SEEK CLOUD Phase III will provide signal outputs to record wind parameters, pressure, altitude, and improved (expanded chart scale) resolutions of radar altitude.

- (2) Installation of a CPU-43 central air data computer (provides true air-speed reference for wind vector computer);
- (3) Installation of CP-721 wind vector computer (N-S vector and E-W vector output);
- (4) Installation of Rosemount (830 B/C type) pressure transducer (provides pressure altimeter signal for recording and as input to central air data computer.)

K. Air Force Project SEEK STORM

Under Project SEEK STORM, two WC-130B aircraft are presently in modification at Lockheed, Ga., receiving the AVQ-30 forward-looking C-band radar. This radar set will replace the old X-band AN/APN-59 on aircraft #495 and #725. (The AVQ-30 should allow the navigator adequate detail of the storm to aid safe navigation into the eye.) Aircraft #725 will also receive a side-looking antenna system at the Sierra Research Corp., Buffalo, New York plant to aid in surveying a larger portion of the storm.

Sierra's system will have a 6-ft parabolic antenna mounted in the forward cargo door of the WC-130, but will require no structural modifications for installation. This added capability will provide the hurricane forecaster with a complete "framework" depiction of the hurricane and a better insight into forecasting intensity and movement of the storm.

L. Navy Improvement Program

The major cost item in reconfiguring a single PV-3 will be the installation of an APS-20 radar. This area was specified in a Request for Proposal (RFP) issued by the Navy in the spring of 1970, intended to provide an austere prototype WP-3A model. A contract was signed on 30 June 1970.

This single aircraft is scheduled for delivery to the Navy by 15 October 1970. Features of the WP-3A configuration include:

- (1) A retractable APS-20 radome-pylon assembly in the bomb bay area.
- (2) A reset of tilt limit switches for the forward APS-80 X-band radar to provide a 30° look above the aircraft level to give cloud height information.
- (3) Provision of a second radar altimeter, with indicators in the cockpit and other new positions.
- (4) Installation of meteorological sensors in the forward fuselage to minimize effects of the propellers, which will be aft of these sensors.
- (5) A flight meteorologist position will be installed at the port window forward of the propellers. Instruments will include:

Radar display of APS-20 or APS-80 radar,
 Ground and airspeed,
 Radar and pressure altitude,
 Barometer,
 Dew point,
 Heading,
 Drift,
 Flight lead wind direction and speed,

Aircraft position,
Appropriate instrument lighting for night observations,
Polaroid camera for radar scope photography,
A thirty-channel data logging system.

- (6) A relocation of the radio operator to a position across from the flight meteorologist, with a capability to extract data from the flight logging system for transmission via HF radio.
- (7) Additional APS-20 radar controls have been installed for the radar operator, and APS-80 or APS-20 display can be selected for the APA-125 indicator.
- (8) Also, the second aerographer's position includes an RO-308/SSQ-36 bathythermograph recorder, a Mosley 680 sea surface temperature recorder, dropsonde control switch, MK 260 brush visual recorder to display wind, temperature, dew point, and "D" value. A five-channel remote display readout, which can display any of the thirty channels in the data logging system is positioned between the two aerographer positions.
- (9) The first of these aerographer stations includes an AMQ-17 aerograph set, an AMR-3 radiosonde receptor, a Cambridge Systems dew point hygrometer, pressure and radar altitude, aircraft position, heading, speed, drift, cabin and external barometric pressure, and time.
- (10) In the aft section, facilities are provided to eject the dropsonde and install the ART-4 radiation thermometer system.

Sketches of the WP-3A are appended. (See Figs. I-10 and I-11.)

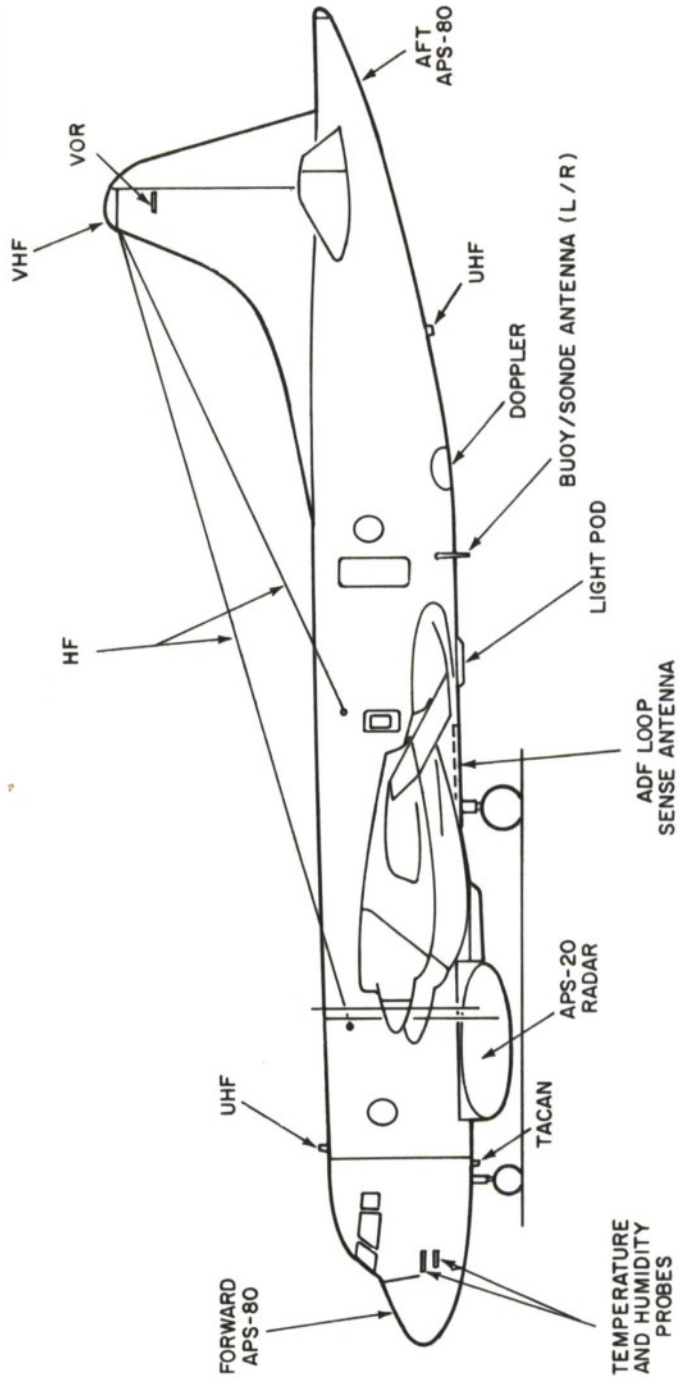


Fig. I-10. Side view of proposed weather reconnaissance configuration of Navy WP-3A aircraft.

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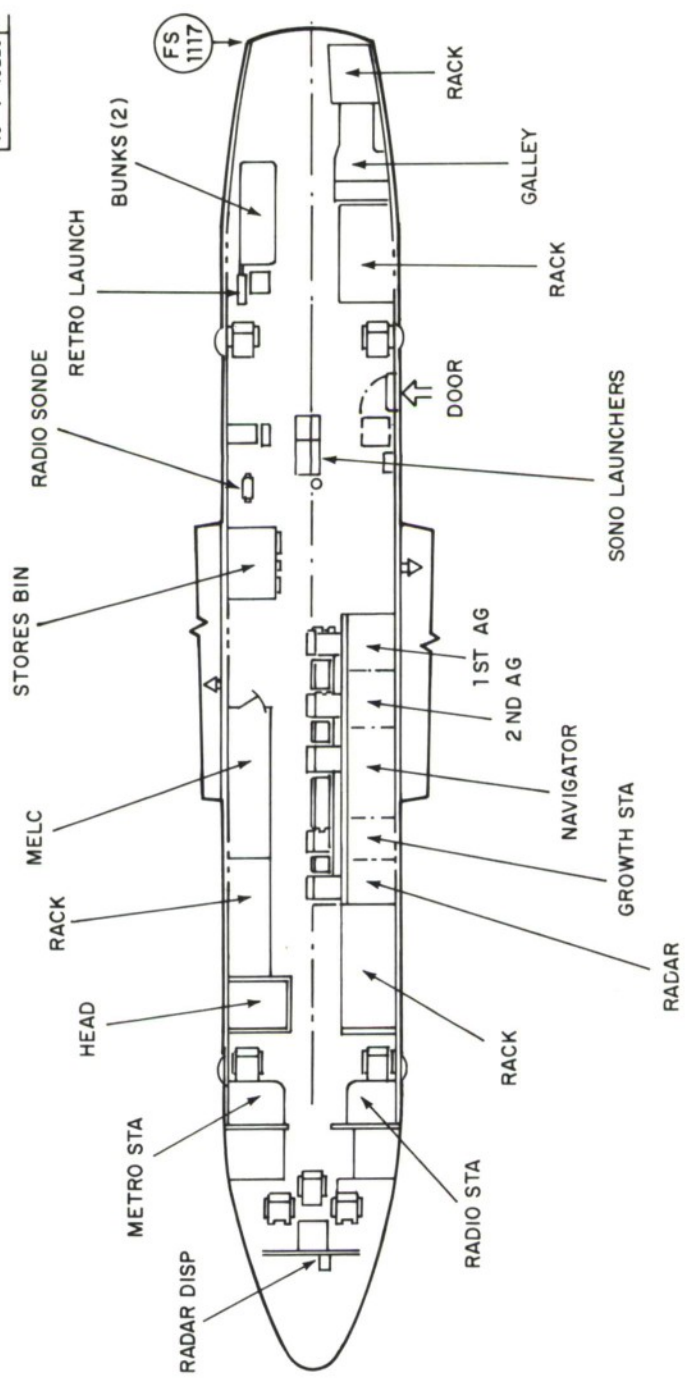


Fig. I-11. Plan view of proposed weather reconnaissance configuration of Navy WP-3A aircraft.

III. PROBLEMS AND RECOMMENDATIONS

The previously mentioned improvement programs and the recommendations of this report should ensure more accurate instrumentation and near-complete collection of the parameters now desired by the meteorological scientist. The present system of voice-relaying the data through weather monitors stationed at selected military air/ground HF sites does not provide the timeliness or accuracy desired by the user.

A. Recommendations

1. All reconnaissance aircraft should be equipped with high-speed teletype equipment.
2. Dedicated weather reporting, HF frequencies should be assigned the reconnaissance mission to eliminate congestion on normal airways frequencies.
3. NHC should be equipped with a dual HF/SSB capability in order to receive the data direct from the aircraft. This would also allow voice contact between the forecaster and the aircraft, so questionable data could be checked and suggested track changes coordinated.
4. Transfer the weather monitors presently augmenting the Charleston Air Force Base Weather Station to CARCAH. They would handle the hurricane work load as well as the normal reconnaissance and East Coast storm data.

B. Operational Requirements

In order to accomplish the researcher's scientific objectives, pre-operation planning must be accomplished. Aircraft and crew capabilities are as important as instrument system capabilities and should be considered prior to the establishment of the Operations Plan.

Reliable communications and aircraft control, air-to-air, ground-to-air, are indispensable for both research and operational missions. Data collected by the aircraft are useless for operational requirements if this data cannot be transmitted to NHC. The establishment of a reliable direct-communications complex between the aircraft and NHC should be implemented as soon as practicable.

Crew training and experience is also an important consideration in order to successfully accomplish hurricane research/operational objectives.

Military crews are routinely rotated from weather assignments to other types of duty. Therefore, they are not able to build up the level of experience presently found at the RFF, whose crew members (professional meteorologists, aircraft operating and maintenance crews, and instrument engineering staff) have been engaged in hurricane research/operations for an average of approximately nine years.

C. Provision of Radar Scope Display to Forecasters in Real Time

Proceedings of this panel have pointed to a downstream development of sophisticated reconnaissance subsystems, which may take years to test and provide for operational purposes.

In the interim, valuable information is available to the airborne weather observer on radar scopes in the aircraft. While the introduction of voice communications between the forecaster and the aircraft would permit a literal description of the radar picture, it seems well within the realm of modern technology to transmit the picture itself to the same forecaster.

Though the radars and the pictures may not represent the ultimate, it seems that for the next few years an immediate improvement in data available to the forecaster could be accomplished by relaying the current scope picture to the ground.

D. Aircraft Clearances

The problem of inserting reconnaissance aircraft into a medium already crowded with commercial flights is difficult. This is particularly true in the East Coast winter storm operations, which generally require flights in and off the megalopolitan area.

Due to the nature of the air traffic control system, clearances for reconnaissance aircraft are sometimes difficult to obtain; safety of all aircraft is very rightly the primary consideration. The situation becomes even more difficult when aircraft are handed off from one air traffic control center to another.

In the case of an active hurricane threatening coastal areas, normal air traffic is considerably less dense than usual, and the problem is not as critical. However, evaluation of priorities in the case of an East Coast snow storm is much more difficult and the situation is further complicated by the existence of warning and restricted areas.

In some instances, cases may arise where the comfort and convenience of passengers on a routine commercial flight may have to be slightly affected to ensure adequate reconnaissance of a storm whose potential damage may run into millions of dollars. It is recognized that this will be a difficult decision at best, and it is emphasized that flight safety is of paramount importance.

Nevertheless, it is strongly urged that DoT/FAA be tasked to provide priority handling of reconnaissance aircraft in these congested areas when a damaging storm is in existence.

E. Sea Surface Temperature

The Phase II modification to the WC-130 fleet will provide sea surface temperatures; however, thick cloud coverage below the aircraft will negate data collection. For this reason, it is recommended that the AWS WC-130/WC-135 fleet be modified to use the Navy Bathythermograph sonde. This will require a removable modification to the single-shot dispenser and installation of the appropriate recorder (RO-308/SSQ-36).

Routine dropsonde observations provide temperature, pressure, and humidity at a series of elevations below the aircraft. At present, these data are manually reduced on-board, though in Phase II of the Air Force SEEK CLOUD program, the process will be automated. However, successful tests of a new capability to determine winds at these same sub-track points have been made by Beukers Laboratories, Inc. Using LORAN-C or Omega, plus a relatively inexpensive receiver aboard the aircraft, and a minor modification to the sonde itself, these winds would convert the present useful dropsonde data into an invaluable equivalent of a rawin-sonde at discrete steps along the flight path. It seems highly desirable to authenticate this technique in further tests and to install the necessary components as soon as the results indicate its true worth.

F. Comparison Flights

One of the major problems in the data utilization area concerns the comparability of measurements. While Air Force, Navy, and RFF each calibrate instruments, the devices are not obtained from the same manufacturer, and there is no assurance that a flight-level temperature (or any other measurement) would be exactly duplicated from any other aircraft at the same time and location.

There are really two situations involved here. In the first place, there are no standards for sounding measurements, if the radiosonde is accepted as an instrument of variable accuracy, itself. Though this is the fundamental problem, it is not as readily attacked as attempting to establish comparability between the systems used in the different aircraft.

With the operational reconnaissance fleets and the RFF heavily committed to hurricane and East Coast winter storm reconnaissance, it seems advisable to establish a comparison run in an interval when aircraft are more readily available. Details can be worked out at a later date, but in general, a few flights over three or four ground-based radiosonde stations, extending on the order of 500 miles out and back from a mutually acceptable base, could establish the comparability of the airborne flight-level data from one aircraft in each facility, and a check of the dropsonde capability. Aircraft would fly parallel and simultaneous routes, with a separation of about a mile to ensure non-interference of radars and to collect data in the routine RECCO and dropsonde formats.

G. Commonality, Standardization, and Single Manager

Historically, the aerial weather reconnaissance program has been plagued with a lack of commonality of equipment used by the various service agencies. The Air Force, Navy, and RFF each have different type air-frames and sensor equipment. The effect of these unlike systems produces differences in capability, procedures, and data acquisition, dissemination, calibration, and accuracy. Only the Air Force and the RFF are completely dedicated to providing the exact East Coast storm route and profiles desired by the NWS. The Navy meets some of these requirements, but usually only where they are compatible with fleet requirements. Hurricane reconnaissance procedures have been standardized, but the Navy WV-121's are not able to perform low-level maneuvers within eyes that are less than twenty miles in diameter. The Air Force has embarked on a program to completely standardize its tropical cyclone fleet and RFF is planning to configure their newly acquired WC-130 with the same basic equipment. Navy has selected the PV-3 as their follow-on weather reconnaissance air-frame and plans to use the same equipment that is presently on the WV-121's. Many of the presentations given to this panel stressed the need for commonality and standardization of the operational equipment. The best method to provide this would be to establish a single manager for operational reconnaissance, keeping the research and development in its proper place with the RFF. Commonality, standardization, and cross-calibration would easily be accomplished with centralized command and control.

IV. CONCLUSIONS

This review of contemporary operations was prepared to give the Study Group an overview of how these vital functions are now being carried out, an indication of current and potential problem areas, and a summary of improvement programs and plans. Currently, we spend less than \$500 million for this nation's entire program of meteorological services and supporting research. Moreover, it is clear that all aircraft used for weather reconnaissance are ad hoc adaptations of air frames designed specifically for other purposes. In spite of handicaps such as hand-me-down air frames and severe budgetary limitations, weather reconnaissance aircraft have made and continue to make unique and key contributions to this nation's ability to warn its citizens of the threat and approach of dangerously violent weather.

APPENDIX A

The Reconnaissance Code (WMO)

The RECCO Code format is depicted in a series of five-digit groups. Listed below is a break-out by group of the coded parameters. For a discussion of the accuracy of the sensed parameters. see Appendix B.

Group No.

- 1 (97779), Indicator group identifying code as a RECCO report with or without radar.
- 2 (GGggiu), Time group and humidity indicator. (ZULU)
- 3 (YOLaLaLa), Day of week, octant of globe, latitude in degrees and tenths.
- 4 (LoLoLoBfe), Longitude in degrees and tenths, turbulence, flight conditions.
- 5 (hhhdtda), True altitude of aircraft in decameters above msl, type and reliability of wind.
- 6 (ddfff), Wind direction at altitude in 10¹ s of degrees true, wind speed at altitude in knots.
- 7 (TTTdTdWg), Temperature and dewpoint in whole degrees centigrade, present weather.
- 8 (mjHHH), Remarks on present weather, index pertaining to HHH, height of standard millibar level in meters (below 700 mb) or decameters (above 700 mb).
- 9 (1KnN1N2N3), Group indicator, total number of cloud layers coded, cloud amounts in first, second, and third layers.
- 10 (ChhHH), Cloud type, altitude of base of cloud, altitude of top of cloud.
- 11 (chhHH), Same as above for each layer of cloud through the third layer; then the 9 group is repeated for all layers beyond the third.
- 12 (4ddff), Group indicator, direction of surface wind in tens of degrees true, wind speed at surface.
- 13 (5DFSDk), Group indicator, direction of surface wind, force of surface wind, state of sea, direction of swells.
- 14 (6WsSsWcDw), Group indicator, significant changes in weather, distance to the change, weather off course, true bearing to weather off course.
- 15 (7lrItSbSe), Group indicator, rate of icing, type of icing and contrails, distance to beginning of icing, distance to ending of icing.
- 16 (7hiHiHi), Group indicator, altitude of base of icing, altitude of top of icing.
- 17 (8drdrSrOe), Group indicator, bearing of echo from aircraft in 10 degree true, distance of echo center in 10¹ s of n.mi., orientation of ellipse.
- 18 (8WeAeCei), Group indicator, ellipse width of echo diameter, length of major axis in 10¹ s of n.mi., character of echo, intensity of echo.

In addition to the coded groups indicated above, plain language remarks are used to further describe any situation not covered within the framework of the code.

A more detailed discussion of the RECCO Code can be found in Air Weather Service Manual 105-1.

APPENDIX B

Atlantic and Eastern Pacific Joint Requirements for Aircraft RECCO Data

Atlantic and Eastern Pacific Joint Requirements for Aircraft RECCO Data

Data Required	Altitudes at which data are required	Areal portion of cyclone in which data are needed	Time or frequency of observation	Accuracy Required
Location of eye or center	At 700 mb or below, except that, if winds are 100 knots or higher, penetration may be made at 500 mb.*	At center or within radar range.	Atlantic-- Every 6 hours at 00Z, 06Z, 12Z, and 18Z, except additional 3-hourly fixes at 03Z, 09Z, 15Z, and 21Z for tropical cyclones within 500 miles or 48 hours of any land areas and not within range of land-based radar. Eastern Pacific-- 1. Two fixes daily when cyclone is within 600 miles of the United States or within 300 miles of Baja, Calif. Fixes at least 6 hours apart, preferably near 15Z and 00Z (15Z if only one). 2. Otherwise, one daily fix at 18Z when cyclone is in San Francisco area of forecast responsibility.	+ 10 mi
Dimensions and configuration of eye.	At 700 mb or any lower level.	"	"	Indeterminate
Central pressure	"	At center	"	+ 2 mb
Radius and strength of maximum winds	Surface or by Doppler radar at 700 mb or lower.	Whenever maximum winds are found, but usually within 50 miles of center.	"	+ 5 mi + 5 kt
Radar echoes and direction of Cb blowoffs	"	Radar echoes-areas outside the principal rain shield. Blowoffs observed.	Irregular.	Indeterminate
Winds, pressure heights, clouds, and weather en-route to cyclone and return	Winds and pressure heights at flight level; clouds and weather as observed from flight level.	From latitude 30° N southward.	At 180-mile intervals except at 120-mile intervals when within 300 miles of cyclone center or as indicated in Atlantic flight patterns.	Winds, 5 kt Pressure heights, 10 meters

Atlantic and Eastern Pacific Joint Requirements for Aircraft RECCO Data - (continued)

Data Required	Altitudes at which data are required	Areal portion of cyclone in which data are needed	Time or frequency of observation	Accuracy Required
Winds, pressure heights, and weather in suspicious areas	Daily tracks as per interservice agreements. At 700 mb or as low as 1,500 ft for investigative flights, as required.	Variable radius 100-300 mi.	Daily tracks as per interservice agreements. Special investigative flights as required.	\pm 5 kt 10 meters
Height of eye wall	Atlantic: as specified in flight pattern. Eastern Pacific: 300 mb.	Atlantic: by quadrant at eye wall within radar range.	Atlantic: as specified in flight pattern. Eastern Pacific: daily observation.	2000 ft
Wind profile	Specified flight pattern altitude.	By quadrant of cyclone	Radial distance from center of maximum, 63 kt, 50 kt, 30 kt.	\pm 5 mi
Temperature profile	"	"	Center, R = 15 n.mi., R = 30 n.mi., R = 45 n.mi., R = 80 n.mi.	0.5°C
Dew point profile	"	"	"	0.5°C
D-value profile	"	"	"	10 ft.
Sea-surface temperature	1,500 ft.	Vortex periphery along specified operational flight pattern.	Equally spaced observations.	0.5°C
Equivalent potential temperature or temperature, dew point pressure	27,000 ft.	Vortex periphery along specified operational flight pattern.	Equally spaced observations.	0.5°C \pm 1 mb

* Low-level reconnaissance to be terminated whenever in the judgment of the aircraft commander the safety of the aircraft and crew would be jeopardized by continuing.

APPENDIX C

Tropical Cyclone Report Forms

INITIAL TROPICAL CYCLONE EYE/CENTER REPORT

UH AIR FORCE GULL
 NAVY _____ EYE/CENTER LOCATED BY _____
 *NOAA

AT _____ DEGREES _____ MINUTES NORTH _____ DEGREES _____

MINUTES WEST AT _____ ZULU

* NOAA participates only in the Atlantic area.

1. The first center fix obtained on each flight will be dispatched as rapidly as possible using Form 1.
2. This form is used in the Atlantic and Eastern Pacific areas.

DETAILED EYE/CENTER DATA MESSAGE				ADDRESSEE(S)
MISSION NUMBER	DATE	SCHEDULE FIX TIME Z		
AIRCRAFT COM-MANDER	AIRCRAFT NUMBER	ARWO		
SIMULTANEOUS FIX WITH OTHER A/C Yes No	TRANSMISSION TIME Z	GROUND STATION RECEIPT TIME Z	PRECEDENCE: IMMEDIATE	
MESSAGE HEADING				
A	SQUADRON CALL SIGN	MISSION NUMBER	CYCLONE/STORM NAME	OBS NUMBER
B	Z	B. DATE AND TIME OF FIX (Zulu)		
C	DEG Min N S	C. LATITUDE CENTER FIX (Degrees/Minutes) (Circle N or S)		
D	DEG Min E W	D. LONGITUDE CENTER FIX (Degrees/Minutes) (Circle E or W)		
E		E. CENTER DETERMINED BY: (Enter appropriate number) 1 - Penetration; 2 - Radar (indicate aircraft position and wall cloud data in Sec. S, REMARKS); 3 - Wind; 4 - Pressure; 5 - Other.		
F	NM	F. NAVIGATION FIX ACCURACY (in nautical miles).		
G	MB	G. MINIMUM SEA LEVEL PRESSURE (in millibars). (Computed, unless otherwise stated).		
H	MB M	H. MINIMUM HEIGHT AT STANDARD LEVEL (millibars/meters).		
I	K	I. ESTIMATE OF MAXIMUM SURFACE WIND OBSERVED BEARING AND RANGE FROM CENTER OF MAXIMUM SURFACE WINDS (Degrees, nautical miles).		
J	° / NM	J. SURFACE WINDS (Degrees, nautical miles).		
K	DEG K	K. MAXIMUM FLIGHT LEVEL WINDS NEAR CENTER (degrees and knots).		
L	° / NM	L. BEARING AND RANGE OF MAXIMUM OBSERVED FLIGHT LEVEL WINDS FROM CENTER (Degrees, nautical miles).		
M	°	M. MAXIMUM FLIGHT LEVEL TEMP INSIDE THE EYE (degrees Centigrade)		
N	°	N. MAXIMUM FLIGHT LEVEL TEMP OUTSIDE THE EYE (degrees Centigrade)		
O	M / M	O. ABSOLUTE ALTITUDE OUTSIDE/INSIDE EYE (meters)		
P	° / Min N S : ° / Min E W : Z	P. CONFIRMATION OF FIX. Position (Degrees/Minutes); Date and Time (Zulu)		
Q		Q. EYE SHAPE/ORIENTATION/DIAMETER. Code eye shape as: C - Circular; CO - Concentric; E - Elliptical. Transmit orientation of major axis in tens of degrees, i.e., 01-010 to 190; 17-170 to 350. Transmit diameter in nautical miles. Examples: C8 - Circular eye 8 miles in diam. E09/15/5 - Elliptical eye, major axis 090-270, length of major axis 15NM, length of minor axis 5NM. CO8-14 - Concentric eye, diameter inner eye 8NM, outer eye 14NM.		

DETAILED EYE/CENTER DATA MESSAGE (Continued)

R		R. EYE CHARACTER: Closed Wall, Poorly Defined, Open SW, etc.
S		S. REMARKS.
T	°/ Min N S	T. AIRCRAFT POSITION IF RADAR FIX (Degrees/Minutes).
	°/ Min E W	
<p>INSTRUCTIONS: Make every effort to eliminate ambiguous or misleading statements. Use authorized contractions. Transmit in flight only that portion beginning with "Message Heading." Significant clouds observed in the Eye/Center should be reported under "Remarks" or be summarized in the written Post-Flight Report. Enter "N/A" for items that are not available.</p>		

FORMAT TO BE USED WHEN REPORTING RADAR EYE
FROM OUTSIDE EYE APPENDED TO RECCO CODE

UH AIR FORCE GULL
NAVY _____ 96669 11304 10189 68466 -----etc----- X
NOAA*

(RADAR EYE) _____ (AT)
(RADAR EYE BY HOLE IN SEA RETURN) (Note 1) CNTRD (NEAR) (Note 2) _____

DEGREES _____ MINUTES NORTH _____ DEGREES _____ MINUTES WEST X

CNTR SELECTION (POSITIVE) (GOOD) (Note 3) X LOCATION (POSITIVE) (GOOD) (Note 4) X
(FAIR) (FAIR)

NAV (Note 5) ACCURATE WITHIN _____ MI BY (LORAN)

(CELESTIAL) (RADAR) (TACAN#) (DOPPLER) (DEAD RECKONING) _____

(RADAR WEATHER REMARKS) (Note 6)

* NOAA participates only in the Atlantic.
Tactical Air Navigation (Radio)

1. This form is used in the Atlantic and Eastern Pacific areas.

SUPPLEMENTARY VORTEX DATA/MESSAGE

Date	Time	Z to	Z
------	------	------	---

Acft Type	Unit	Observer
-----------	------	----------

Message Heading

DTG

Mission Identifier	Ob. No.
--------------------	---------

VORTEX DATA PROFILE	AZIMUTH
---------------------	---------

1	2	3	4	5
LEFT	REAR	QUAD	IWALL	
6 80	7 45	8 30	9 15	10 00
11 8	12 4	13 3	14 1	15 0
16 MX	17	18 63	19 50	20 30
21 RIGHT	22 FRONT	23 QUAD	24 IWALL	25
26 80	27 45	28 30	29 15	30 00
31 8	32 4	33 3	34 1	35 0
36 MX	37	38 63	39 50	40 30
41 LEFT	42 FRONT	43 QUAD	44 IWALL	45
46 80	47 45	48 30	49 15	50 00
51 8	52 4	53 3	54 1	55 0
56 MX	57	58 63	59 50	60 30
61 RIGHT	62 REAR	63 QUAD	64 IWALL	65
66 80	67 45	68 30	69 15	70 00
71 8	72 4	73 3	74 1	75 0
76 MX	77	78 63	79 50	80 30

REMARKS:

NOTES: Groups 5, 25, 45, and 65 are height of eyewall. Report to nearest 1000 ft. in a give digit group. // indicates hgt unk.
 Groups 6-10, 26-30, 46-50, and 66-70 are "D" values. Indicator is distance from eye. Report in tens of feet. Add 500 for negative values.
 Groups 11-15, 31-35, 51-55, and 71-75 are temp and dew point. Distances from eye are the same as "D" values. Report to nearest degree centigrade. Add 50 for negative values.
 Groups 16-20, 36-40, 56-60, and 76-80 are wind data. Indicator MX will be followed by the max wind. Report to the nearest knot in 3 digits. Next block is radial and distance of max wind from the eye. Report as five digit group in degrees and nautical miles. Indicator 63, 50, and 30 will be followed by three digits representing the distance of the indicated wind speed from the eye.
 If data unobtainable, slashes will be reported.

Monitor	TOR
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APPENDIX D

Operational Flight Patterns

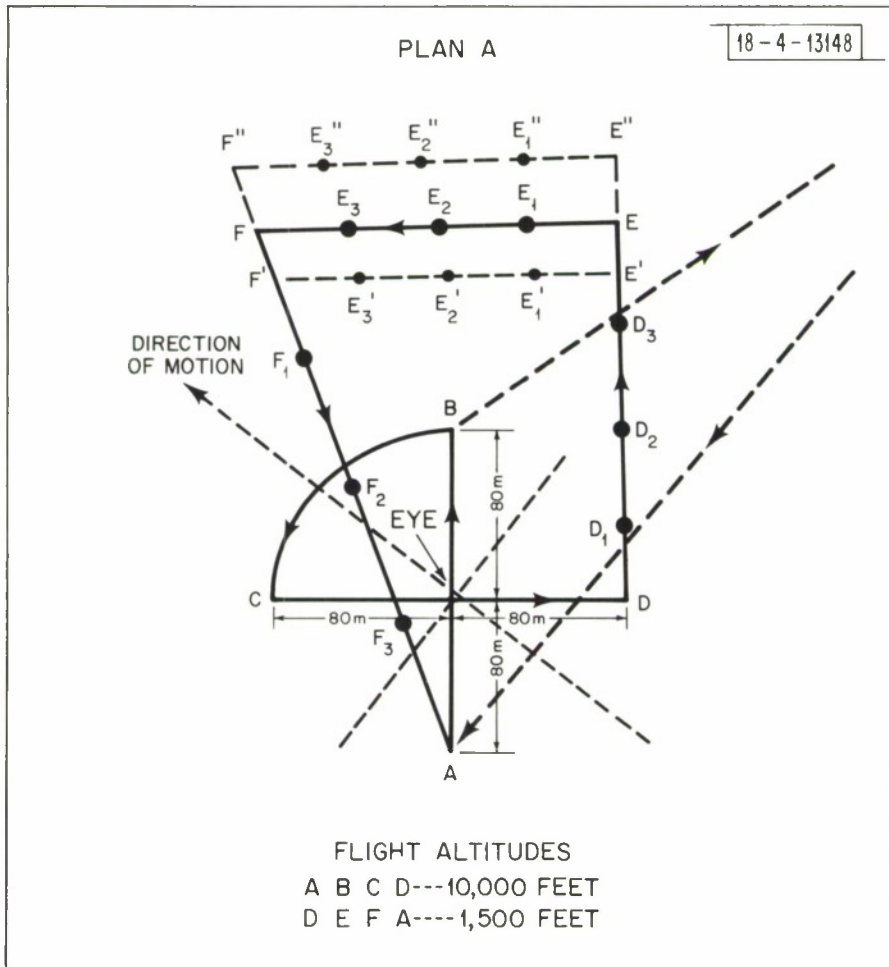


Fig. ID-1. Operational flight pattern A.

OBSERVATION DETAILS FOR OPERATIONAL FLIGHT PATTERN "A"

ALPHABETIC POINT	OBSERVATION DATA	TRANSMIT ASAP AFTER
A	First 8 groups RECCO Code.	A
Eye	Eye/Center and Dropsonde.	Eye (Initial Eye) Dropsonde may be appended to Point B Message.
B	First 8 groups RECCO Code.	B Detailed Eye/Center Message.
C	First 8 groups RECCO Code.	C
Eye	Eye/Center and Dropsonde.	Eye (Initial Eye) Dropsonde may be appended to Point D Message.
D	First 8 groups RECCO Code.	D Add new Detailed Eye/Center Message, if any significant changes.
D ₁ D ₂ D ₃ E	99999 GGggi ddfiff TTT _d T _d w mjHHH SST (see note 4). Same as D ₁ , except omit 99999. Same as D ₂ . First 8 groups RECCO Code and SST (see note 4).	E Data for Point E transmitted first, then data for D ₁ , D ₂ , and D ₃ in chronological order, followed by SST for E, D ₁ , D ₂ , and D ₃ . See example below.
E ₁ E ₂ E ₃ F	99999 GGggi ddfiff TTT _d T _d w mjHHH SST (see note 4). Same as E ₁ , except omit 99999. Same as E ₂ . First 8 groups RECCO Code and SST (see note 4).	F Data for Point F transmitted first, then data for E ₁ , E ₂ , and E ₃ in chronological order, followed by SST for F, E ₁ , E ₂ , and E ₃ . See example below.
VORTEX	VORTEX DATA	Supplementary Vortex Data Message transmitted between Points F and A.
F ₁ F ₂ F ₃ F ₄ A	99999 GGggi ddfiff TTT _d T _d w mjHHH SST (see Note 4). Same as F ₁ , except omit 99999. Same as F ₂ . Same as F ₂ . First 8 groups RECCO Code and SST (see Note 4).	A Data for Point A transmitted first, then data for F ₁ , F ₂ , F ₃ , and F ₄ in chronological order, followed by SST for A, F ₁ , F ₂ , F ₃ , and F ₄ . See example below.
Eye	Eye/Center and Dropsonde.	Eye (Initial Eye) Dropsonde may be appended to Point B Message.
B	First 8 Groups RECCO Code	B Detailed Eye/Center Message.
VORTEX	VORTEX Data for last penetration	B

EXAMPLE OF RECON MESSAGE TRANSMITTED AT POINT E:

```

9xxx9 GGggi YQLaLaLa(1) LoLoLoBf(1) hhhdt da dfff
TTTdt dw mjHHH 99999 GGggi(2) dfff TTTdTdw mjHHH
GGggi(3) dfff TTTdTdw mjHHH GGggi(4) dfff TTTdTdw
mjHHH SST(5) 287 265 270 280
    
```

- (1) Latitude and longitude of Point E.
- (2) Time at Point D₁.
- (3) Time at Point D₂.
- (4) Time at Point D₃.
- (5) Sea-Surface Temperature at:

	E	D ₁	D ₂	D ₃
SST	28.7C	26.5C	27.0C	28.0C

NOTES: (1) The track and altitude to observation Point A is unspecified as is the track home from the last observation point.

(2) En route to and return from storm area, the first 8 groups of the RECCO Code should be observed and transmitted every 30 minutes.

(3) The lengths of the vortex pattern legs (DE, EF, FA) may be adjusted to permit the aircraft to return to Point A in time for a fix 6 hours after the first penetration. Because of this adjustment, the supplemental observation points (D₁, D₂, D₃, E₁, etc.) will be selected before departure on each leg. The points should be equidistant (approximately 60 nautical miles apart) on each leg.

(4) Sea-surface temperatures should be reported only when measured at 1,500 feet or lower. Otherwise, slants should be reported.

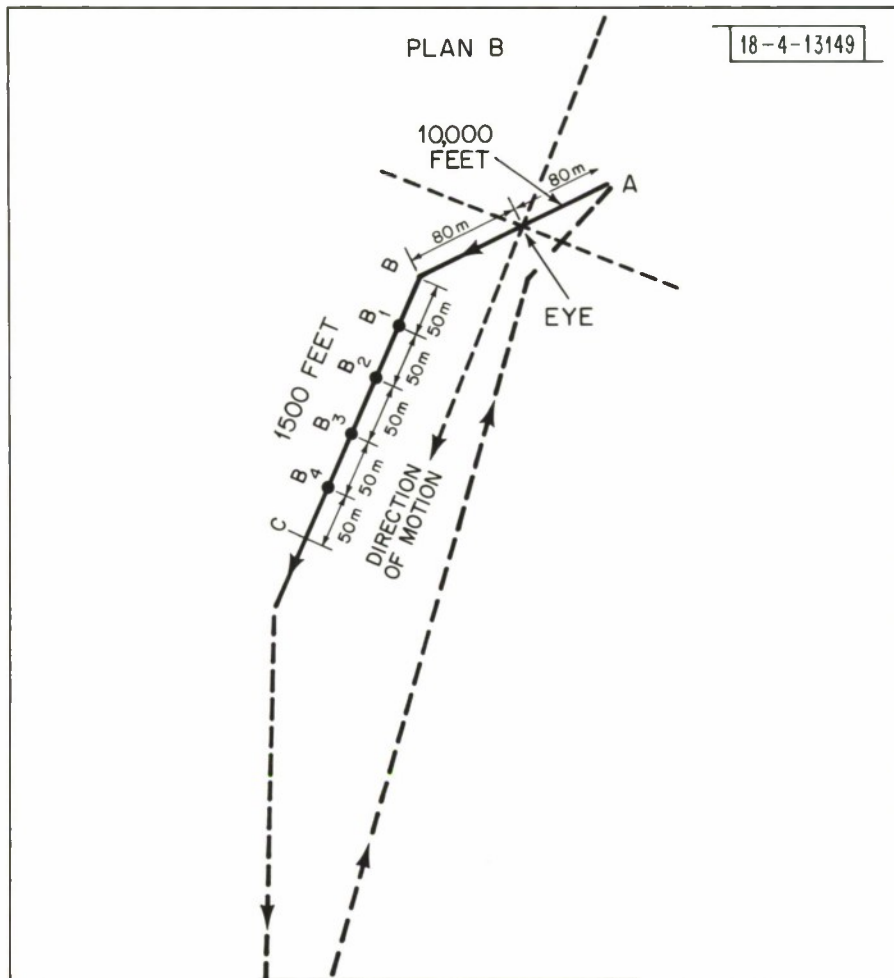


Fig. ID-2. Operational flight pattern B.

OBSERVATION DETAILS FOR OPERATIONAL FLIGHT PATTERN "B"

ALPHABETIC POINT	OBSERVATION DATA	TRANSMIT ASSAP AFTER
A	First 8 groups RECCO Code.	A
Eye	Eye/Center and Dropsonde.	Eye (Initial Eye) Dropsonde may be appended to Point B Message.
B	First 8 groups RECCO Code.	B Detailed Eye/Center Message.
VORTEX	VORTEX DATA	Supplementary Vortex Data Message transmitted between B and C.
B ₁ B ₂ B ₃ B ₄ C	99999 GGggi dfff TTT _d T _d w mjHHH SST (See note 1). Same as B ₁ , except omit 99999 Same as B ₂ . Same as B ₂ . First 8 groups RECCO Code and SST (see note 1).	C Data for Point C transmitted first then data for B ₁ , B ₂ , B ₃ , and B ₄ in chronological order followed by SST for C, B ₁ , B ₂ , B ₃ , and B ₄ . See example Appendix A, Attachment 1a.

NOTE: (1) Notes 1, 2, and 4 of Appendix ID, page 2. Observation Details for Operational Flight Pattern "A" are applicable to Pattern "B."

(2) Point C is 250 nautical miles from Point B. The four Intermediate Points - B₁, B₂, B₃, and B₄ - are about 50 nautical miles apart.

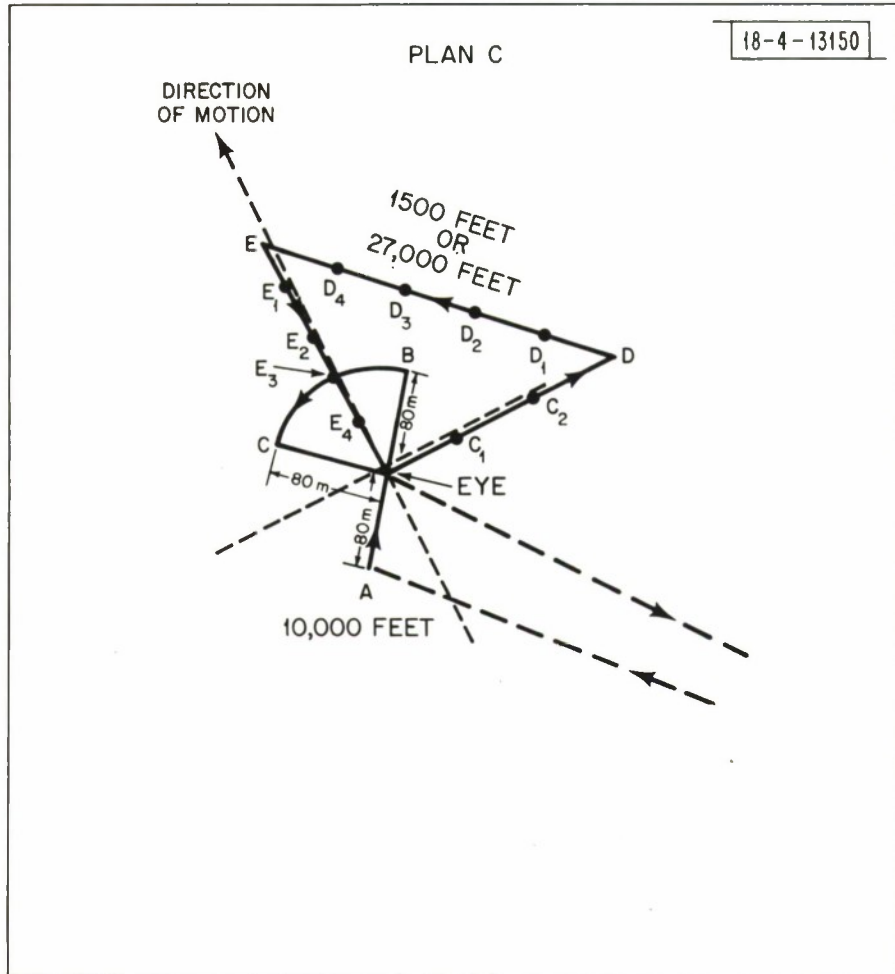


Fig. ID-3. Operational flight pattern C.

OBSERVATION DETAILS FOR OPERATIONAL FLIGHT PATTERN "C"

ALPHABETIC POINT	OBSERVATION DATA	TRANSMIT ASSAP AFTER
A	First 8 groups RECCO Code.	A
Eye	Eye/Center and Dropsonde.	Eye (Initial Eye) Dropsonde may be appended to Point B Message.
B	First 8 groups RECCO Code.	B Detailed Eye/Center Message.
C	First 8 groups RECCO Code.	C
Eye	Eye/Center and Dropsonde.	Eye (Initial Eye) Dropsonde. New Detailed Eye/Center Message, if any significant changes.
C ₁ C ₂ D	9999 GGggi dffff TTT _d T _d ^w mjHHH and SST (see notes 1 and 2). Same as C ₁ , except omit 9999 (see note 3). First 8 groups RECCO Code and SST (see note 1).	D Data for Point D transmitted first, then data for C ₁ and C ₂ , in chronological order followed by SST for D, C ₁ , and C ₂ . See example Appendix ID, page 2.
D ₁ D ₂ D ₃ D ₄ E	9999 GGggi dffff TTT _d T _d ^w mjHHH and SST (see note 1). Same as D ₁ except omit 9999 Same as D ₂ . Same as D ₂ . First 8 groups RECCO Code and SST (see note 1).	E Data for Point E transmitted first, then data for D ₁ , D ₂ , D ₃ , and D ₄ in chronological order, followed by SST for E, D ₁ , D ₂ , D ₃ , and D ₄ . See example, Appendix ID, page 2.
VORTEX	VORTEX DATA	Supplementary Vortex Data Message transmitted between Point E and Eye.
E ₁ E ₂ E ₃ E ₄ Eye	9999 GGggi dffff TTT _d T _d ^w mj HHH and SST (see note 1). Same as E ₁ except omit 9999 Same as E ₂ . Same as E ₂ . Eye/Center and Dropsonde.	Eye (Initial Eye) Initial Eye/Center Message transmitted first, then Data for E ₁ , E ₂ , E ₃ , and E ₄ in chronological order, followed by SST for E ₁ , E ₂ , E ₃ , and E ₄ . See example Appendix ID, page 2. Detailed Eye/Center Message and Dropsonde.
VORTEX	VORTEX data for last penetration.	Eye

NOTES: (1) Notes 1 through 4 of Appendix ID, page 2, Observation Details for Operational Flight Pattern "A" are applicable to Pattern "C".

(2) Intermediate Points C_1 and C_2 are between center and Point D.

(3) Flight altitude from C_2 for peripheral data is either 1500 feet for sea-surface temperature or 27,000 feet for equivalent potential temperature, but dependent upon flight safety and aircraft endurance. Because equivalent potential temperature will not be computed onboard the aircraft, temperature, dew point, and pressure will be transmitted for each observation point.

(4) If the flight altitude for peripheral data is 27,000 ft., dropsonde observations will be made at points D and E. Approval of dropsonde release will be requested from the ARTCC concerned at least 10 minutes before the drop point.

(5) Dropsonde releases in the Eye do not require prior coordination with the ARTCC.

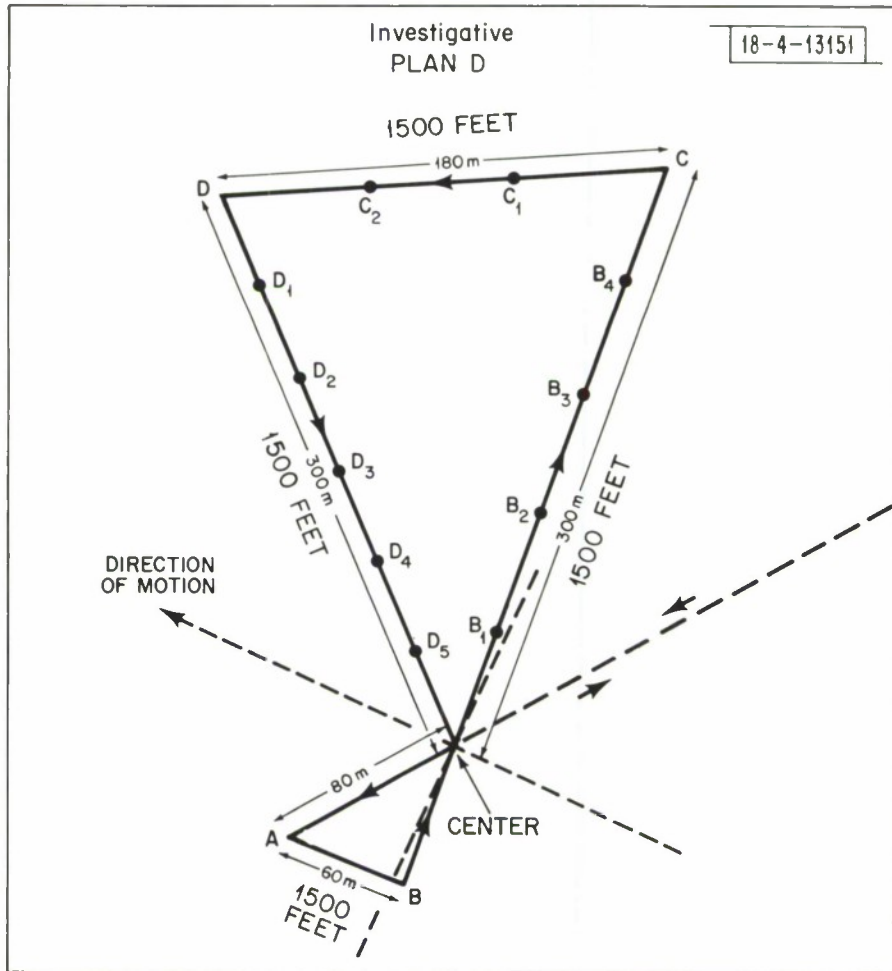


Fig. ID-4. Operational flight pattern D.

OBSERVATION DETAILS FOR OPERATIONAL FLIGHT PATTERN "D"

ALPHABETIC POINT	OBSERVATION DATA	TRANSMIT ASSAP AFTER
A	First 8 groups RECCO Code and SST.	A
B	Same as A.	B
Center	Center	Center (initial Center Message when applicable).
B ₁ B ₂ B ₃ B ₄ C	99999 GGggi dffff TTT _d T _d w mjHHH SST Same as B ₁ except omit 99999 Same as B ₂ . Same as B ₂ . First 8 groups RECCO Code and SST	C Data for Point C transmitted first, then data for B ₁ , B ₂ , B ₃ , and B ₄ in chronological order, followed by SST for C, B ₁ , B ₂ , B ₃ , and B ₄ . See example Appendix ID, page 2.
C ₁ C ₂ D	99999 GGggi dffff TTT _d T _d w mjHHH SST Same as C ₁ except omit 99999 First 8 groups RECCO Code and SST.	D Data for Point D transmitted first, then data for C ₁ and C ₂ in chronological order, followed by SST for D, C ₁ , and C ₂ . See example Appendix ID, page 2.
D ₁ D ₂ D ₃ D ₄ D ₅ or Center	99999 GGggi dffff TTT _d T _d w mjHHH SST Same as D ₁ except omit 99999 Same as D ₂ . Same as D ₂ . First 8 groups RECCO Code and SST or Center Data, if applicable.	Center or D5. If Center Data Message applicable, send first, then data for the intermediate points. If no Center Data Message, send D ₅ data first, then data for D ₁ , D ₂ , D ₃ , and D ₄ in chronological order, followed by SST for D ₅ , D ₁ , D ₂ , D ₃ , and D ₄ .
VORTEX	VORTEX DATA (if applicable)	Supplementary Vortex Data Message transmitted ASSAP after last observation.

NOTES: (1) Notes 1 through 4 of Appendix ID, page 2, Observation Details for Operational Flight Pattern "A" are applicable to Pattern "D".

(2) No dropsondes because entire flight pattern will be flown at 1,500 feet.

(3) If Leg B to C is along or parallel to an easterly wave, this leg should be flown parallel to the wave on either side. The side of wave (easterly) should be reported in Remarks.

APPENDIX E

Communications and Transmission of Meteorological Data

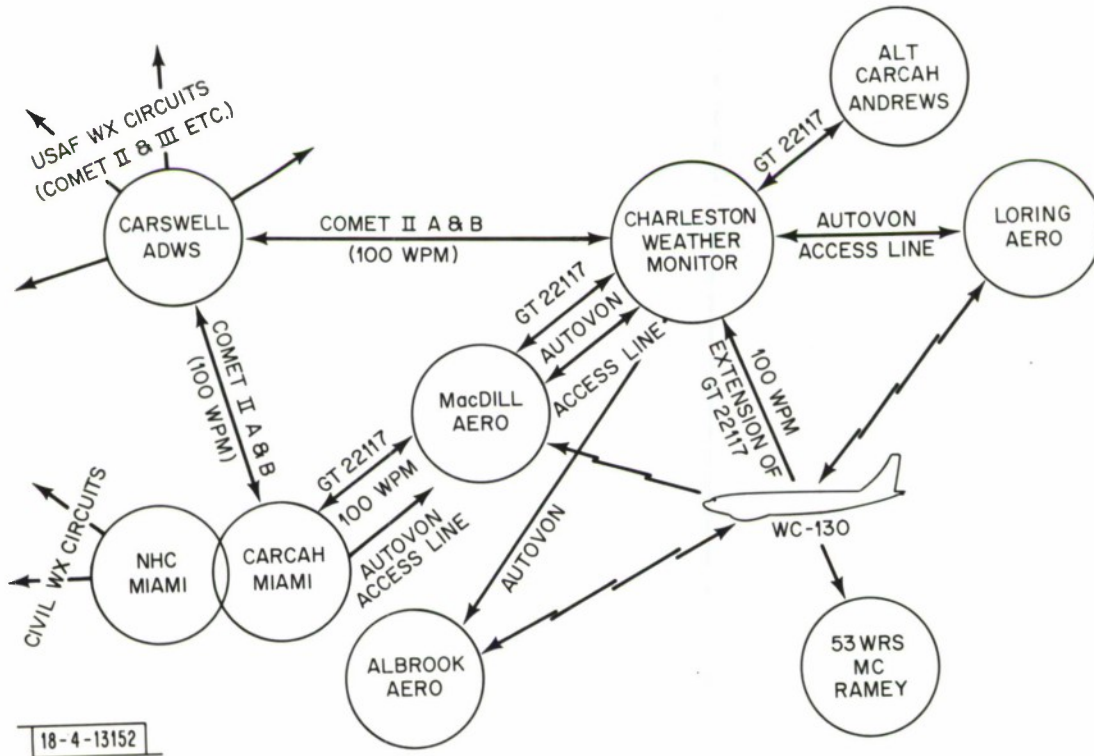


Fig. IE-1. USAF Atlantic Hurricane Communications System.

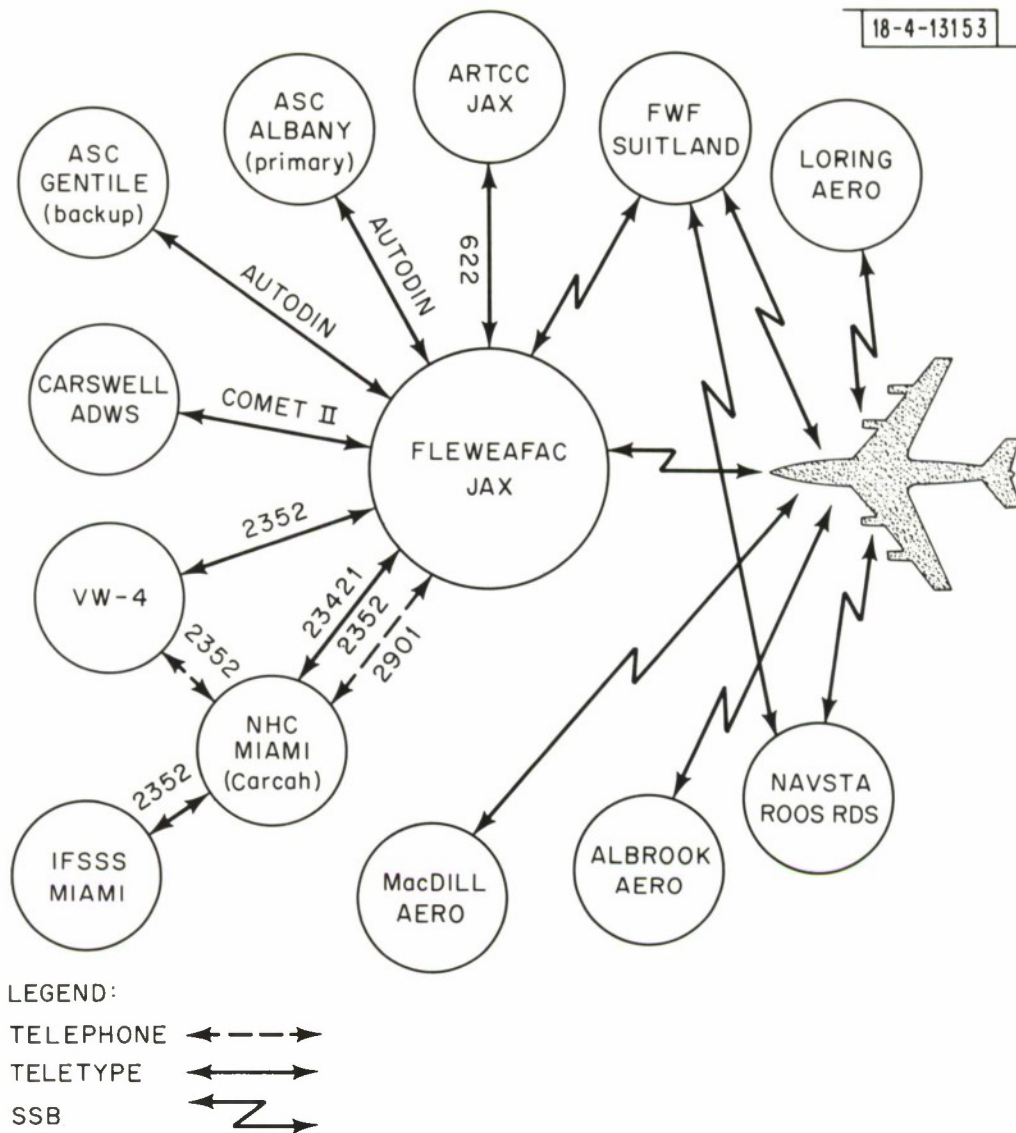


Fig. 1E-2. FLEWEAFAC Jacksonville Communications Diagram.

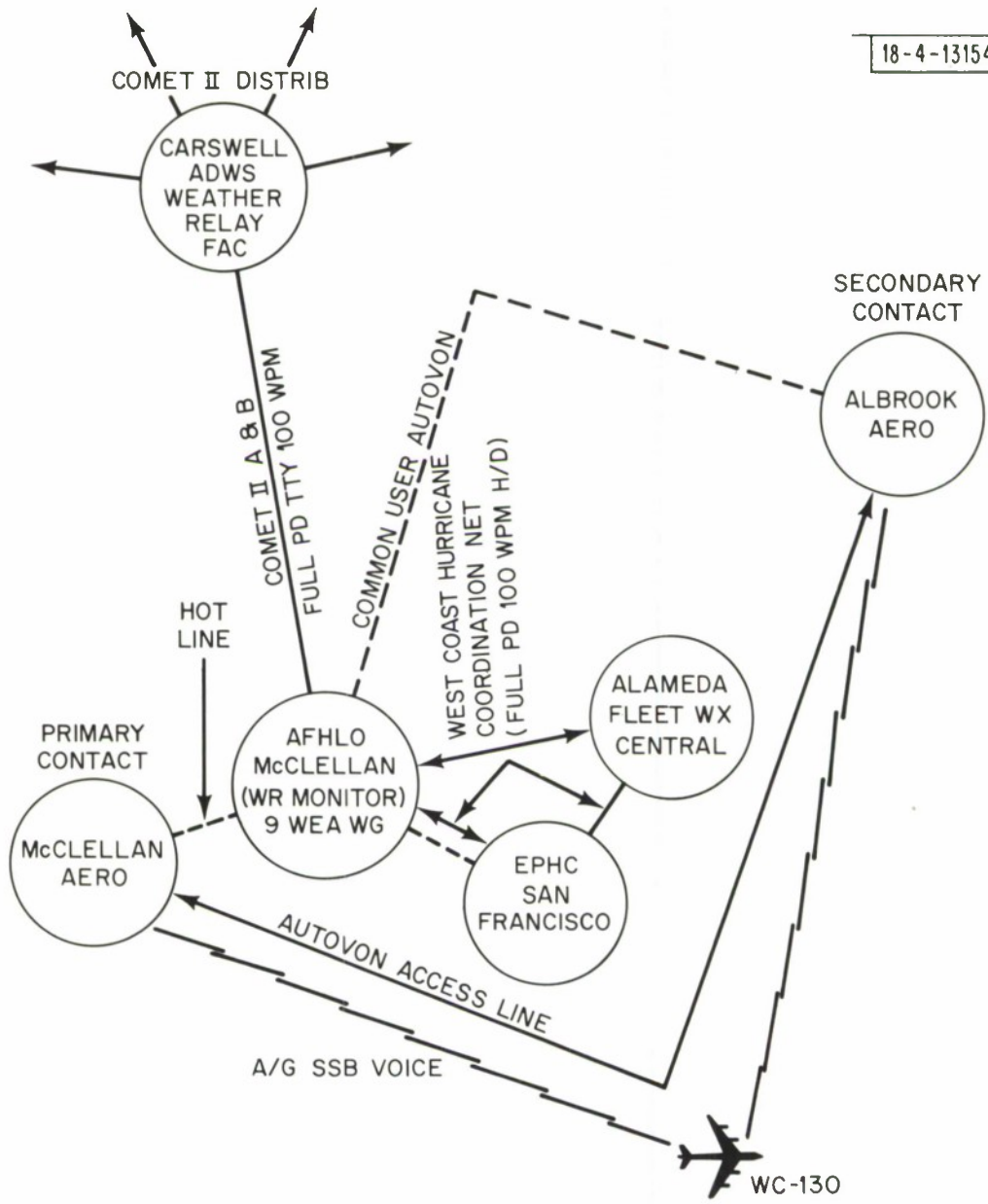


Fig. IE-3. USAF East Pacific Hurricane Communications System.

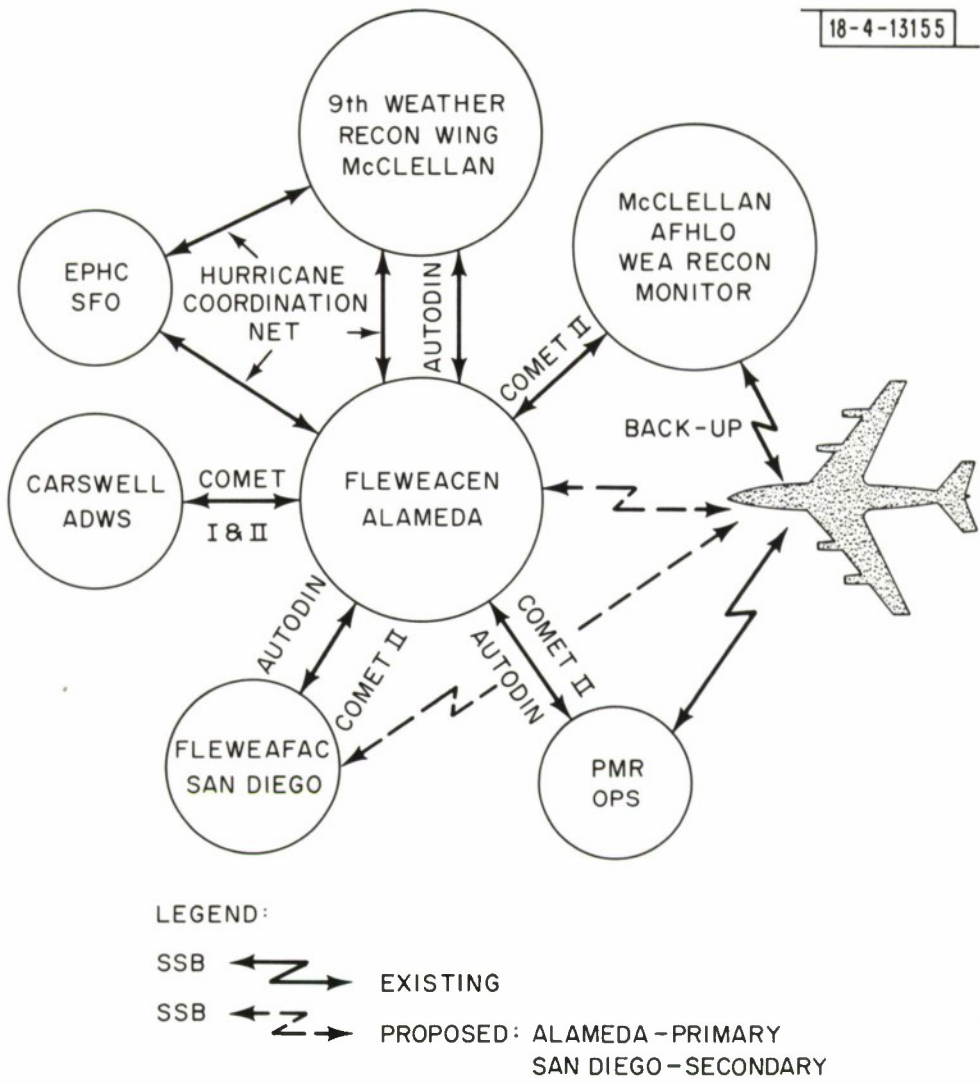


Fig. IE-4. USN East Pacific Hurricane Communications Diagram.

APPENDIX F

Extract from Request for Proposal F19628-70-R-0012, Airborne Weather Reconnaissance Systems (AWRS), Project 5222, Vol. II, Sec. VII

The AWR System is intended to significantly upgrade the capability of the present Air Weather Service weather reconnaissance aircraft fleet to meet global meteorological data requirements. This goal shall be accomplished by (a) the replacement of existing obsolete sensors by new ones now within the current technology, (b) the use of new sensors capable of collecting meteorological data never obtained before from reconnaissance aircraft, and (c) the integration of data processing and transmission equipment for the most effective handling and display of the data aboard the aircraft and the transmittal of the meteorological data from the aircraft to ground stations. In addition, AWRS will be designed with sufficient growth capability to accommodate additional sensors now under exploratory development to meet advanced meteorological data requirements.

Performance. The performance requirements outlined in the following paragraphs specify system performance in terms of system characteristics and operability, and define the system in terms of functional requirements and the interrelationships of system equipments and facilities.

Performance Characteristics. The performance requirements specified below are necessary to provide the Air Weather Service reconnaissance aircraft with a capability to meet mission requirements for meteorological data collection, processing, and transmission. The accuracies specified are system accuracies, which are defined as the accuracy of parameters measured at the output of the data transmission antenna on the aircraft. Performance accuracies shall be within three standard deviations, assuming a normal distribution.

Meteorological Requirements. The AWR System shall have the ability to collect the following information to the accuracy specified when deployed within the operating envelope of both the AWRS modified WC-130B/E, and WC-135B aircraft.

(1) Flight Level Measurements. The following measurements shall be made with sensors located on the aircraft to provide meteorological information representative of conditions encountered by the aircraft at flight level.

The AWR System shall be capable of measuring the stated parameters in all conditions of flight, with no effect due to aircraft altitude, attitude, air speed, winds, turbulence, icing, rain or sea state. The measurements shall be continuous to provide for data samples as required.

All response rates and/or time constants for flight level measurements that are to be determined by the contractor must meet the objectives of the mission and satisfy all other requirements. Further, the response rates/time constants must be approved by the program office.

(a) Temperature. The AWR System shall be capable of measuring the free air temperature to a resolution of 0.1°C with an accuracy of $\pm 0.5^{\circ}\text{C}$ and a response rate of 10° per second over a temperature range of 50°C to -90°C . If temperature measurement is accomplished with a total temperature or stagnation temperature sensor, free air static temperature is calculated by the equation:

$$T_s = \frac{2T_I}{2 + (\gamma - 1) KM^2}$$

Where: T_s = Static free air temperature, $^{\circ}\text{K}$
 T_I = Indicated Temperature, $^{\circ}\text{K}$
 γ = Ratio of Specific heats, $C_p/C_v = 1.4$
 K = Sensor recovery factor
 M = Mach number

If another equation is used, approval must be obtained from the SPO.

(b) Pressure. The AWR System shall be capable of measuring flight level atmospheric pressure to a resolution of 0.1 millibar (mb). The measurements shall be accurate to ± 0.3 mb for pressures between 1060 and 500 mb, and accurate to ± 0.1 mb for pressures between 500 and 150 mb. (The response rate/time constant for this sensor(s) shall be specified herein by the contractor.)

(c) Dew Point/Relative Humidity Measurement. The AWR System shall be capable of measuring relative humidity (RH) at flight level, over the range of 10% to 100% relative humidity, under all conditions of temperature and airspeed, with resolution to 0.5% RH. The required accuracy is a function of temperature and relative humidity, and is stated in the following chart.

<u>Temperature</u>	<u>Accuracy</u>	
	<u>10% - 70% RH</u>	<u>70% - 100% RH</u>
+ 40°C to 0°C	$\pm 5\%$ RH	$\pm 2\%$ RH
0°C to -20°C	$\pm 6\%$ RH	$\pm 3\%$ RH
- 20°C to -40°C	$\pm 10\%$ RH	$\pm 5\%$ RH
- 40°C to -85°C	$\pm 15\%$ RH	$\pm 10\%$ RH

(The response rate of this sensor shall be determined by the contractor during definition phase and specified herein. If the contractor elects to measure Dew Point, the contractor shall provide charts, graphs, and conversion factors to demonstrate range, accuracy and response rates in terms of relative humidity.)

(d) Airspeed. The AWR System shall measure true airspeed to obtain accurate temperature correction factors and flight level winds. True airspeed shall be measured to an accuracy of ± 2 Kts, with resolution to 1.0 Kt. (The response rate and/or time constant shall be specified herein by the contractor.)

(e) Winds. The AWR System shall be capable of measuring absolute (true) wind velocity at flight level, independent of aircraft speed, direction or attitude, to an accuracy of ± 5 knots in magnitude and $\pm 5^\circ$ in direction. Resolution shall be one knot and one degree, respectively. The range of wind velocity to be measured extends from 3 Kts to 350 Kts in magnitude and 0 to 360 degrees in direction. (The response rate(s)/time constant(s) shall be specified herein by the contractor, and shall be such as to provide a representative gradient of wind velocity.) Both short-term fluctuation(s) (as might be found in the periphery of a tropical storm, but not turbulence as such) and long-term trends (necessary to define areas of maximum winds) must be reported. To insure correct reports, the response of the wind measuring subsystem must be cognizant of the period of wind velocity fluctuations encountered in the various missions. (The contractor shall determine and specify herein such response rate.)

(f) Density. A requirement exists for the preparation of atmospheric density information at flight level. The parameters necessary to calculate the density will be obtained from the sensors specified in (1) (a) through (e). The AWR System shall be capable of computing density to an accuracy consistent with the collected data. Density shall be calculated by the following formula:

$$\text{Density} = \frac{MP}{R^* T_v} \quad \text{Where M is the mean molecular weight, } R^* \text{ is the universal gas constant, P is pressure and } T_v \text{ is the virtual temperature, defined by}$$

$$T_v = \frac{T}{1 - 0.379(e/P)}$$

T_v , the Virtual Temperature, is the temperature which dry air must have at the given pressure P in order to have the same density as a water vapor-air mixture at the same pressure P, temperature T, and vapor pressure e.

The contractor's method for calculation of computed density accuracy is subject to the approval of the program office. (The system performance requirement for density measurement shall be incorporated herein during Contract Definition Phase.)

(g) Absolute Flight Altitude. The AWR System shall measure absolute flight altitude to a resolution of 5.0 feet. This measurement shall maintain an accuracy of ± 10 feet $\pm 0.025\%$ of the altitude. The minimum altitude to be measured shall be 500 feet. To the extent possible and practicable, this measurement shall be independent of sea state. (The response rate and/or time constant of this sensor shall be determined by the contractor and specified herein.)

(2) Vertical Profile Measurements. Atmospheric parameter measurements are required from flight level to the earth's surface. For purposes of specifying these requirements, flight level is defined as being between 900 and 45,000 feet above the surface of the earth. One complete cycle of temperature, pressure and humidity data shall be required at a constant time interval, which shall not exceed the time necessary for the sensor(s) to fall 15 feet when at sea level and has achieved the terminal velocity of the sensor.

If expendable sensor packages are used, the response rates of the various sensors so employed shall be consistent with the fall and sampling rates. (The contractor shall specify herein response and fall rates of the sensor packages as an output of definition phase.)

The Government desires that expendable sensor packages, if they are used, weigh less than four pounds and have a maximum fall time of 20 minutes when dropped from 30,000 feet. Data from dropped expendable sensor packages must be received by the aircraft while the aircraft is flying away from the sensor package drop point at maximum speed.

In the event that on-board sensors are employed to measure vertical profile data remote from the aircraft, the measurements shall be made at 15-foot intervals. The complete vertical profile data, from sea level to 30,000 feet, shall be measured in less than 20 minutes.

(a) Temperature. Measurements of the free air temperature are required from flight level to the earth's surface with a resolution of 0.1°C , and an accuracy of $\pm 0.5^{\circ}\text{C}$ over the range $+50^{\circ}\text{C}$ to -85°C . (The time constant or response rate will be specified herein by the contractor.)

(b) Pressure. Measurements of the pressure of the atmosphere are required from flight level to the earth's surface with a resolution of 0.1 mb, and an accuracy of ± 2.0 mb over the range of 150 to 1060 mb.

(c) Density. Determination of the density of the atmosphere is required between flight level and the earth's surface. (This measurement shall be a computer program function as specified in (1)f and will be reported at intervals to be specified herein by the contractor based upon his computer selection and program office approval.) Accuracy will be $\pm 0.5\%$.

(d) Atmospheric Moisture. Measurements of atmospheric Relative Humidity (RH) from flight level to the earth's surface over the range of 10% to 100% relative humidity, with a resolution of 0.5% RH. The accuracy required is a function of temperature and RH and is specified in the following chart.

Temperature	Accuracy (% RH)	
	10% - 70% RH	70% - 100% RH
$+40^{\circ}\text{C}$ to 0°C	$\pm 5\%$ RH	$\pm 2\%$ RH
0°C to -20°C	$\pm 6\%$ RH	$\pm 3\%$ RH
-20°C to -40°C	$\pm 10\%$ RH	$\pm 5\%$ RH
-40°C to -85°C	$\pm 15\%$ RH	$\pm 10\%$ RH

(If the contractor elects to measure Dew Point, the contractor shall provide charts/graphs, conversion factors and response rates to demonstrate the performance in terms of relative humidity.)

(e) Winds. Measurements of wind speed and direction, from flight level to the earth's surface, over a range in speed of zero to 300 Kts and in direction of 0° to 360°. Accuracies shall be $\pm 10^\circ$ and ± 5.0 Kts in direction and speed, respectively. The wind direction shall be reported with a resolution of 1.0° . Wind speed data shall maintain a resolution of at least 1.0 Kt for wind speeds up to 100 Kts, at least 2.0 Kts for wind speeds from 100 to 200 Kts, and at least 5.0 Kts for wind speeds between 200 and 300 Kts. The wind data sampling rate may be either a fixed time interval, a fixed fall interval, or pressure dependent. In no case may the interval between measurements exceed 1000 feet of fall.

The government would prefer that the measurements listed in la, b, d, and e above be made, if on-board sensors are not employed, in a single expendable unit. However, if due to cost, size or weight limitations, this is not feasible, wind velocity may be measured with a separate expendable. In this case, the contractor shall provide some method to allow wind profile data to be presented as a function of altitude.

(3) Other Measurements. Other measurements of atmospheric parameters (turbulence, upper air parameters and ionosonic parameters) may be incorporated into the AWR System. At the discretion of the Government, such sensors may be required as part of the AWRS modification.

(a) Turbulence. This subsystem shall be capable of objectively measuring atmospheric turbulence encountered by the aircraft at flight level. The output of this subsystem must be in relative values of turbulence intensity, independent of aircraft type and speed. (The contractor shall specify during the Definition Phase the overall accuracy of the turbulence measuring sensor and the standard to be used for the determination of the accuracy.)

(b) Upper Air Measurements. The measurement of upper air atmospheric parameters (air density and free air temperature) from flight level to 400,000 feet, shall be accomplished, either by on-board instrumentation for remote measurements, or by a rocket propelled sonde. The desired accuracies, resolutions and sampling intervals are stated below. The response rates for on-board sensors, if they are used, shall be consistent with the specifications below.

(i) Temperature. Measurements of free air temperature from flight level to 200,000 feet are required. A resolution of 0.1°C and an accuracy of $\pm 1.0^\circ\text{C}$ shall be maintained over the range of -90°C to $+50^\circ\text{C}$. The maximum sampling interval shall be the equivalent of 1000 feet vertically, with response rates consistent with the fall/rise rate of the sensor. (If on-board sensors are used for remote measurements, the contractor shall specify herein the time required to complete measurements of the vertical profile.)

(ii) Density. The measurement of atmospheric density from flight level to 400,000 feet. The maximum sampling interval shall be 1000 feet vertically, with response rates consistent with the fall/rise rate of the sensor employed. The accuracies required are a function of the altitude of the measurement, and are given in the table below.

<u>Altitude of the Measurement</u>	<u>Accuracy</u>
Flight level to 100,000 feet	$\pm 0.5\%$
100,000 feet to 200,000 feet	$\pm 1.0\%$
200,000 feet to 300,000 feet	$\pm 1.5\%$
300,000 feet to 400,000 feet	$\pm 2.0\%$

(c) Ionospheric Sounding Requirements. An ionospheric sounding capability will be incorporated into the AWR System to measure the following parameters to the accuracy specified.

$f_o F_2$ - Ordinary wave critical frequency for the F_2 layer. Identifies the peak electron density in the upper ionospheric region called F. An accuracy of ± 0.3 MHz is required.

- f_{oE_s} - Highest frequency at which a mainly continuous ordinary wave trace is observed from the sporadic E layer. An accuracy of ± 0.5 MHz is required.
- f_{min} - The lowest frequency observed on the vertical sounding. The accuracy of ± 0.2 MHz is required.
- f_oE - Ordinary wave critical frequency for the E layer. Identifies the peak electron density in the lower ionospheric region called E, except for an occasional sporadic E layer. An accuracy of ± 0.1 MHz is required.
- MUF (3000) F_2 - Maximum usable frequency (MUF) for a path of 3000 Km for transmission by the F_2 layer. This frequency is obtained by applying the standard transmission curve for 3000 Km to the ordinary branch of the F_2 trace. An accuracy of ± 1.0 MHz is required.

Additionally, the system should be capable of receiving and processing signals from ground-based oblique sounders to measure the following parameters to the accuracy specified.

- MOF - The highest frequency on which the ground-based sounder transmitter signals are observed on the ionogram. An accuracy of ± 0.5 MHz is required.
- LOF - The lowest frequency on which the ground-based sounder transmitter signals are observed on the ionogram. An accuracy of ± 0.5 MHz is required.

It is anticipated that the above Ionospheric Sounding information will be required at 400-nautical-mile intervals throughout a weather reconnaissance mission. Near real-time transfer of the ionospheric data from the aircraft to ground stations will be possible by employing a digital ionosonde sensor and a data processing link consisting of the airborne computer and an interface unit. This data loop will be required to take a complete ionogram, extract the necessary parameters, and transmit the required information in a separate reporting transmission.

Near continuous oblique sounder data shall be made available in the aircraft to assist in determining data transmission frequencies.

Navigation Requirements. The mission of the aircraft navigation subsystem shall be to provide precise positional data to enable computation of flight level wind vectors to the accuracies specified in section (1) e and the location of hurricane features to ± 5 nm accuracy. (The contractor shall update this specification to include the navigation performance requirements including the \pm three standard deviation positional accuracy of the navigational subsystem capable of meeting the wind measuring requirements world-wide operational capability specified, and the accuracy required for the location of hurricane features.)

Weather Radar Requirements. The following are the requirements for the weather radar. (The contractor shall determine, as an output of analyses and trade study task 3.1.4.1.4 of Annex 3 of the Contract Definition Statement of Work, the degree to which he will meet these requirements and still be consistent with the AWRS time frame and state-of-the-art limitations. The requirements so determined will be incorporated herein and shall replace the requirements as listed below.)

(1) The radar shall have the capability to search for and locate precipitation areas (from light to heavy intensity). Resolution must be sufficient to identify significant meteorological features (hurricane eyes, hook echoes, and echo-free vaults in thunderstorm, etc.) up to a range of 200 nautical miles from the aircraft.

(2) The radar shall have the isoecho capability to contour the strength of storms (hurricanes, squall lines, etc.) by displaying (at a fixed gain setting) the intensity of the precipitation echoes in five distinct values (shades of gray). A specific range of signal intensity shall be immediately assignable to each shade of gray, using the knowledge of the basic radar settings. The radar must be equally capable of displaying long and short distance views, whether exterior for intensity mapping the entire extent of a storm under reconnaissance or interior to such storms for locating maximum precipitation intensity areas for mapping and aircraft avoidance. Attenuation shall be sufficiently small to preserve the capability to observe the entire extent of the storm.

(3) The radar must have a range of at least 200 nautical miles, with PPI range presentations of 30, 100, and 200 nautical miles. Range inaccuracy must be less than 1.0%. In azimuth the radar must have an accuracy of 1.0 degree. The entire system, in size and weight, must be compatible with the WC-130 and WC-135 aircraft. The radar must be capable of displaying storm eyes as small as 5 NM at 200 NM.

(4) The heights of both cloud tops and bases, relative to the sea level, must be discernible under all environmental conditions including heavy precipitation or icing. The heights should be measured with an accuracy of ± 1000 feet with a resolution of 500 feet. Altitude of tops and bases at horizontal ranges up to 50 NM shall be measured.

Data Transmission Requirements. The Data Transmission Subsystem employed by the AWRS shall interface with existing ground stations. High Frequency (HF) Single-Side-Band (SSB) 100 WPM teletype in Reconnaissance Code (RECCO) format is now employed. The basic design of the data transmission subsystem employed by AWRS shall provide growth capability to interface with the results of Statement of Work Task 3.1.4.1.3, Annex 3, in which either a HF aircraft to ground or an aircraft-satellite-ground data transmission technique shall be selected for future incorporation into the AWRS.

In the satellite technique, a central weather facility, such as Air Force Global Weather Central, at Offutt AFB, Nebraska, will be the prime data receiver. In addition, several remote satellite ground stations may be equipped to receive the data as required.

Of prime importance in data transmission in AWRS shall be reliable and accurate data relay. The extent of data degradation and loss shall be held to an absolute minimum. (The contractor shall incorporate herein the system level data transmission requirements as a result of definition phase trade studies and analysis.)

Data Reception Requirements. The data receiving equipment in the AWR System shall have the capability to receive the telemetry signals from any sensor released from the aircraft. To provide for multiple sensor package operation, the system(s) shall have the capability to receive at least two separate signals simultaneously. All receiving and transmitting functions between the aircraft and a released sensor package shall be conducted only at the two standard assigned meteorological frequencies of 1670 - 1690 MHz and 400 - 406 MHz. (The contractor shall incorporate herein the system level performance requirements for data reception, developed during definition phase, including data quality requirements for receiving sensor-transmitted data.)

Airborne Computer Requirements. The computer required in the AWR System shall be used for four principal functions: monitoring data, computation of transfer functions for selected sensor outputs, processing/formatting of data for transmission, and system diagnostic tests. Software programming and language shall consider use of in-house government personnel and facilities. The specific requirements for each of these functions are as follows:

(1) Monitoring. The computer shall be required to monitor the data output from selected sensors to accumulate (select/compute) the significant data points as a function of position (latitude, longitude and altitude) for later printed display and transmission to the ground. The Weather System Operator shall have the capability to set the initial value (calibration value, if required) into the computer. The computer must then monitor the required incoming data and accumulate the significant points (locations where values of specified parameters change by the set amount) in accordance with the set criterion. Examples of particular data outputs to be monitored in this manner are:

Temperature
Pressure
Wind Direction
Wind Speed
Dew Point or Relative Humidity
Altitude
Location (Latitude, Longitude)
Density

(2) Computation. The computer shall be required to:

(a) Convert the telemetered information received in the aircraft from the released sensor packages to actual parameter values through the associated transfer functions.

(b) Compute values of atmospheric density (vertical profile and flight level) at selected locations on a reconnaissance mission.

(c) Compute geopotential height from given values of latitude, longitude and altitude.

(d) Compute thicknesses of layers of atmosphere between standard pressure surfaces.

(e) Compute and use correction factors for the sensors/transducers employed by the system.

(f) Compare computed (extrapolated) atmospheric parameter values with standard parameters, outputting significant differences.

(g) Compute equivalent potential temperatures.

(3) Processing/formatting: The computer shall be required to process and format the sensor data in accordance with the following requirements:

Upon command, the computer shall place the flight level measurement data at a given specific location into the standard weather reconnaissance coding format for transmission to the ground. The significant data points encountered between this specific location and the specific location previous to this will also be coded and added to the standard report as "remarks."

For the transmission to ground, the computer will place the vertical profile measurement data into the appropriate coding format required by the standard weather coding regulations. The computer shall scan the complete profile data and select significant levels in accordance with criteria established by the Weather System Operator. These significant levels must then be coded and added to the report in accordance with coding regulations.

(4) System Diagnostic. The computer shall be required to perform system diagnostic tests for ground and airborne determination/detection and isolation of malfunctions. The level to which the system diagnostic tests shall be performed shall be a result of the evaluation performed in definition phase.

(5) Control. The AWRS operator shall have the capability to instruct the computer as to which subroutines/subprograms are to be used. Examples are: Trace, dump, programming de-bugging routines, system self-test routines; and, if they exist, specialized subroutines/subprograms for particular mission requirements (e.g. storm penetration, storm reconnaissance, special mission, etc.).

The computer shall control all displays outlined in Section --Data Display Requirements.

Data Display Requirements. The AWR System shall have the capability to display the following meteorological parameters to the Weather System Operator for his continuous evaluation of the mission progress:

(1) Flight Level Measurements. The data shown below shall be displayed at the Weather System Operator's console on command, in electronic display digital form (e.g. Nixie tubes, or other display). The Weather System Operator shall have the capability of selecting any two parameters to be displayed at the same time upon his command. Each display shall reflect a measurement resolution of its respective parameter consistent with the resolution of the sensor being monitored. The data for each display shall be updated one every 2 seconds. The parameters selectable for display shall be:

Temperature
Pressure
Dew Point or Relative Humidity
Winds (Speed and Direction)
True Airspeed
D-Values

In addition, a readout of the current values of all parameters shall be available in printed form at any time upon the Weather System Operator's Command.

(2) Vertical Profile Measurements. The data shown below shall be available to the Weather System Operator at his command, on paper in digital printout form. The parameters to be displayed are:

(a) All measurements taken by the sensor packages released from the aircraft after initial processing to convert the raw data to actual parameter values (pre-"Final Code" or "Significant Values"). Data shall be printed out as a function of sensor altitude.

(b) Measurements taken by any vertical profile sensor requiring computational support and located on the aircraft.

(3) Formatted Data. That data which is formatted for transmission to ground (both that required by the coding regulation - "final code" - as well as the significant points selected) will be available in printout form at the Weather System Operator's console, on command.

(4) Weather Radar Display. A cathode ray tube (1 or more CRT's, as required) display of the weather radar shall be included at the Weather System Operator's console. A radar scope photograph capability is required.

(5) Location Display. The Weather System Operator's console shall include a location display which will present aircraft location in latitude, longitude and altitude to a resolution of one minute of latitude and longitude, and 5 feet for altitude.

(6) Time of Day. A continuous display of time in GMT.

Recording/Reading Requirements. The recording/reading subsystem in the AWR System shall have the following capabilities:

(1) Store all computer programs required to perform all necessary Computer Operations. Read-in provisions for both punched and magnetic tape shall be incorporated.

(2) Ability to record all meteorological data (vertical profile and flight level, except radar display) available at the display console. The capability to change magnetic tape in flight is required.

(The contractor shall incorporate quantitative recording subsystem performance requirements, at the system level, herein as a result of definition phase analyses).

Aircraft Modification. As the AWR System is intended for operation aboard weather reconnaissance aircraft, the contractor shall be responsible for performing all the aircraft modification necessary to install all elements of the AWR System. It is anticipated that a First Article AWR Systems will be installed and tested aboard a C-130-type aircraft.

(The contractor shall update performance requirements at the system level herein as a result of definition phase analyses and study.)

(The contractor shall update performance requirements at the system level herein as a result of specific definition phase tasks, in addition to other definition phase analyses.)

Growth Capability Requirements. The AWR System shall have a designed growth capability to minimize future modifications when advanced sensors, now under development, are incorporated. However, initial concern must be directed towards improving the accuracy of sensor packages released from the aircraft. The particular sensors involved and the needed accuracies are as follows:

Pressure (31 Km to ground)	± 0.1 mb
Humidity (31 Km to ground)	± 2 %
Temperature (61 Km to ground)	$\pm 0.5^{\circ}$ C

The following is a list of sensors now under consideration for eventual integration into the AWR System.

- (1) Remote Detection of Clear Air Turbulence (CAT)
- (2) Remote Measurements of Temperature and Humidity
- (3) Remote Measurements of Storm Winds
- (4) Aerosol Detection and Evaluation System
- (5) Remote Measurement of Surface Temperature and Sea State

As a design goal, the AWR System shall possess sufficient growth capability to facilitate integration of the above sensors. Additional information on advanced sensors will be found elsewhere.

The contractor shall update this section as a result of definition tasks:

System Growth Capability
Transmission of data to ground - HF/Satellite Relay
Coding Formats for Sensor Measurements
Computer Requirements

(The basic system design shall allow for the growth to incorporate the above study results.

Weather System Operator's Console. The Weather System Operator shall:

- (1) Have monitoring and positive control of all on-board Prime Mission Electronic and Meteorological Equipment (PMEME).
- (2) Have the capability to communicate with ground installations and with the aircraft commander without interfering with normal flight crew operations.
- (3) Have information display as delineated in Display Requirements.
- (4) Have the capability to insert information into the data transmission subsystem, such as visual observations.
- (5) Have visual observation capability, to permit the observation of a 120° cone of vision to each side of the aircraft. This visual capability shall be obtainable to at least one side of the aircraft while the Weather Officer is strapped in his seat.
- (6) Have a work table, which includes: Oxygen outlets; aircraft interphone and HF radio controls; the teletypewriter keyboard; a paper tape reperforator/reader; the radar scope repeater; a light; an ashtray and coffee cup holder.

Timing. Generation and recording of time codes and repetition rates shall be provided as specified in IRIG Document 103-59 (Revised 1968), Instrumentation Timing Systems Brochure.

Operational. The Operational Airborne Weather Reconnaissance System shall consist of a fleet of WC-135B and WC-130 B/E aircraft modified and instrumented to provide significantly improved meteorological data over that presently available in areas not covered by ground weather stations. The System shall provide the Air Weather Service data required for making global forecasts and monitoring weather on a global scale. The System shall measure, process, record, display, and transmit meteorological data as specified in the performance characteristics in Section - Performance Characteristics.

The system shall provide all parameters referenced to time and geographical locations.

SECTION 11

REPORT OF THE METEOROLOGICAL PANEL

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Airborne Severe Storm Surveillance Summer Study

August 1970

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I. SYNOPTIC INFORMATION ON TROPICAL CYCLONES AND THEIR ENVIRONMENTS NEEDED BY OPERATIONAL HURRICANE ANALYSTS AND FORECASTERS

The success of a Hurricane Warning Service obviously depends on meteorological observations for the analysis and prognosis of tropical cyclones. For forecasting the entire life cycle of each hurricane, it would be helpful to have data showing where conditions are favorable for the storm's formation and intensification. When a tropical cyclone forms, it must be detected and its size and strength measured. The speed and direction of its translation must be found by a time sequence of the positions of its center. Finally, predictions should be made of the weather conditions along its path, particularly where it crosses a coastline from the ocean to land. The information required for these operations by hurricane analysts and forecasters will now be considered.

A. Environmental Conditions Favorable for Tropical Cyclone Formation or Intensification

Since the potential energy of a hurricane is primarily the latent heat of vaporization of water, the increase of its kinetic energy requires the condensation of a large amount of water vapor by wet adiabatic cooling with lifting of a large volume of air from the surface. This air must have a high absolute humidity, which is characteristic only of moist air at a high temperature, since the saturation absolute humidity is nearly an exponential function of absolute temperature. A necessary condition for hurricane formation is that the surface air temperature should exceed about 23°C in a tropical maritime air mass, whose heat and moisture are derived primarily by conduction and evaporation, respectively, from a sea surface having a surface water temperature greater than about 26°C .

The voluminous updraft requires a large horizontal inflow of surface air. The only force available to accelerate the air inward is the horizontal pressure gradient force. Hence, every hurricane development is preceded by a weak low-pressure area, called a tropical depression. This depression may appear on a surface weather map in any one of a number of possible pressure troughs, such as the inter-tropical convergence zone, an easterly wave, or an inverted trough ahead of or along the tropical extension of an extra-tropical cold front. But only seldom does such a tropical depression undergo a full development into a hurricane.

Aside from the two basic dynamic and thermodynamic requirements of an updraft and moisture for hurricane development, there is no general agreement among meteorologists as to what the other requirements are, since there are many theories and models of how a hurricane gets started. From the statistics of meteorological parameters associated with hurricane formation, the following environmental features should be noted as synoptic indicators of possible tropical cyclone inception.

In an active convergence zone, the ascent of the air is accelerated if the environment is moist and conditionally unstable up to the base of the dry inversion at a height of 3 or 4 km. If the latitude is at least 4° , the Coriolis force may deflect the inflow into a cyclonic spiral. The upward extension of the cyclonic flow is achieved most easily if the vertical shear of the environmental wind is a minimum.

There are a number of cases on record in which tropical cyclogenesis occurred after a middle-latitude circulation system extended equator-ward of latitude 30° and made itself felt at some level in the troposphere. At the surface, when the polar front moves into the tropics as a cold front, it introduces an increase in horizontal temperature gradient and cyclonic shear into the tropical environment. At 700 mb (3 km), a trough or cut-off low-pressure center at low

latitudes is attended by an advection of a cyclonic vorticity maximum. The vorticity-divergence relation requires a horizontally convergent wind field at the same level and favors convergence from the surface up to that level. At 200 mb (12 km) in the upper troposphere, a warm high-pressure area supplies a compensating horizontal divergence, keeping the pressure low at sea level by removing mass from the vertical air column, assumed to be hydrostatic. The polar intrusion at the 12-km level is indicated by an equatorward displacement of the jet stream. At the maximum wind speed along its axis, the jet stream also curves anticyclonically because its Coriolis force exceeds the horizontal pressure gradient force. The significance of the jet stream is that it augments updrafts and anticyclonic divergence by the chimney effect of drawing air upwards and carrying it away. These factors related to a polar air intrusion favor the inception of a tropical cyclone.

When a tropical convection system has formed, it can be maintained or strengthened by a "feeder band," which is a low-level wind belt bringing in warm moist air from a lower latitude.

For the identification of all of the above environmental features, one needs weather maps, upper air charts and satellite pictures to supply data on sea-surface and atmospheric temperature, humidity, pressure, wind, and clouds.

B. Presence and Intensity of a Tropical Cyclone

Once a tropical cyclone is formed, it is identifiable by its features. A search for these features must be made routinely if every tropical cyclone is to be detected at low latitudes near its source region.

What is sought is an organized convection system coincident with a low-pressure system tens of miles in diameter. In particular, there should be a cyclonic circulation of surface winds around the sea-level pressure area. The convection is indicated by large cumulonimbus clouds producing showers or thundershowers.

Of great importance is the intensity of the tropical cyclone. On the basis of its maximum steady wind speed, it is called a "tropical storm" if its maximum wind is between 34 and 63 knots. A lesser disturbance is called a "tropical depression," and a more powerful storm, a "hurricane." If the maximum wind speeds are not measured, they can be estimated by their statistical relationship to the storm's minimum sea-level pressure, according to NHC. The regression equation, which calls for stronger maximum winds for lower central pressure, gives a good approximation when the intensity of the tropical cyclone is fairly steady. The relationship is independent of the size of the storm, which is theoretically true of a cyclostrophic vortex.

Nevertheless, the size of a tropical cyclone needs to be known because it determines the area for which a hurricane warning is to be issued. There are several linear dimensions of a tropical vortex. If storms differ more in scale than in shape, then any one dimension might be sufficient to determine the other dimensions by fixed proportions. In order of decreasing value, the following radii can be defined on the basis of the storm's surface winds: outer limit of cyclonic flow, of gale winds, and of hurricane winds; and the circle of maximum winds. The circumference of the hurricane eye could be defined as the circle of discontinuity between the innermost hurricane winds and the light variable winds in the central region. However, in operation, the diameter of the eye (about 10 miles) is measured by the distance between the eye-wall clouds on opposite sides of the center, even though these clouds are entirely in the main vortex wind field outside the eye.

For the detection and measurement of tropical cyclones, aircraft reconnaissance and

radar play a larger part than in the mapping of the larger-scale environmental factors. The primary data needs include pressure, wind, clouds and rainfall. Sferics could be added for thunderstorm identification.

C. Internal Conditions Favorable for Intensification of a Tropical Cyclone

The continued existence and development of a tropical cyclone can be related to internal factors as well as external environmental factors. Internal conditions include the moisture supply, the flow pattern, and the pressure distribution in three dimensions.

The moisture needed by a tropical cyclone is derived from the tropical maritime air mass in which it is embedded. Since there are large variations of humidity within this air mass, there are correspondingly large variations in latent heat energy entering the tropical cyclone at low levels. Some of this variability relates to the thermal stability of the surface air just outside the storm. A conditionally unstable lower atmosphere carries moisture up to greater heights by convection, thus increasing the depth of the moist layer. This can be recognized by large areas of convective clouds with high tops, and extensive shower activity with precipitation at high levels as well as at the surface. An important internal addition to the moisture supply is the evaporation of water from the wind-driven waves and spray within the storm.

The flow pattern which affects the intensity of a tropical cyclone is that of the air exchange across its boundaries. The deepening of a storm is represented by a decrease in its sea-level pressure. Hydrostatically, this corresponds to a loss in weight of the vertical air column constituting the cylinder of the entire storm. Hence, for a storm to intensify, there must be a net horizontal divergence which is recognizable as a large radial outflow in the upper troposphere. For the cyclone's sea-level pressure to remain relatively constant, its radial outflow aloft must be balanced by a radial surface inflow, leaving no net horizontal divergence of the entire air column. Later, when the cyclone is filling up, there is a net convergence, the low-level inflow exceeding the high-level outflow.

Corresponding to these horizontal motions, there is always a considerable upward transport of air in the hurricane vortex, outside the eye, by the equation of continuity. The updraft is not uniform, but is strong in the eye wall, as indicated by the heavy precipitation there. Similar conditions exist in the spiral rain bands outside the eye-wall radius. Within the eye itself, there is an adiabatically warming downdraft to account for the development of the warm core, which indicates the cyclone is deepening. A weak downdraft in the eye continues throughout the life of the storm to make up for losses of air from out of the eye into the eye wall.

A vortex will get stronger when it contracts if it is in dynamically stable equilibrium. In such a vortex, if a parcel of air were removed to a different radial distance from the center, the difference between the centrifugal force and horizontal pressure gradient force would carry it back to its original radial distance. The observed radial profile of the surface wind speed outside the radius of maximum winds in a typical hurricane reveals that the wind speed varies nearly inversely as the square root of the radial distance:

$$v = cr^n \quad \text{where the exponent } n = -\frac{1}{2} \quad ,$$

v = surface wind speed, c = constant, and r = radial distance. The criterion for dynamic stability is that $n = -\frac{1}{2}$, which means that the radial profile of wind speed is flatter than that of a typical hurricane. (If there were no surface friction, the criterion for n would have been -1^0 , which is equivalent to an irrotational vortex, or the conservation of angular momentum.)

When an outer ring of this stable vortex contracts, its increase of wind speed with decreasing radial distance exceeds the initially existing radial increase. Hence, there is a local increase of wind speed with time, the inward advection of angular momentum leading to a local increase of kinetic energy in spite of some frictional dissipation at the surface. Therefore, a flat-profiled vortex will intensify if it contracts.

A decrease of minimum sea-level pressure indicates an intensification of the maximum winds. The deepening creates a greater radial pressure gradient. The resulting excess of the pressure gradient force over the initial centrifugal force would produce the contraction of the radius of maximum wind required for acceleration. Also, it would maintain the ring of maximum wind at a new reduced radial distance without allowing it to expand back to its original radial distance, because the increased radial pressure gradient force would not be exceeded by the increased centrifugal force.

The pressure distribution at the tropopause level favoring a deepening tropical cyclone is a high-pressure area. It has the role of helping the horizontal divergence of mass. Even without the high-pressure area, there would be some divergence because the centrifugal force of the strong winds rising from below would exceed the weak horizontal pressure gradient force at that high level.

The internal conditions discussed in this section involve the measuring of humidity, pressure, wind and vertical motion, clouds, and precipitation.

D. Location and Translation of a Tropical Cyclone

Suppose that sufficient information were on hand to completely describe and forecast the size and intensity of a particular tropical cyclone. Forecasters would still be faced with the serious problem of its location and future path, which is vital for determining where hurricane watches and warnings will have to be posted. Tracking of a storm is done most easily by following its center.

A tropical cyclone has a variety of centers, each with a unique definition. If the storm is strong enough to have an eye, each of the following centers will probably be inside the eye: the point of lowest sea-level pressure, the center of the circle of maximum winds, the center of cyclone circulation in the eye, and the geometric center of the eye.

The low-pressure center has traditionally been used to define the location of a tropical cyclone. It tends to be situated on the side of the eye closest to the highest part of the eye wall, which may vary from one quadrant of the eye to another. Instead of this, the center of the ring of greatest wind is now being used because it traces out a smoother path as the storm advances. The center of circulation in the eye is hard to define because the winds are so weak and variable, and often there are two or more such centers in one or more eyes. The geometric center of the eye can be measured relatively easily as the center of the eye wall, which may be a complete circle, a long circular arc, or even an oval.

There are many ways of forecasting the translation of a tropical cyclone center. The similarity of projected positions by different techniques gives a measure of confidence in the forecast.

The simplest procedure is an extrapolation, or persistence of the present translation at constant speed and constant direction. In spite of its simplicity, this method often works as well as sophisticated methods. Climatological translation based on a mean path of all previous tropical cyclones is useful for storms not subject to unusual environmental pressure patterns, such as blocking highs. Good forecasts are often made by use of a steering current,

based on what the 500-mb wind would be if the storm were absent. This views the vortex as an eddy drifting in an environment without modifying it. However, an intense hurricane of large size does alter the larger-scale environment wind pattern. With the aid of computers, translation can be based on analogs of earlier storms with similar characteristics of position, motion, and date of occurrence. Finally, the path of a tropical cyclone can be projected on the basis of computerized dynamic models, such as Sanders' model, now being used operationally by NHC.

Parameters for location and tracking of a tropical cyclone must include navigational fixes as well as the meteorological parameters of pressure, wind, and clouds, with emphasis on aircraft reconnaissance.

E. Hurricane Landfall - Coastal Conditions

The watch and warning service goes into full swing as a hurricane approaches a coast. Problems that forecasters must consider include hurricane-force winds, the storm surge, floods, and smaller-scale phenomena such as thunderstorms, tornadoes, and severe gusts.

The maximum surface winds on land will normally occur on the coast because the storm weakens rapidly as it moves inland. Over flat land, the area of hurricane winds is theoretically a triangle with its base along the coast and its apex inland, where the width of the hurricane wind area decreases to zero. This triangle is located mostly to the right (left in the S-hemisphere) of the track of the hurricane center because that is where the rotation is augmented by the current translating the hurricane. The greatest prevailing wind at the shore is expected to the right (left in S-hemisphere) of the hurricane landfall by a distance equal to the radius of maximum winds. The length of coast subject to hurricane winds or gale winds depends on the velocity profile of the hurricane. If the coast has rugged topography, there may be small areas of very high speeds due to orographic channeling.

The most dangerous aspect of a hurricane on the coast is the storm surge driven onshore by the hurricane winds. The greatest danger is to the right (left on S-hemisphere) of hurricane landfall. The water level starts rising slowly before the outermost part of the hurricane arrives. Later, as the wind increases to a maximum locally within the storm, the water rises rapidly to levels as much as 10 feet or even 20 feet above the normal astronomical tide. On the left (right on S-hemisphere) of the hurricane center, the water may drop 5 feet below normal due to the strong winds blowing from off the land. Once the center moves inland and the wind direction changes locally, there is danger of a sudden inundation from the sea.

The responsibility for forecasting the local heights of water with a storm surge rests with local forecasters who are familiar with the peculiarities of their particular coast. The height of a storm surge is greater under the following conditions. A stronger wind blowing from sea to land, a longer fetch of water subject to one wind direction, a longer duration of hurricane winds along the fetch, and a flatter slope of the sea bottom near the coast.

The area of flooding includes coastal land at elevations less than the storm surge height. But water damage extends even higher on the shore due to pounding surf. Torrential rainfall, sometimes over 20 inches, attending the hurricane, raises the water levels higher still and produces flooding inland. The heaviest rains occur usually to the right (left on S-hemisphere) of landfall and particularly if the hurricane's translation speed is slow. Disastrous flash floods can occur where rainfall is greatly augmented orographically, such as where land rises steeply in hills and mountains. Major floods continuing as long as a week after the hurricane may occur in river valleys draining areas of heavy rain.

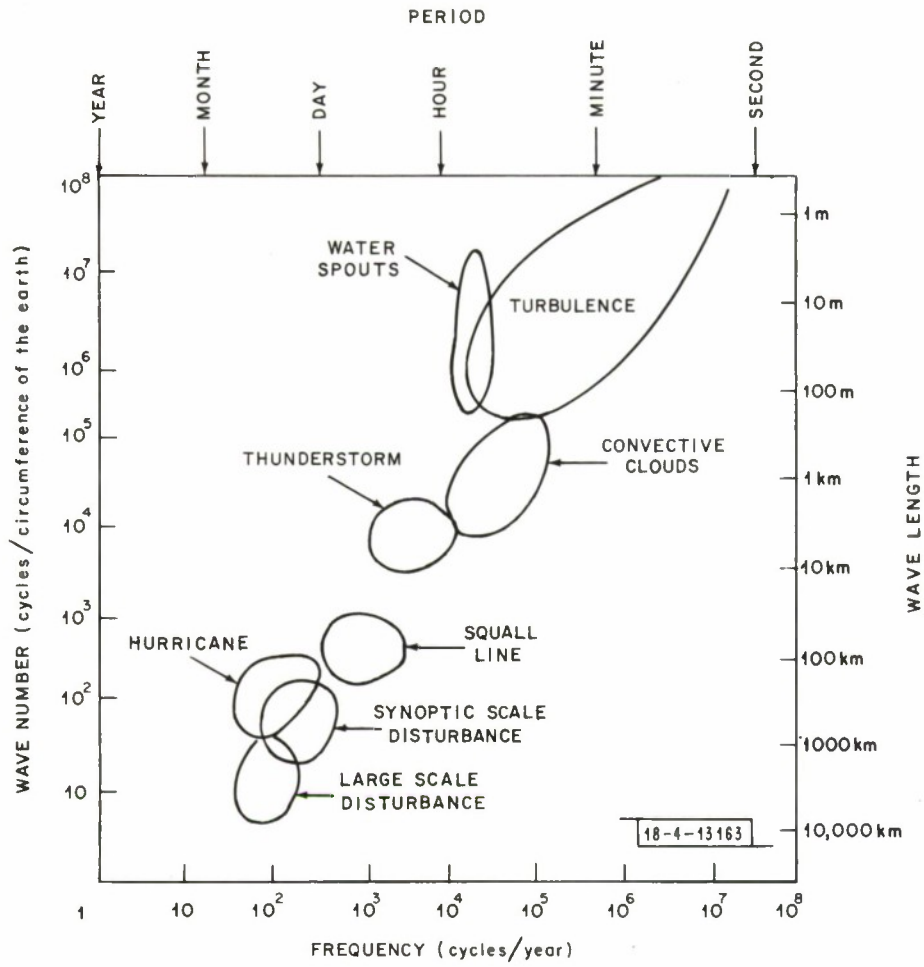


Fig. II-1. Scales of selected atmospheric phenomena.

The precipitation is by no means uniform, even over flat country. Thunderstorms are concentrated in the relatively slow-moving outer rainbands of the hurricane in its right (left in S-hemisphere) quadrant. It is not uncommon for small tornadoes to occur locally in these same rainbands. Nearer to the hurricane center, the rainbands are closer together and the showers are more numerous. The heaviest sustained rains occur where the rainbands merge into the eye wall. Within the maximum wind belt, the wind drives the rain nearly horizontally in sheets. Severe wind gusts may cause parallel streaks of damage.

There are many variations from the average hurricane rainfall distribution. When a tropical storm becomes stationary, its rainfall and winds tend to be more symmetrically distributed about the center. In some cases, such as in the New England hurricane of September 1938 and the Miami hurricane of October 1941, the rainfall is almost entirely on the left side instead of the right side of the path.

Parameters for hurricane landfall include surface parameters of water height and surface friction between the wind and the surface, navigation fixes, wind, rainfall, and thunderstorm electricity.

II. METEOROLOGICAL MEASUREMENT DATA

A. Observational Data Requirements

The observational data requirements quantify the characteristics of the input data for data-use techniques of a particular user. The atmosphere has natural variability on a broad range of scales. The scales at which significant natural variability occurs range from ($< 10^0 < f < 10^8$ cycles per year (period of greater than one year to less than one second) and $10^0 < k < (\times 10^8)$ cycles per earth circumference (wavelength of 4×10^4 km to less than 1 meter). The data-use techniques in meteorology usually focus on a much narrower range of scales than that mentioned above. In prediction, a match is sought between the scales of significance to the ultimate user and the scales by the data-use techniques to predict information in the desired scales. Since energy in the atmosphere is transferred between scales, in both directions, the data-use techniques should take this interaction into account.

Figure II-1 contains the scales of selected atmospheric phenomena which are related to or interact with hurricanes and tropical disturbances. The natural variability of a parameter, e. g., wind, temperature, is dependent upon the scale of the natural phenomena which influence the parameter, i. e., a wave number (k) in the horizontal, a wave number (n) in the vertical, and a frequency (f) in time. The variability of a parameter also is a function of space (i. e., x , y , and z locations on the earth) as well as time of the year or season. Of particular importance to observational system design is the fact that natural phenomena occur over very broad ranges of scale, and due to cost limitations, the natural variability in all scales cannot be observed routinely. The designer must, therefore, select observing system characteristics that measure information only as it is relevant to the data requirements and the intended data-use techniques. Unwanted scales should be filtered to the extent feasible in a prescribed manner.

Before one can specify the data requirements, one must consider the meaning of a "representative" observation. This will be discussed with reference to Fig. II-2. Observation characteristics such as time between observation (f_N), grid interval (k_N), observation representative period (f_{C_1}), instrument response time (f_{C_2}), path length (k_{C_1}), and instrument characteristic length (k_{C_2}) delineate "windows" in the frequency wave-number space within which the natural variability may be fully resolved (i. e., in time and space) by the observing system. For certain

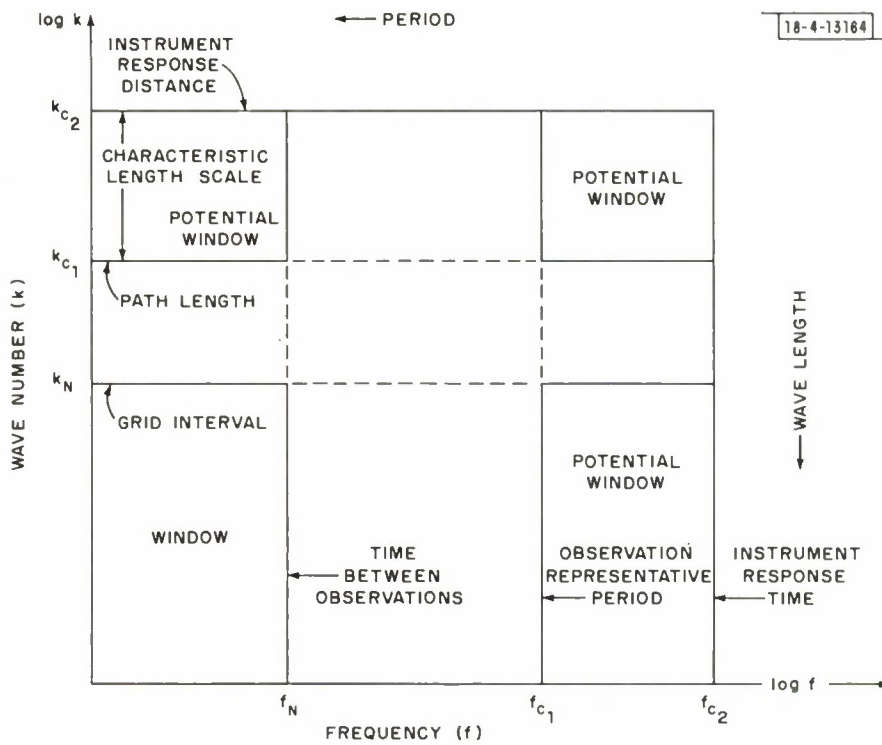


Fig. II-2. Resolution of natural variability by observational characteristics.

bands of scales, the natural variability is only partly resolved (i. e. , in time only or in space only). The significance of partly resolved information is dependent upon: (1) the intended data-use techniques; (2) the variability amplitude in relation to the amplitude of the variability in the resolved scales; and (3) the accuracy of requirements for data use. Likewise, the variability may be aliased from some wavebands which are only partially resolved.

The data requirements are visualized to satisfy the needs (i. e. , data-use techniques) of various users. Requirements sets are visualized for the following types of uses:

Operational - Hurricane Warning Services

National Hurricane Center - 1970-1975

Research

Hurricane warning forecast improvement (various numerical weather prediction researchers)

Understanding - (energetics of hurricanes/TROMEX)

Hurricane Modification - National Hurricane Research Laboratory

The data-use techniques and therefore the data requirements of each data user will differ. It is visualized that the above classification of data users will generate a degree of homogeneity.

B. National Hurricane Center (NHC) Data Requirements

The NHC has responsibility for the hurricane warning forecasts for the United States. Hurricanes occur climatically primarily in the summer and fall seasons of the year (June to November). While different weather regions of the National Weather Service have responsibility for issuing the official bulletins when the storm comes within their jurisdiction, the NHC maintains cognizance of hurricanes (and tropical disturbances) and has data requirements over a large geographical area. This area covers some 22 million square miles and is contained by latitudes 20°S to 40°N, longitudes 0° to 120°W.

There are three major hazards from hurricanes:

1. Water - The high tide along the coastal region related to the astronomical tide, the storm tide, wind-waves, swell, breakers, and surf. This is related to the topographical terrain both above and below mean sea level. In a hurricane, water is a major natural hazard to both life and property in the lower elevations along the coast.

2. Wind - The maximum sustained wind, as well as peak gusts, is a major cause of property damage within 200 miles of the coast along the path of the hurricane. The wind is also the energy source for the generation of waves and swell, which can cause damage to shipping and to coastal regions well removed from the path of the hurricane.

3. Floods - Heavy precipitation is frequently associated with hurricanes, occurring with the greatest intensity in the eye wall and in the major cumulonimbus clouds (hot towers) at the inner ring of the spiral rain bands. Floods come about from intense areal precipitation. The resulting runoff can cause streams and rivers to overflow their banks. The danger of floods persists even after the storm is in the dissipation stage and the surface winds have decreased to less than hurricane force (74 mph).

The data requirements listed in Table II-1 are based on available documents, interaction with NHC, and our interpretation of the NHC operations and data-use techniques to provide warnings of hazardous water, wind, and flood.

C. Numerical Weather Prediction or Numerical Forecasting

NHC utilizes several objective data-use techniques and procedures. Included are the following methods of numerical weather prediction (NWP):

1. Objective Methods

NHC-67: This is a statistical method to predict the 12-, 24-, 36-, and 48-hour translation and intensification of a hurricane. This is a regression method. The dependent variables are the displacement (in latitude and longitude) and intensity (central pressure). Independent variables represent hurricane location and intensity as well as synoptic scale circulation (500-mb height) parameters.

The Sanders model: This is an equivalent barotropic model of the synoptic scale flow field in the subtropics, which utilizes a measure of the vertically integrated wind field (in terms of a stream function) as the dependent variable. The hurricane represents a minimum in the stream function. This model predicts the hurricane translation over a 48-hour forecast interval.

Navy models: These models are based upon the barotropic model which predicts the flow field. The hurricane is subtracted from the flow field. The vortex is translated by the forecast flow for a prognostic interval of 72 hours. Empirical corrections are added to the barotropic prognosis.

Hurricane Analog (HURAN): This is an analog technique. A history of hurricanes over the last 100 years is stored in a data base. Descriptions include latitude, longitude, heading, speed, and circulation parameters. The current storm is matched to the data base to find the storms which it most resembles. Probable ellipses are derived for 24, 48-, and 72-hour translation prognoses.

In addition to the objective NWP methods mentioned above, the NHC forecasters use subjective methods to diagnose the expected changes in intensity of hurricanes. These subjective methods involve analysis of present and past history of hurricane parameters such as maximum wind, central pressure, maximum pressure gradient, radius of maximum wind, eye diameter, height of eye wall, eye geometry, and sea-surface temperature.

Flood forecasts are prepared by the River Forecast Offices of the NWS, using runoff models. Forecasts of hurricane-induced high water are prepared by computer models which incorporate the effects of tide and wind effects.

D. Data Requirement in Tabular Form

The NHC operational data requirements for the valid period 1970-75 are contained in Table II-1. The columns identify the data requirements for eighteen parameters, properties, profiles, or fields. The Roman numerals on the columns identify a subjectively assessed precedence associated with each parameter. There is little significance to the relative ranking of parameters close to one another in the table.

The rows of this table identify the parameters and the requirement characteristics. A description of the requirement characteristics follows. Table entries are referenced for the first column to make the description explicit.

1. Observation Accuracy — This specifies the desired and maximum allowable ($3 \times$ RMSE) error in the units that the parameter will be measured or reported. The parameter location of center is desired with an accuracy of 5 n. mi. The maximum allowable error is specified as 10 miles.
2. Time between Observations — This is the temporal sampling intensity (f_N on Fig. II-2). For hurricanes greater than 36 hours from landfall, an observation of center location should be made at least every 6 hours. Within 36 hours of hurricane

- landfall on the U. S. Coast, a more frequent observation (every 2 hours) is specified.
3. Transmission Lag - The desired transmission of the location of center is in real time (R. T.), the maximum allowable transmission time is one-half hour.
 4. Format - The location involves coordinates of latitude and longitude. Voice communication is desired between the meteorologist on the reconnaissance aircraft and the forecaster at NHC. A reconnaissance code (RECCO) message is also necessary.
 5. Range - The range is the minimum and maximum value of the parameter that may occur climatologically. The range of central pressure (at sea level) in hurricanes and tropical disturbances is listed as 900 to 1 050 mb.
 6. Absolute Location Accuracy - The absolute location accuracy (3 x RMSE) of the central pressure observation is desired as 5 n. mi; a maximum location error is listed as 10 n. mi.
 7. Vertical Location - The central pressure of the hurricane is required at sea level.
 8. Observation Representative Period - This defines the frequency cutoff or filter for the natural variability in the parameter (f_{c1} on Fig. II-2). For the maximum wind, no frequencies less than 0.5 min. are desired in the wind data. All natural frequencies greater than 2 min. are desired in the wind observation.
 9. Relative Location Accuracy - Relative to the location of the hurricane center, the maximum wind observation should be located within 1 n. mi.
 10. r-Sampling Interval - Paths or profiles across the hurricane will be specified. Along the wind profile, a sampling interval of 5 n. mi is specified (k_N on Fig. II-2), with additional observations, as required, to identify the maximum and other significant points.
 11. X-Y Sampling Interval - This refers to a field of data in the horizontal. The precipitation intensity in the eye will be observed on a 1- to 2-mile grid interval in the north-south and east-west (k_N on Fig. II-2).
 12. Characteristic Length Scale - This refers to a wavelength cutoff (or filter) in the north-south, east-west, or vertical direction. For tornadoes, gustiness, and turbulence, the requirement calls for measurements of the maximum value of wind eddies ($|\mathbf{V} - \bar{\mathbf{V}}|$) within the range of length scales of 1 to 200 meters (k_{c2} to k_{c1} on Fig. II-2).

E. A Description of Parameters

Since there is some ambiguity on the meaning of the parameters listed in the NHC data requirements, a description follows.

Location of Center (I) - The center of the hurricane is defined as the point of minimum pressure (or geopotential) in the horizontal at levels 10,000 feet or below. A wind center derived as the geometric center of the ring of maximum wind may be a suitable alternative. The location of the center involves inaccuracies due to both meteorological identification and navigation.

Central Pressure (II) - This refers to the sea-level pressure at the center of the hurricane.

Wind-Area Grid (III) - This refers to the synoptic scale wind field (representative period of one hour) covering the large area (22×10^6 sq. mi) 20°S to 40°N latitude, 0° to 120° W longitude. Measurements are desired at several elevations in the vertical, specified as 1000, 900, 600, and 200 mb. The latitudinal shear of the east-west wind component ($\partial n/\partial y$) will be resolvable north of the hurricane center.

Maximum Wind (IV-A) - This represents the maximum horizontal wind at a level at or below 10,000 feet along a profile through the center of the hurricane. Maxima of different magnitude may occur in each quadrant.

Eye Diameter (IV-B) - This represents the distance across the center to the cloud at the eye wall. Elliptical eyes will have diameters representing the major and minor axes.

Radius of Maximum Wind (V) - This represents the radial distance from the center to the maximum wind as measured for the right front and left rear quadrants.

Wind Profile (VI) - This represents the wind speed and direction along profiles through the center of the hurricane between left rear and right front, and right rear and left front. The profile is specified in the vertical at one elevation between 1500 and 10,000 feet. The observation representative period of 0.5 minutes to 2 minutes specifies that natural variability with periods less than 0.5 minute should be filtered from the observation. Observations at significant points (the wind maxima) will be necessary to supplement the 5-n. mi grid interval specified.

D-Profile (VII) - This represents a profile of the geopotential departure from standard atmosphere at an elevation between 1500 and 10,000 feet along crossing profiles which pass through the hurricane center. A maximum D gradient will be derivable for comparison with the maximum wind.

Temperature Profile (VIII-A) - This represents profiles of temperature in the free atmosphere at an elevation between 1500 to 10,000 feet along paths through the center of the hurricane.

Mixing Ratio Profile (VIII-B) - This represents profiles of the moisture parameter in the free atmosphere at an elevation between 1500 to 10,000 feet along paths through the center of the hurricane. Other moisture parameters (e. g., dewpoint) would be acceptable.

Sea-Surface Temperature Grid (IX) - This represents the sea-surface temperature over an area covered by and in advance of the hurricane. A path length (k_{c1} on Fig. II-2) of 1 n. mi is specified to filter smaller-scale horizontal fluctuations. Ideally, the sea surface refers to the depth of the upper mixed layer.

Precipitation Intensity - Eye (X-A) - This refers to the average precipitation intensity in the eye wall.

Precipitation Intensity, Radar Reflectivity (X-B) - This refers to the precipitation intensity over an area which includes the total hurricane. A 1- to 2-mile x-y grid interval is specified. Natural variability with periods less than 15 minutes should be filtered. When the hurricane is located over water, this measurement will be used primarily to diagnose the intensity and change of intensity. As the hurricane approaches landfall and after passing over land, this measurement is a major input to the flood forecast.

Height of Eye Wall (X-C) - The average and maximum height of the eye wall should be reported for the four quadrants of the hurricane.

Tide Anomalies (XI) - This parameter represents the height of the sea surface at stations along the shoreline; a grid interval of 1 n. mi is indicated. The storm tide is one of the three major hurricane hazards which cause destruction and loss of life. This observation will be used as guidance to direct survival operations of the civil agencies (Office of Emergency Preparedness, Civil Defense, etc.), and a data base is necessary to develop improved prediction methods.

Swell (XII) - This parameter is desired on a grid with a 3° latitude grid interval in the deep ocean near hurricanes. The waves and swell generated by hurricane winds cause seas which are dangerous to shipping and small boats. In addition, the swells are the energy sources for breakers and surf which can cause significant danger to life and property at considerable distance from the hurricane path. Waves with periods less than 5 seconds should be filtered.

Gustiness, Tornadoes, Turbulence $|\bar{V} - \bar{V}|$ (XIII) - This parameter is a measure of the maximum wind gusts ($|\bar{V}, \bar{V}|$) with characteristic length scales of 1 to 200 meters (see Fig. II-2). This is the space scale which must be resolved to measure the desired scales. The observation representative period will filter frequencies less than 5 seconds. The average wind (\bar{V}) should have an observation representative period of 2 minutes, a path length (k_{c1} on Fig. II-2) of 3 n. mi. This parameter will be most useful 0 - 24 hours prior to landfall to estimate the destructive maximum gusts which may characterize the hurricane.

Bright-Band Height Profile (XIV) - This parameter will yield profiles of the height of the zero degree isotherm in a hurricane and will be useful in combination with the temperature profile sea-surface temperature (parameter IX) and mixing ratio (parameter VIII-A), parameter VIII-B) in deriving profiles of convective instability.

TABLE II-1
 NHC OPERATIONAL DATA REQUIREMENTS
 VALID PERIOD 1970 - 1975

Parameter	I	II	III	IV-A	IV-B
	Location of Center	Central Pressure	Wind- Area Grid	Max. Wind	Eye Diam.
Obs. accuracy (de- sired/max. allowable)	5/10 mi	2/6 mb	3 KT	5 KT	3 n. mi
Time between obs. (de- sired/max. allowable)	1/6* hrs.	2/6* hrs.	6 hrs.	2/6* hrs.	2/6* hrs.
Transmission lag (de- sired/max. allowable)	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.
Format	Voice/Recco	Voice/recco	A. N.	Voice/Recco	Voice/Recco
Range (min. -max.)		900-1050 mb	0.360° 1-80 KT	200 KT	3-30 n. mi
Abs. location accuracy (desired/max. allowable)		5-10 n. mi	5-10 mi.	5-10 mi.	NA
Vertical location		Sea level	1000 200 mb 900, 699	1.5-10 kft	NA
Obs. repres. period			1 hr.	0.5/2 min.	Inst.
Relative loc. accuracy			NA	1 n. mi	1 n. mi.
r Sampling interval			NA	1 n. mi	1 n. mi
X-Y grid interval			3° lat.		

* A function of distance from landfall.

(continued)

TABLE II-1 (continued)

Parameter	V Radius Max. Wind	VI Wind Profile	VII D Profile	VIII-A T Profile	VIII-B Mixing Ratio Profile
Obs. accuracy (desired/max. allowable)	1 n. mi	5 KT	20-60 m	.5/1°C	1.0/1.5 gm kg ⁻¹
Time between obs. (desired/max. allowable)	2/6* hrs.	2/6* hrs.	2/6* hrs.	2/6* hrs.	2/6* hrs.
Transmission lag (desired/max. allowable)	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.
Format	Voice/Recco	Recco or Equ.	Recco or Equ.	Recco or Equ.	Recco or Equ.
Range	5-50 n. mi	5-200 ^{KT} 0-360 ^o	10m-1km	0-30°C	1-30 gm kg ⁻¹
Abs. location accuracy (desired/max. allowable)	NA	NA	NA	NA	NA
Vertical location	1.5-10 kft	1.5-10 kft	1.5-10 kft	1.5-10 kft	1.5-10 kft
Obs. repres. period	0.5/2 min.	0.5/2 min.	0.5/2 min.	0.5/2 min.	0.5/2 min.
Relative loc. accuracy	1 n. mi	1 n. mi	1 n. mi	1 n. mi	1 n. mi
r-Sampling interval		5 mi [†]	5 mi [*]	5 mi	5 mi
	IX	X-A	X-B	X-C	XI
Parameter	Sea Surface Temp. Grid	Precip. Inten. (Eye)	Precip. Int. Radar Refl. Area Grid	Height of Eye Wall	Tide Anomalies
Obs. accuracy (desired/max. allowable)	.5/10°C	3 in. day ⁻¹	0.5/1 in. day ⁻¹	2-4 kft.	1 ft
Time between obs. (desired/max. allowable)	2/6* hrs.	2/6* hrs.	2/6* hrs.	2/6* hrs.	1 hr.
Transmission lag (desired/max. allowable)	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.
Format	Recco	Video/AN	Video/AN	Vocode/voice	A. N.
Range	15-35°C	5-50 in. day ⁻¹	0.5-30 in. day ⁻¹	25-60 kft	-10/+30 ft
Abs. location accuracy (desired/max. allowable)	NA	NA	5-10 n. mi over water, 1-2 mi over land	NA	0.1 n. mi
Vertical location	Sea surface	NA	NA	NA	NA
Obs. repres. period	0.5/2 min.	0.5/2 min.	15 min.	inst.	1 min.
Relative loc. accuracy	1 n. mi	1 n. mi	1 n. mi	1 n. mi	NA
r-Sampling interval		NA	NA	NA	NA
X-Y Grid interval	5 mi.	1-2 mi.	1-2 mi.	NA	1 n. mi
Path length	1 n. mi				

* A function of distance from landfall.

† Plus significant points.

(continued)

TABLE II-1 (continued)

Parameter	XII Swell	XIII Gustiness, Tornados, Turbulence	XIV Bright Band Height Profile
Obs. accuracy (desired maximum allowable)	0.5 - 1 ft	< 20 Kts 40-80 Kts 20-40 Kts > 80 Kts	1 kft
Time between obs. (desired/maximum allowable)	1 hr.	15 min/2 hrs.	2/6* hrs.
Transmission lab (desired/maximum allowable)	RT/0.5 hrs.	RT/0.5 hrs.	RT/0.5 hrs.
Format	AN	Voice/AN	Recco/AN
Range	1-30 ft	0.125 Kts	15-20 kft
Abs. location accuracy	0.1 mi.	5-10 mi. over water, .5-1 mi. nr. landfall	NA
Vertical location	NA	Sfc to 1 kft	NA
Obs. representative period	5 sec	5 sec	Inst.
Relative loc. accuracy	NA	NA	1 n. mi
r-Sampling interval	NA	NA	5 n. mi
X-Y grid interval	3° lat.	NA	NA
Char. length scale	NA	1-200 m	NA

* Significant observation close to landfall.

Abbreviations Used

NA	Not applicable
RT	Real time
Recco	Reconnaissance code
Inst.	Instantaneous
Equ.	Equivalent
AN	Alpha numeric code

APPENDIX A
A CRITIQUE OF CONTEMPORARY
AIRBORNE METEOROLOGICAL INSTRUMENTATION
A. H. Miller

I. INTRODUCTION

Since the inauguration of a weather service over one hundred years ago, certain basic meteorological parameters or anomalies in sets of these parameters have been continuously monitored in a successful effort to determine what predictor values are required to foresee a particular weather phenomenon. Man's understanding of the atmosphere in three dimensions has increased many fold since the inception of the weather service. As mankind uses and abuses more of the atmosphere, he must attempt to better understand it in all its manifestations. To accomplish this, he has made good use of all the facilities at hand. Obviously, the scale of weather which was previously understood was a function of the area from which accurate weather observations were available. Because approximately seventy percent of the earth's surface is comprised of ocean, little on the global or even hemispheric scale was known until the advent of weather observations from ocean vessels and even more recently, from aircraft and satellites.

In the pre-World War II years, historical records of occurrence were about the only data kept on severe storms and, in particular, tropical Atlantic hurricanes and Pacific typhoons. In the post-war years, since the second "age of enlightenment" with our increased knowledge of the characteristics of incipient storms and the availability of platforms that could withstand the severe stresses encountered in reconnoitering these severe storms, man has been able to attempt to further understand the cause of, the driving and steering forces of, and the dissipating of hurricanes. Real-time analysis of certain standard meteorological parameters has recently been automated and computer models, both symmetric and asymmetric, of hurricanes have come into being. The pertinent question of "does the model even closely approximate what is really happening?" arises. The answer can only come from empirically monitoring those parameters which the model predicts and also those required as inputs to the model.

II. A NON-RIGOROUS THEORY OF METEOROLOGICAL MEASUREMENTS

In general, instrumentation state of the art has advanced many fold in this post-war era. Specifically, however, meteorological and/or cloud physics measuring instruments would appear to lag appreciably and commonly are the inadvertent result of research in an unassociated field. The foremost airborne temperature sensor system presently available is the result of the needs of a rapidly advancing aircraft industry. Several other instruments of comparable notoriety are the result of this country's space or defense effort. Now that the atmospheric sciences have been given the incentive to develop sensors, a feedback problem between the empiricists and theoreticians has evidenced itself. How much time and money should be expended in developing the absolute instrument in a field so sorely lacking when the theoretical models are insensitive to factor of two or more changes? Somewhat the reverse of this problem is that of measurement accuracies presently quoted by the empiricist. A complete understanding of instruments does not commonly exist.

Any given measurement is made by a system rather than an instrument. Such a system is made up of the following:

- 1) A housing or probe which is usually intended to "isokinetically" convert a dynamic condition to a quasi-static condition while simultaneously separating all phases of water other than vapor, if present from the sample volume;
- 2) The sensor which is meant to couple to the variable in question in a prescribed manner;
- 3) The transducer which translates the sensor's variations into a function which has an electrical equivalent that is easily converted to a voltage;
- 4) Conditioning electronics to facilitate convenient recording or transmission of the data. These would include bridges, amplifiers, discriminators, resolvers, and if further required, analog-to-digital converters.

In determining the system accuracy for a particular parameter, one must take into account instrument accuracy as given by the manufacturer, convert that to an electrical equivalent, and systematically add and in the case of an amplifier with gain, multiply the component errors, nonlinearities (assuming a linear function), and both short- and long-term drift characteristics as well as error induced by first-order smoothing of data. In the case where analog-to-digital conversion is involved, another factor, the least significant bit, plays an important part in final accuracy and resolution.

The subject of parametric resolution is frequently misunderstood. The resolution of any instrument must necessarily be well within the accuracy of the instrument as the σ value of the accuracy must be added to the resolution to determine the absolute limits of instrument accuracy. The greater the resolution error, the greater the total error. Spatial and temporal resolution of airborne instruments are usually synonymous. They are strictly a function of the time constant, τ , of the instrument or the degree of intentional smoothing or integration of the signal. In designing an instrument, however, one is obliged to design in a τ large enough to make the measurement statistically representative of the parameter.

III. CONTEMPORARY METEOROLOGICAL INSTRUMENTATION

The measurement of any particular meteorological parameter can commonly be accomplished with any one of a number of types of instruments. To attempt a complete list for all parameters would prove too voluminous for this report. However, a broad spectrum treatment is at least warranted. The parameters to be considered are temperature, pressure, altitude, humidity, wind direction and speed, liquid water content, cloud particle and hydrometeor spectra, ice/water ratios, vertical and lateral velocities, and turbulence.

To attempt to accurately measure free air temperature aboard an aircraft, the researcher must be provided with such information as the recovery factor of a total temperature sensor (the percentage of the total temperature recovered), the function of the sensor with respect to temperature, the response time and accuracy of the device. For many years, the aviation industry relied on what is known as a flush bulb temperature sensor. This sensor was a total temperature device with a dubious recovery factor and a variable time constant dependent on many things, such as angle of incidence of incoming solar radiation, icing condition, position in which mounted, etc. By even today's standards, accuracies were unquotable.

The military replacement for the flush bulb, which still finds itself in limited use, is the AN/AMQ-8 vortex thermometer developed at the Naval Research Laboratory. The basic concept was to slow down the air to be sensed with counteracting adiabatic compression and expansion. An added benefit was the centrifuging effect of the vortex, which would minimally eliminate the larger cloud particles. Air speed compensation was fixed, but could be tuned for a specific air speed by reducing the size of the inlet orifice. Two effects that evidence themselves in cloud penetrations are an apparent temperature increase upon entry due to condensation of water onto the sensor, and a subsequent temperature deficit at cloud exit due to evaporation of water from the sensor. Originally, the actual sensor was a coil of fine wire with a near-linear temperature coefficient. To give the sensor structural integrity, the wire was buried in a ceramic matrix which served to effectively integrate the temperature over a period of several seconds. The AN/AMQ-8, neglecting its frailties, was a true free-air temperature monitor.

Though still in use by a few groups, the unavailability of replacement sensors is responsible for the waning number of vortex temperature sensors. A few groups are attempting to modify the housing to accept thermocouples or more recently, microminiature silicon diodes. Although thermocouples have prevailed for years as a standard reference, they are frequently used in conjunction with self-powered reference junction compensators, which are in themselves questionable. Too, the highest output couple generates only about $0.04 \text{ MV } ^\circ\text{C}^{-1}$, which dictates a very stable, high-gain amplifier to condition the signal for recording. In the more recent past, ultraminiature silicon diodes have been adopted for use in measuring temperature. A silicon junction has the unique characteristic of having a linear forward voltage drop from about 200°C to -273°C of about $2.0 \text{ MV } ^\circ\text{C}^{-1}$. Consequently, two orders of magnitude less amplification is required, which subsequently reduces the stringent stability requirements of the thermocouple amplifier.

Currently, the leading airborne temperature sensor is the Rosemount total temperature sensor. The actual sensor exists in a series of different configurations, but for work in the atmospheric sciences, the Series 102 is most commonplace. These sensors have boundary-layer control and are constructed to separate the majority of cloud particles from the sample volume to eliminate the wet bulb effect (see Fig. IIA-1).

Errors inherent in the total temperature system include: 1) de-icing heat induced errors; 2) radiation errors; 3) recovery errors; and 4) self-heating errors. At typical hurricane penetration speeds, the errors amount to about: 1) 0.3°C max; 2) $< 0.1\%$ max; 3) 0.05% of absolute temperature; and 4) $< 0.02^\circ\text{C MV}^{-1}$, respectively. Conversion of total temperature to static or free air temperature is accomplished by applying the formula $T_o/T_s = 1 + (\lambda - 1) M^2/2$, where T_o is total temperature in degrees Kelvin, T_s is the static temperature in degrees Kelvin, λ is the ratio of specific heats of air at constant volume and constant pressure and is roughly 1.4 and M^2 is the Mach number squared (about 0.2 to 0.3 for typical aircraft penetrating speeds). The response time for this instrument is of the order of 0.5 sec, but may be acquired with a faster sensor. In a standard configuration, open-wire and sealed units are available, the sealed unit being more rugged at the expense of speed. In either case, the primary sensor, usually a platinum wire element, is well calibrated and NBS traceable.

Other temperature sensors which are available but more or less developmental in nature include variations of the vortex housing, blunt-body stagnation point housing, reverse-flow sensor, and infrared temperature sensors. In the infrared sensor, a wavelength corresponding to a

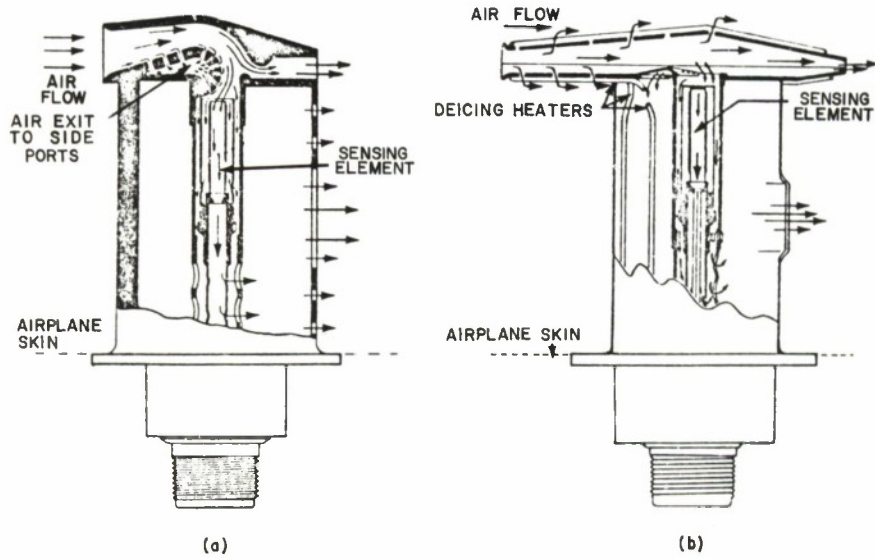


Fig. II A-1. Internal configurations of Model 102 deiced sensors showing boundary layer control, particle separation path, and hermetically sealed sensing element.

strong CO₂ absorption band is used such that the total path length over which the instrument integrates is of the order of 30 to 50 meters. Measurement accuracy is a function of reference temperature stability primarily and electronic stability secondarily in this radiometric instrument.

According to the present requirements of NHC, central pressure (lowest in the eye) is second only to location of the hurricane center in priority. Included in the AWRS Project 5222, pressure is also a primary measurement. The sought-after specifications, however, are likely to be only theoretically possible. In today's typical ruggedized pressure sensors, a full-scale output of 5 volts over a range of zero to 15 PSI is equal to less than $5 \times 10^{-3} \text{ V mb}^{-1}$ or per AWRS specifications, $\sim 1.5 \times 10^{-3}$ volt accuracy ($\sim 0.06\%$) for the pressure range 1060 mb to 500 mb and 0.5×10^{-3} volt accuracy ($\sim 0.02\%$) for the range 500 mb to 150 mb. Regardless of the type of sensor, signal-conditioning electronics of this caliber are not usually found outside the laboratory nor are aircraft power sources nearly stable enough to provide signals of this accuracy and resolution. Pressure transducers are available in any one of a number of forms. These include variable capacitance, variable reluctance, variable resistance, and as a variable differential transformer or strain-gage type.

Each type of sensor has inherent problems, some of which are common to several, some unique to an individual. Variable capacitance pressure sensors are made with a sealed reference cavity having as one side a diaphragm which is movable and also forms one-half of an air variable capacitor. This capacitance which is in the output of an oscillator circuit (usually several hundred kHz) has a charging current ($i = dQ/dt$) proportional to capacitance, a function of pressure. One of the problems with most variable capacity transducers is their sensitivity to dielectric changes such as changes in pressure and humidity or both in combination, since the dielectric constant of the medium directly affects capacity. Temperature also affects output accuracy, as does shock vibration and overpressure. These are, however, secondary effects. If condensation in the line or cavity occurs, or if liquid from any source is allowed to enter, severe effects result, usually making the sensor useless. This effect is most severe in the capacitance-type transducer.

Variable reluctance transducers are constructed similarly to the capacitance transducers. However, the magnetically permeable diaphragm is spaced equidistant between two magnetically permeable "E" cores upon which inductance coils have been wound. These coils are excited by an AC carrier voltage. Displacement of the diaphragm causes an increase of inductance on one side and a decreased inductance on the other. These inductances form two sides of a bridge, the output of which when demodulated is linearly proportional to pressure. Mechanically, the variable reluctance pressure transducer is sound. It can be built to withstand severe environmental stresses, but is subject to electronic frailties as are the others.

Potentiometric transducers are without doubt the least expensive of all, but coincident with the price is reliability, more important repeatability and hysteresis. Their accuracy is dependent upon the aneroid cell which is mechanically coupled to a potentiometer. The coupling allows backlash and extreme hysteresis. As there are moving parts, there will be friction and wear, leading one to conclude the usable life to be short.

One family of transducers which has never come into great favor is the strain-gage type. In this instance, once again, a diaphragm is the backbone of the device upon which a strain gage is bonded. Displacement of the diaphragm creates strain, which is reflected as a variation in resistance of the gage. In normal strain-gage applications, a second identical strain gage is

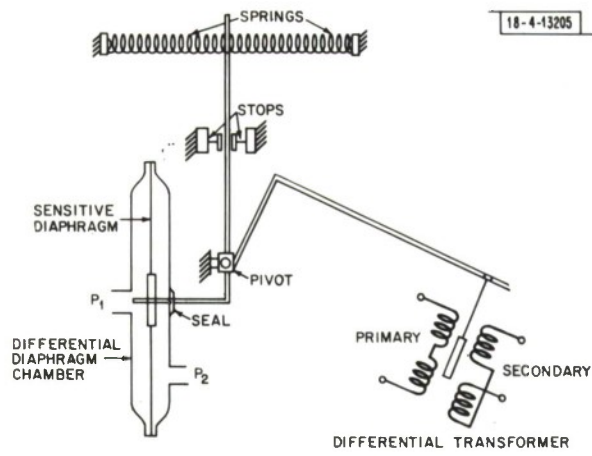


Fig. IIA-2. Differential diaphragm pressure transmitter.

firmly mounted to a non-moving part of the cavity and is used as the second leg of a bridge circuit to compensate for temperature effects. The biggest drawbacks to the strain-gage sensor are poor stability and low output voltage. The output impedance by the same token is sufficiently low to make the signal quite easy to work with.

If ease of use were of primary consideration, the differential transformer transducer would certainly lead the field. However, with accuracy, reliability, and repeatability as primary goals, one tends to place the differential transformer device well down on the list for reasons immediately obvious in Fig. IIA-2. As with the potentiometric system, there is quite a bit of mechanical linkage to provide backlash and friction, a seal which could easily leak, and lever arms or beams which could get warped or bent. Also, a regulated source of primary AC voltage is a necessity. Typical specifications for temperature, shock, vibration, and over-pressure are some of the poorest.

While being critical of the many forms of transducers, it should be pointed out that much work has been done on proper placement of static pressure ports and the effects of skin ripples and pitch and yaw angles on the apparent pressure at these ports, and yet little heed is taken of these effects in placing static ports on research aircraft. It would appear reasonable to recommend the complete installation of a de-iced, aerodynamically compensated, pitch and yaw insensitive pitot-static tube for the express purpose of providing a good static source for the necessary pressure transducer. Inasmuch as altitude recording goes hand in hand with pressure, it suffices to conclude that with today's radar altimeters as required on all Category II aircraft, the altimetry problem is well in hand. Presently, accuracies of ± 20 ft are claimed.

The subject of humidity measurements on aircraft, whether relative or absolute, is at least a venerable one. Presently, humidity is measured in terms of dew point, vapor pressure, or mixing ratio. Available sensors include: 1) infrared humidimeters; 2) dew-point devices; 3) ultraviolet absorption humidimeters; 4) electronic psychrometers; 5) P_2O_5 coulombic hygrometers; 6) salt cells, 7) sintered glass conductivity cells; and 8) nylon element hygrometers.

The infrared hygrometer which is used by only a few organizations depends on the absorption of infrared radiation over about a one-meter folded path. The instrument is electrically and mechanically stable but has a rather large volume, and consequently, has a long time constant.

The most widely used device today is the Cambridge Systems Dew Pointer, which operates on the principle of keeping a polished, high thermally conducting surface at a temperature equal to the dew point, whereupon a simple relationship exists between dew point temperature and mixing ratio. One effect seldom taken into account is the water deficit at temperatures below freezing, or said another way, the dew point/frost point relationship. Secondly, the time constant of the device is on the order of several seconds, but is reduced at higher altitudes or lower temperatures. The dew point temperature sensor is curiously enough an NBS traceable Rosemount platinum wire sensor.

Another device manufactured by Cambridge and about out of the development stage is the hydrogen Lyman Alpha humidimeter or total water content probe. This probe relies on the absorption of the hydrogen Lyman Alpha emission at 1215.6 \AA . This source is almost uniquely sensitive to water, but is somewhat attenuated by O_2 (a factor of 10^3 down) and O_3 , which is seldom found in quantities sufficient to become a problem. The total water device has a fast time constant and in clear air, can respond to a 63 percent step change in mixing ratio in

in about 30 msec. This fast response is attributable to the 0.5-cm path length. In the past, stability of the Lyman Alpha source has been a problem, but recent developments have led to a source which does not appear to deteriorate in less than several thousand hours.

A very recent entry into the market is the electronic psychrometer, which just as its name suggests, gives one the difference in wet bulb and dry bulb temperature (ΔT) and the dry bulb temperature. Using a multi-pressure hygrometric chart (for aircraft use), one can determine the saturation vapor pressure. The manufacturer claims very good stability and accuracy. The actual sensing elements are a pair of diodes, one of which is wicked and kept wet, while the other is dry. As in other diode applications, the output is linear with respect to temperature. With this instrument, however, distinguishing dew point from frost point is also necessary and may cause some ambiguity.

The phosphorous pentoxide coulombic hygrometer was first developed as a potential moisture sensor for a Martian atmosphere probe. It has the advantage of measuring mixing ratio (gms kgm^{-1}) directly over very wide ranges ($10^4:1$) and at extreme temperatures. The actual sensor is a small dielectric tube within which is wound a double helix of platinum. A 10 percent solution of P_2O_5 and acetone is then introduced into the tube, which after the evaporation of the acetone, leaves a low vapor pressure residue of P_2O_5 . As sample air is passed through this tube, the P_2O_5 absorbs the water contained and becomes an electrolyte. If a potential exists between the helices, the subsequent current flow is proportional to vapor contained per unit volume sampled. Although this type of sensor has been available from CEC Division of Bell and Howell and Meteorology Research, Inc., it has never been widely accepted outside the laboratory. Some of the apparent problems with such a system are the stability due to erosion of deposited P_2O_5 , a servo controlled pump to maintain a constant volume, and the mass flow sensor necessary to control the pump.

The remaining humidity sensors are all more or less untried on aircraft and depend on matrices which undoubtedly change with time, creating an extreme calibration and, hence, accuracy problem. Consequently, further comments on such sensors are best left unsaid. One problem not previously mentioned with regard to monitoring humidity from an aircraft is that of separating out any liquid phase which happens into the sample. This problem has yet to be properly solved, hence, measurements in a cloudy atmosphere are not to be trusted.

The measurement of winds, particularly from an airborne platform, is well discussed in the report of the Radar Panel elsewhere in this document (see Section IV, Report of the Radar Panel). However, at least a cursory look at what is presently in use or under consideration is warranted here. The crudest form of wind measure still in limited use in hurricane research is simply eyeball estimation of the Beaufort wind scale. In this day and age, such a sensor would appear out of place and qualitative and subjective at best. A slightly less crude method that still suffers from human error is calculating wind from a wind triangle provided by the aircraft navigator. In reality, however, winds are usually measured by the dual or 4-beam downward-looking Doppler radar technique. These radars are usually X-band (3-cm) radars. In relatively clear air, the 4-beam system displays reasonable accuracy (± 2.5 kts) except during maneuvers where the system rejects the radar return and "remembers" what the winds were prior to the maneuvers. This memory system appears to be a necessary evil until the day that research aircraft are equipped with small digital computers on board. A second more serious problem exists in hurricane work in that the highly reflective reference surface (the ocean) is moving, which proves to cause ambiguity in the measurement. Thirdly, X-band (3-cm)

radar is severely attenuated by large cloud droplets and rain, which also proves to cause ambiguity. Future wind measurement will probably be accomplished through the use of a longer-wavelength Doppler radar, which will use the actual motion of the cloud particles as wind traces. For winds at flight altitude, an expensive system does presently exist but as of this moment, has not been incorporated into research airframes. This system is the inertial guidance system being used by some airlines. This instrument has also been well discussed elsewhere in this report.

In future hurricane modification experiments, a predetermination of the amount of liquid water available for seeding could become a necessity. Airborne measurements of liquid water can be made by utilizing any one of several instruments currently available. The types of sensors include the Johnson-Williams Liquid Water Content Meter, the Cambridge Systems Lyman Alpha Total Water Content Probe, the Levine Cloud and Rain Water Probe, or the paper tape sensor.

The Johnson-Williams sensor is a simple device incorporating an exposed hot wire which is normal to the flow of air and a similar wire which is parallel to the air flow. Cloud droplets impact on the hot wire normal to the airstream, cooling it and, hence, reducing its resistance and causing current to flow through this one leg of an AC bridge. The parallel wire is unaffected by the droplets as they do not impact on it, and this wire acts as a reference leg in the bridge to compensate for temperature differences. The J-W has an apparent problem in that droplets above about $60\text{-}\mu$ diameter have no more effect on the cooling rate of the wire than do $60\text{-}\mu$ diameter droplets. Therefore, an under-estimate of the actual liquid water content is the result. The degree of under-estimate is a matter of debate. Typical cloud droplet spectra indicate the greatest portion of the cloud water (probably > 85 percent) occurs in droplets $\leq 60\text{-}\mu$ diameter, thereby indicating an accuracy of better than twenty percent. The most recent version of the J-W incorporates a low-drift chopper amplifier which gives a 0-5 volt output for either $0\text{-}2\text{ gms m}^{-3}$ or $0\text{-}6\text{ gms m}^{-3}$. If properly set up, drift is not a severe problem.

The Cambridge System Lyman Alpha Total Water Probe works as a liquid water sensor in that sample air including any water present enters the system by way of an evaporator of sufficient thermal capacity to totally evaporate as much as 30 gms m^{-3} of liquid water or ice. The output of the device is exponential with respect to vapor pressure and is best calibrated by comparison with an inline dew point device while in clear air. A thorough ground calibration is necessary prior to flying. This is accomplished by flushing dry nitrogen through the system, which should give a dew point of at least -30°C and zero percent attenuation of the 1215 \AA emission, and a second flushing with dry air, which will also give a -30°C dew point, but a 20 percent attenuation at sea level due to the oxygen absorption. Because of the instrument's fast response, an encounter with an individual rain-sized drop will be easily identifiable if the data acquisition rate is fast enough ($> 50\text{ samples sec}^{-1}$). Because of the exponential relationship of output to input, linearization and first-order integration becomes necessary if a relatively slow data acquisition is used. Under these circumstances, accuracy within 0.1 gms m^{-3} is possible.

A third device worthy of mention is the Levine Cloud and Rain Water Probe. Although not commercially available at present, the Levine instruments certainly have merit. The basic concept of the cloud water probe is variations on a theme of the J-W hot wire, but with a longer wire having a higher collection efficiency. The second part of the instrument is the rain water probe, which is a hot wire device also except that the hot wire is wound on a porous ceramic

cone of sufficient dimension to have a high probability of collision with the lesser large drops in the cloud. In this case, drift over a long time has proven to be a problem, but once at an altitude, occasional rezeroing is all that is necessary. A liquid water content is proportional to the current in each of the two probes. The ratio of these LWCs is used to determine the volume median drop diameter, which is that diameter of drop above and below which one-half the water mass per unit volume sampled exists. This information qualitatively implies a spectrum of cloud and water drops as well as giving liquid water drops. Accuracy and time constant of the instruments are ten percent and twenty percent, respectively, for the cloud water and rain water probes and 1 and 3 seconds, also respectively.

The paper-tape-type liquid water sensor is also not a commercially available sensor but should be mentioned for completeness. As in almost all water content meters, the LWC is again proportional current flow. In this instance, a chemically treated paper tape (facsimile paper) is advanced over a pair of electrodes and the current flow is proportional to the area that is wet. Obviously, due to the nonlinear relationship between drop size and imprint size, the output is nonlinear. Insufficient calibrations of this instrument will not allow an accuracy quotation.

The remaining instrument categories of cloud particle and hydrometeor spectra and ice-water ratios can most easily be spoken of together, as can vertical and lateral velocities and turbulence. Real-time data acquisitions systems on hydrometeor spectra are advancing rapidly. There are two prevalent concepts being attacked vigorously at present. One is the momentum transfer device, which segregates acoustic impulses from the impaction of hydrometeors on a crystal "microphone" into size bins, which in essence gives a particle-size spectrum, and a second system which uses a laser back-lighting a coherent fibre-optic with each fibre terminating on a photomultiplier tube. The output from the PMTs is then put through a matrix to determine size and discriminate one particle from another. The momentum transfer device shows promise but is still plagued with coupling problems and noise. A soluble problem which has appeared in Russian literature is the transfer function. The Russian authors claim an r^2 relationship, whereas the American school claims an r^3 relationship. The laser/fibre optic device also shows promise but at present, requires a near-full-time nursemaid and lots of TLC.

The role of turbulence and gustiness in severe storms is not completely understood. Obviously, small-scale turbulence is important to the transfer of water vapor from the surface, and in hurricane modification it is important in estimating the turbulent diffusion of seeding material as well as water vapor. Large-scale motions (on the order of 100 meters and longer) can be measured by monitoring parameters from an inertial guidance system (accelerometers in three axes and rate gyros for three axes). If one is willing to accept a Kolmogorov theory of turbulence frequency spectrum in the inertial subrange, then the Meteorology Research, Inc. universal indicating turbulence system is acceptable. This instrument measures the eddy dissipation rate in a filtered bandwidth ($\sim 5-15$ Hz) constituting a spot measurement, and defines the total spectrum of turbulence. The theoretical background for this instrument is quite well understood and the instrument well accepted.

APPENDIX B
OBSERVATION REQUIREMENTS IN SUPPORT OF RESEARCH TO PERMIT
EFFECTIVE HURRICANE MODIFICATION

A. H. Miller

The subject of hurricane modification is treated separately here because the requirements are diverse. Hurricane modification experiments are primarily field programs. Theoretical models do not yet simulate nature well enough to make them the sole experimental tool for modification research. The objective of hurricane modification is the dissipation of the destructive energy of the hurricane. To accomplish this goal, a thorough knowledge of the cause and reasons for intensification of hurricanes is imperative. We use the knowledge developed by operational forecasters and students of tropical storms. The scientific community is not duplicating and cannot duplicate these efforts because there is so much to learn.

For socio-political reasons, hurricane modification experiments have been limited to hurricanes having certain properties. Restrictions have been slightly relaxed in the past few years. Now, a "seedable" storm is one which has a low probability (< ten percent) of moving to within 50 nautical miles of a populated land mass within 24 hours. Improvement in the forecast of tracks over the past few years has permitted the reduction of the time factor. Because of these restrictions, however, very few hurricanes have been modified.

Conceptually, hurricane modification experiments involve two approaches. First is modification of the primary energy source, the sea surface, by reducing evaporation, and second is "seeding" either the eye wall or seeding an outward-bound spiral-arm rain band. The desired effect is the release of energy well outside the eye by the release of heat by phase transformation of water to ice. The storm, as it attempts to conserve momentum, expands, and consequently, is reduced in intensity.

Today, verification of the effect of modification is made by measuring the wind and pressure field for comparison with the pre-seeding winds and pressures. The problem with such verification is the number of positive observations necessary to obtain statistical significance. Recently, some work has been done to try to measure directly certain micro-physics parameters which should reflect the effects of seeding. We do not have enough aircraft capable of penetration at altitudes between 16,000 and 30,000 feet. An aircraft penetrating at these altitudes is subject to severe icing, turbulence, and shear in the vertical. "G" loading can exceed 2.5 g's. Air frames which can withstand such loading are presently available; however the plane must be flown by the seat of the pants in the storm environment. Pilot fatigue during typical ten- to twelve-hour missions is an important factor. Along with this basic platform deficiency, we also have an instrumental deficiency. We need instruments to measure actual liquid water content, ice-water ratios, and ice and water size distributions. Present instruments are more qualitative than quantitative and require penetration to get the data.

Some of the information required by NHC is also important to NHRL's work. Parameters such as location of center, tide anomalies, and swell are of little value or interest to the modification researchers, but ice and cloud nuclei, drop and droplet spectra, ice-water ratio and liquid water content are very important for verification of the efficacy of modification attempts. New approaches utilizing remote sensors which could measure change and provide quantitative data as well, particularly over broad areas and from outside the most turbulent and dangerous part of the storm, would be major contributors to an effective national storm suppression program.

SECTION III

REPORT OF THE RESEARCH AND NOVEL MEASUREMENTS PANEL

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Airborne Severe Storm Surveillance Summer Study

August 1970

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I. INTRODUCTION

A. Report Context

We have categorized our report in three parts, viz., a discussion of (1) those techniques and instruments that can be used in a short time (1970 to 1972 period), (2) techniques for implementation by 1975 which have not as yet been flown in aircraft, and (3) techniques for which we anticipate operational use beyond 1975 because further research and study are necessary to evolve them to demonstrable usefulness.

1. Summary Chart of Instrumentation

In Table III-1 we have a summary chart of instrumentation: current instrumentation, developing instrumentation, and research instrumentation. We wish to emphasize that we were impressed by the dedication and ability of the people working in this field. Our recommendations concerning instrumentation do not reflect a feeling on our part of deficiency in the operation or in understanding by the instrument users. Rather, we point out that inadequate funds have been available to do the job, and that with adequate funds to set up a central facility, the job can be done better. The thrust of our concern is not principally with operational problems, but instead, with possible errors in measurement principles, which may or may not be involved. We couldn't be sure on the basis of evidence presented that optimism is justified.

B. Current Instrumentation

1. Instruments Reliable with Adequate Calibration

Current instrumentation techniques used in hurricane reconnaissance are divided into two categories: first are instruments that should be reliable with adequate calibration. For example, the pressure altimeter, the radar altimeter, and sea surface temperature measurement using infrared radiometry in clear normal atmosphere with the normal sea state appear to be in good shape.

2. Instruments Possibly Requiring Better Basic Understanding

Second, there are a number of instruments being flown which might produce errors because we don't understand the physics well enough or where improvement in methodology might be appropriate. In this category, we have dropsondes (pressure, humidity, temperature), temperature (Rosemount and Vortex), and the dew-point measurements. For example, the Rosemount thermometer is a very highly developed instrument produced by a manufacturer who has impressive calibration facilities (subsonic, transonic, supersonic wind tunnels). Some tests are made in two-phase systems with water. Yet from these calibrations and from the manufacturer's instruction books, we can't be completely sure that the particular environmental problems encountered in hurricane measurements are adequately accounted for; i. e., the de-icer, the boundary-layer control, and the inlet design are such that in the presence of water and ice, the Rosemount thermometer really measures the temperature. Everything may be fine — we cannot be sure. We would like to see the establishment of a central facility, independent of manufacturers, to do calibrations, and if necessary, to do research required to bring measurement techniques and the reduction of errors to within necessary limits.

3. Developing Instrumentation

We also list a number of techniques we consider promising; those are under study but have not yet been installed in aircraft and tested in aircraft in a hurricane. We believe our estimate of the time schedule for development of these new, promising techniques to be conservative. We recommend development of these instruments. We also recommend that they be tested and flown

TABLE III-1
SUMMARY OF INSTRUMENT TECHNIQUES USED FOR
LOCAL MEASUREMENTS IN HURRICANES

I. <u>Current Instruments and Techniques Used in Hurricane Reconnaissance</u>	
<u>Reliable with Adequate Calibration</u>	<u>Calibration Procedures Requiring Improvement (in Methodology and/or Understanding)</u>
Pressure altimeter (pressure at altitude)	Dropsonde pressure
Radar altimeter (absolute altitude)	Dropsonde humidity element
Infrared radiometer (sea surface temperature in clear, normal atmosphere with normal sea state)	Dropsonde temperature
	Rosemount temperature probe
	Vortex thermometer
	Dew-pointer
II. <u>Techniques Under Study (Not Yet Flown in Aircraft)</u>	
<u>Promising</u>	<u>Doubtful</u>
Laser wind-velocity measurement in clear air	Honeywell windsondes (dropped from aircraft)
Radar velocity measurements of condensed phases	
Radiometric soundings for temperature measurements and cloud-structure determinations	
Total water content using Lyman- α absorption	
III. <u>Techniques Requiring Further Research and Study</u>	
Simultaneous measurement of amounts of H ₂ O in all phases and of particle- and drop-size distributions	
Spectroscopic temperature soundings	
Remote sensing of sea state using radar or laser scattering	
Atmospheric component densities from laser-Raman scattering	
Total density measurements from laser-Rayleigh scattering	
Aerosol-concentration estimates using appropriate differences between laser-Rayleigh and laser-Raman scattering	

on aircraft. If this is done, it will be possible to make important measurements in a new way. In this list we include the Lyman- α absorption for total water content, already being developed.

We list as doubtful a windsonde designed to measure a local wind speed when dropped from an aircraft. This particular windsonde, a development under way for about five years, does not require tracking for wind speed measurement because it measures local wind speed by integrating local acceleration over a short time interval, but it has not yet been tested in aircraft. Other wind speed measurements are discussed in Section IV, Report of the Radar Panel.

4. Research Instrumentation

In this category we have techniques requiring further research and study. For instance, an ambitious program in cloud physics might require simultaneous measurements of liquid and gaseous water, of ice, of ice-particle distributions, and of water-drop-size distributions. With adequate instrumentation, one could make these measurements. In fact, much of this has already been done, but in a somewhat more benign environment than a hurricane. We list research related to spectroscopic temperature soundings, remote sensing of the sea state using radar or laser, the determination of component densities from laser Raman scattering, the total density measurement and aerosol concentration measurements using combinations of laser-Raman and laser-Rayleigh scattering.

We wish to emphasize that these are all point measurements made with reasonable spatial resolution, not integrated measurements.

II. SUMMARY RECOMMENDATIONS

A. Current and Developing Instrumentation

In the 1970-73 time period, beginning immediately, and in line with current operational usage — we recommend:

- 1) The establishment of a central calibration facility.
- 2) Current technology permits a real-time optical video link between the aircraft and the ground. We discussed to some extent what might be derived from this link for techniques considered by us and were not convinced that the return would be worth the effort. However, others might well come to a different conclusion.
- 3) We fully support steps that have been taken and urge further augmentation of the direct link between earth satellite sensors and the NHC, so that more effective use can be made of the most sophisticated satellite data that we can possibly get.

In the 1970-75 time period, we foresee testing, development, and learning how to use, on the aircraft, new instrumentation that should be appropriate for operational usage after 1975. See Section II of Table III-1.

B. Research

We studied to some extent research programs with unforeseeable application dates — programs that have as their principal objective the learning of more about hurricane modification and control. This is risk research, as is all basic research. We can't be sure that it will pay off. We are sure that it should be done. We make no attempt to list priorities for basic research. We don't know enough to do that. We do believe that the modification and control program, or the hurricane seeding program, has an inadequate budget for supporting basic risk research.

We are convinced that improved satellite sensor data obtained with much more sophisticated instrumentation will prove to be of great practical utility, both in tracking and in forecasting storms. Such data may even have application in establishing the efficacy of seeding.

We believe that the development of new forecasting procedures, based on the use of improved satellite-sensor data, will be of great practical utility. We recommend that serious and continued efforts be made to utilize these data effectively in forecasting and reconnaissance.

We are aware of hurricane model-building programs. They are at once both rudimentary and sophisticated. These are enormously complicated interdisciplinary problems. Current workers are doing an outstanding job in attempting this difficult feat of describing a hurricane with a computer program, so that computer "experiments" can be done to ascertain what seeding will do to the computer model, and then make a connection between that and field observations.

Increased effort in model building and, in particular, attempts to tie computer model programs to the direct field observation are needed. We need better ways of getting the reconnaissance data into the computer model, which would really help improve computer modeling of hurricanes.

There is need of increased effort on advanced model building and field verification through critical experimental studies and initiation of complementary basic "risk" research (e. g., resonance in coupling of axial energy addition into azimuthal energy; studies on vortex stability and disintegration; investigation of actual speeds in turbulent, multi-phase flows; interactions of rotating flows and complex structures; velocity mapping of hurricanes by using chemical injectants; remote sensing of the sea state, etc.).

We also list a number of other suggestions of basic risk research. We recommend additional work on velocity mapping of hurricanes using chemical injectants that can be determined by remote sensing. It is possible in principle, and probably in practice, to use injectants like NO and then study the continuum radiation resulting from NO oxidation in the atmosphere.

We believe it desirable to support laboratory and field research required for development of new instrumental techniques listed in Section III of Table III-1.

III. SHORT-TERM IMPROVEMENTS

A. Improving the Confidence Level in Current Measurements

Present facilities for severe storm surveillance will be used for some time. New facilities will be compared with those on an experimental basis until their efficacy is amply demonstrated. For the near term, then, we must consider whether significant steps are possible which will increase the accuracy and reliability of the existing facilities. Implicit in this consideration is the need for such steps to be feasible in terms of cost and personnel.

Because of the near-term nature of the approach, it is also necessary to confine it to changes which will affect operations and forecasting. We envision no modifications of aircraft or equipment which would be effective in the 1970-71 time period other than those already implemented by the agencies involved. Rather, we shall attempt to steer these modifications so that they result in a system with increased utility to the forecaster and greater reliability for his forecasts. Having increased the forecaster's confidence in the information with which he is presented, he will, in turn, compose his forecasts and bulletins in terms which give higher confidence to the general public.

1. Instrument Calibration and Reliability

It has become quite evident in the course of our study that there is no completely satisfactory calibration of the meteorological instruments carried by or dropped from the surveillance aircraft. The three services involved in reconnaissance make good use of the inadequate facilities available. Furthermore, there is no intercomparison program which permits an aircraft instrument complex of one type to be measured against that of another organization. Since three organizations are involved, with differing sets of instruments, it is exceedingly important to institute a plan and a facility for performing field calibrations at a confidence level at least equal to that specified in the purchase of the instruments.

Our discussion also revealed an even more disturbing fact: the whole field of meteorological measurements in the U. S. seems to lack a central laboratory for instrument standards. Except for research instruments built for specific purposes and calibrated by means of basic physical measurements in the laboratory, the routine gathering of meteorological data is carried out with instruments calibrated and certified by the manufacturers. While we shall not attempt to address this wider problem here, it may be that the obvious needs in severe storm surveillance may act as a stimulus to implement activity throughout the field.

The need for common standards of measurement in the aircraft sensors is made more obvious by the organizational division of observation efforts. Each group of aircraft assigned to the surveillance task has listed severe storm surveillance only as part of its mission. The two military organizations have multiple missions concerned with weather problems peculiar to their operations, and the RFF is dedicated primarily to the support of meteorological research programs. This produces an approach to instrumentation which is bound to increase the complexity and multiplicity of instrument types, even though the best match of mission and instrument is sincerely sought in each case.

In addition, each of these organizations is based at a different point and presumably conducts ground checks of its equipment there. One can certainly justify this procedure in view of the differing geographical operating areas imposed on the military organizations, but it would still be very desirable if all of the aircraft operating in Atlantic storms, for instance, could perform instrument calibrations at a single airbase.

The logical place and facility for this is the RFF at Miami, Florida. All aircraft can be brought to this facility and could be scheduled for check-in on a routine basis specifically for calibration of the instruments. At Miami, a Calibration Branch should be established, the primary function of which is maintenance of standards and testing of facilities for all of the principal sensors in operational use. This branch would be tasked to develop test and calibration procedures for the instruments used by each organization, and certifications should be provided which indicate that specifications have been met or that corrections must be applied. The initial establishment of the function should use equipment available immediately at RFF, and plans to increase the facilities should be made as soon as possible so that the instruments could be calibrated under flight conditions.

a. Temperature Reliability: To be specific, we can look at some of the sensors in use on the various aircraft and consider the errors to which they are subjected. The Air Force aircraft and three of the RFF aircraft are equipped with Rosemount temperature probes which measure the total temperature in the airstream. These readings must be corrected for dynamic heating and compressibility, which are determined from true airspeed measurements.

The Navy aircraft and the RFF aircraft are equipped with Bendix vortex thermometers, which are independent of airspeed. However, the Rosemount probes are guarded against liquid water collection while the vortex thermometers are not. Neither has de-icing equipment. It is known that the wet-bulb effect occurs with the vortex thermometer, and it is believed to be completely eliminated for the Rosemount probe by boundary-layer control.

Both probes utilize an electrical bridge circuit to measure the resistance of the temperature-sensitive element. The vortex probe is rebalanced by the servo-circuit, with automatic recording, while with the Rosemount probe, the output is recorded directly. Assuming that the reading accuracies of the element resistances can be made the same, what other errors enter into the measurements? The Rosemount probe readings must be corrected for true airspeed, which is itself derived from the indicated airspeed and corrected for individual instrument calibration, pressure, altitude, and free-air temperature. These absolute corrections are quite large, and it is probable that true airspeed is known to only ± 5 knots at best. This would give errors in free-air temperature of $\pm 0.5^{\circ}\text{C}$, and if the probe has $\pm 0.5^{\circ}$ errors as alleged, then errors of at least $\pm 1^{\circ}\text{C}$ should be expected, with a 20-msec response, even if the instrument were calibrated. The vortex thermometer is quite slow (about 10-sec response time) and is subject to reading errors, assumed to be $\pm 0.5^{\circ}\text{C}$, and to unknown errors when flying through liquid water. It seems logical to fly both instruments on the same aircraft, as RFF does, in order to reduce the effects of systematic errors on each type of thermometer and increase the accuracy of temperature determinations.

The manufacturers of these probes have tested and calibrated them in wind tunnels, both for development and for attaining the required specifications. However, we were not able to ascertain whether individual instrument calibrations include two-phase flow, using water, ice, and snow, over the expected velocity ranges. Certainly, none of the users maintain this type of facility.

The Air Weather Service is now procuring a new reconnaissance system (AWRS), in which free air temperature is to be measured to an accuracy of $\pm 0.5^{\circ}\text{C}$ and with 0.1°C resolution. The response rate is to be $10^{\circ}/\text{sec}$. It seems doubtful whether these specifications can be met with present instrumentation, but it is certain that the instruments could not be maintained at these levels of accuracy.

b. Pressure Reliability: Pressure-activated instruments such as the pressure altimeter and indicated airspeed meter are calibrated more intensively than other airborne meteorological instruments, primarily because they are among the most precise instruments carried on-board and also because of their close relationship to altitude determinations and aircraft safety. For meteorological purposes, the pressure altimeter is considered and used as an in-flight barometer, but it is identical to the pilot's altimeter and both are calibrated so that they can be used as alternates for one another.

The AWS maintains a regular program of altimeter calibration, which results in a complete historical record of performance, averaged every two weeks and published monthly for each instrument. This historical calibration sums all of the instrumental errors unique to the device itself, except for the static pressure error, caused by aerodynamic effects, and separately calibrated for each aircraft installation.

The historical calibration is accomplished by regular flights in the vicinity of rawinsonde stations, and the calculated height of a standard pressure surface from rawinsonde soundings is used to correct the reduced height of that pressure surface computed on the aircraft. If the

rawinsonde station is more than ten miles distant from the ground point of calibration, a further correction for the geostrophic effect of the mean wind is made. These corrections are made for all of the standard pressure surfaces, and in addition, a sea-level correction is determined from a reference ground station.

The effect of all of these corrections is to introduce uniformity into the network of aircraft and rawinsonde stations. The pressure altimeter used on the aircraft is inherently a more precise instrument than its rawinsonde counterpart, but they must both be used on the same synoptic charts and in the same statistical models. A policy of uniformity for this purpose seems eminently sensible. We may ask, however, whether these procedures in any way degrade the specific mission of an aircraft engaged in hurricane reconnaissance. The answer is probably the same, because the hurricane forecaster must use all of the information available to him. The only single-point pressure of special concern is the central pressure in the eye, obtained either from a dropsonde (which is separately calibrated) or from the D-values calculated on the aircraft. In the latter case, we are again concerned with large-scale consistency, since the forecaster will apply a "standard" tropical atmosphere in interpreting the D-value gradients.

The RFF instrument manual refers only to single-point, ground-level calibrations of pressure-activated instruments. The Navy procedures are not presently available, although they are believed to be similar to those of the Air Force.

The errors in pressure altimeters used on reconnaissance aircraft are considered to vary from ± 5 mb to ± 0.5 mb, depending upon the instrument type. The AWRS specification for such an instrument is ± 0.3 mb from 1060 to 500 mb, and ± 0.1 mb from 500 to 150 mb, with a resolution of ± 0.1 mb. Such precisions are probably attainable and are comparable to the precision of radar altimeters. Radar heights in combination with pressure heights are used to compute D-values. However, the accuracy of the computed heights can never exceed that of the rawinsonde net. An estimate of the error in pressure determined from this net, using randomly selected sondes, is ± 2 mb (± 70 feet at 10,000 feet).

c. D-Value Reliability: The reported D-value is the departure of the height of a pressure surface from its "standard" height, as determined from an idealized atmospheric sounding, such as the ICAO standard atmosphere, or a "hurricane standard" atmosphere.

The D-value is calculated in the following way: The difference between the true altitude, Z , as measured by a radar altimeter, and the corrected pressure altitude, CZ_p , measured by the pressure altimeter, is the D-value at flight level, or $D_f = Z - CZ_p$. One then obtains from a standard atmosphere chart or table the height of the nearest standard pressure surface, Z_s (such as 850 or 700 mb), and finds the difference $Z_s - CZ_p$. Using another nomograph which yields changes in D as a function of virtual temperature and pressure altitude, one obtains a correction:

$$\Delta D = | (Z_s - CZ_p) | D^* ,$$

where D^* is the incremental change in D per 1000 feet in the standard atmosphere. The sign of ΔD is positive if the standard surface is below the aircraft and negative if it is above the aircraft. This correction is usually quite small, since in practice, reconnaissance aircraft fly near standard pressure surfaces. Finally, the reported D-value is given by $D = D_f - \Delta D$ and the height of the standard pressure surface used by the forecasters is $Z_s + D$.

The D-value reported to the forecaster is thus a derived quantity, obtained from measurements of pressure altitude and absolute altitude, and using tables which compile corrections due to the moisture content of the air at flight altitude, the observed pressure altitude, and the geopotential correction.

The errors considered to be effective in the calculation of pressure height vary from ± 195 feet for the WC-135, ± 106 feet for the WC-130 aircraft, and ± 77 feet for the ESSA and Navy aircraft, at a nominal altitude of 10,000 feet. The larger errors in the case of the Air Force aircraft are presumably due to their lack of dew-point measurements and their somewhat less accurate altimeters.

These errors are large compared to the quantities being calculated and reported. D-values of the 700-millibar surface are of the order of a few hundred feet, so that the errors can easily be ± 25 percent or even larger. Obviously, if these values are to be intercompared among the various aircraft, we need to introduce some absolute standards of calibration, presumably by having the aircraft fly over a standard rawinsonde station, which is maintained for this purpose, and which uses rawinsondes of greater than average accuracy. (This will be discussed later. See Section VI.)

Of course, D-value gradients can be calculated with more accuracy than this, and these are of the greatest value to the forecaster. The limitation in the gradient values is the precision with which the instruments can be read and their consistency. Nevertheless, until the establishment of an intercomparison or calibration station is carried out, it will not be possible to place dependable limits on the D-value gradients reported by the various aircraft.

d. Dew-Point Reliability: At present, only the Navy and RFF aircraft are measuring dew-point temperature at flight level. The RFF aircraft have used and compared several instruments designed to measure atmospheric water vapor and liquid water as well. The consensus seems to be that dew-point temperature can be measured to $\pm 2^{\circ}\text{C}$, with a 10-sec response, using a cooled-mirror technique and various methods of sensing the condensed moisture.

The uses of dew-point measurement at flight level are the determination of dew-point profiles across the storm and the calculation of virtual temperature for use in pressure-level computations. The dew-point profiles are undoubtedly of considerable qualitative value to the forecaster in identifying regions of dry air movement. For this purpose, the errors are probably not excessive and all of the aircraft should be equally equipped to do this. However, foreseeing the time when quantitative measurements of liquid-water content can also be made, either remotely or directly, the same accuracy in dew-point temperature as free-air temperature would become desirable for correlation with the data from saturated regions.

The AWRS specifications are in terms of relative humidity over various temperature and humidity ranges, and call for dew-point temperature errors ranging from $\pm 0.5^{\circ}$ to $\pm 3.5^{\circ}\text{C}$. The standard practice is to use charts to determine dew-point depression from relative humidity measurements, and also to determine virtual temperature from dew-point temperature and pressure. At the temperatures encountered in flights over or through hurricanes, the difference between virtual temperature and free-air temperature is often of the same order or smaller than the error in dew-point temperature determination, which makes the whole process rather meaningless.

If dew-points are to be measured and used in an absolute sense, it is imperative to introduce a single type of instrument into all aircraft, which is removable and can be calibrated in

the same facility as the temperature probes, preferably using controllable moisture content and also two-phase capability. Liquid-water instruments could also be tested in the same facility.

e. Sea-Surface Temperature Reliability: At present, the Navy and RFF aircraft are equipped with infrared radiometers which sense the emitted radiation from the sea surface and are calibrated in equivalent black-body temperature. For bodies which have a known and nonvarying emissivity, the accuracy of such measurements is about $\pm 1^{\circ}\text{C}$. The field of view is 3° and is usable at most aircraft altitudes to yield a meaningful measurement to the forecaster, who is primarily concerned with sea-surface temperature gradients which will lead to intensification or weakening of the storm.

Use of the infrared sensors requires that there be no intervening clouds which would also emit radiation, probably at a lower effective temperature. However, the temperature gradients ahead of the storm are those usually desired, and mapping can be conducted in clear areas in most cases. The presence of clouds, although not always visible, is usually betrayed by pronounced fluctuations in signal level, and real-time inspection of the output permits a choice of suitable measurement regions.

The radiometers can be calibrated by removing them from the aircraft and viewing laboratory sources at various known temperatures. In addition, overflights of specified target areas could be conducted for intercomparison of the instruments installed in the aircraft.

f. Dropsondes: Two types of dropsondes are now in use by the various reconnaissance aircraft, the AN/AMT-6 and -13 radiosondes. In terms of instrument accuracies, they differ only in the pressure sensors, the sampling intervals, and the fall rates employed. They do not sense winds, although the AWRS specifications for a new dropsonde have included wind measurements.

The fundamental calibration of the T-6 instrument, as with balloon-borne instruments, is the factory calibration of the aneroid-type pressure sensor which actuates a contact arm over a commutator bar. The pressure at the ground level where the instruments are inspected and prepared for flight is used as a single-point calibration by using personnel. The fall rate is about 2000 feet/minute and the pressure-sampling interval is about 650 feet.

The T-13 radiosonde, however, employs an electric motor to contact the commutator segments, and the fundamental calibration is between pressure and resistance of the coupled element. As with the other sondes, the fundamental calibration is carried out at the factory and a baseline or ground station pressure is used to reference the calibration curve. The fall rate is about 5000 feet/minute and the pressure sampling interval is about 240 feet.

In both sondes, the temperature and humidity elements are variable resistance elements, which control the pulsed modulation of the radio frequency carrier. In the T-13 sonde, the pressure also functions in this manner. Errors in pressure sensing are estimated to be ± 6 mb for the T-6 and ± 3 mb for the T-13. However, during the course of the study, we were told by A. Miller of an experiment performed with some of the T-13 sondes, which gave surface pressure values consistently about 4 mb too high. This is opposite to the expected result if the effect were one of response lag due to the rapid fall rate and is as yet unexplained. J. Morrissey of AFCRL also stated that the alleged ± 3 mb accuracy of the T-13 sonde may be too optimistic.

R. Simpson of the NHC gave us his operational estimate of dropsonde usefulness. From his own experience, also, the indicated surface pressure measurements have been consistently too high and often not considered to be usable. He prefers to use D-value profiles at aircraft altitudes, together with either the temperatures derived from the sounding or a "standard

hurricane" atmosphere to derive a surface pressure value. His desired accuracy of central pressure measurement specifies less than 2-mb error, which dropsondes are not now equal to.

It appears highly desirable to perform a number of in situ calibrations of dropsonde pressure gauges before release at the known pressure at release altitude and in pressure-chamber integral with the launching system as primary airborne reference standards.

B. A Calibration Facility

A significant improvement in the use of contemporary aircraft and instruments may be made by standardization, intercomparison, and calibration of meteorological instruments, which could be done starting with facilities now available and continuing with added equipment and tasks until the needs of all instruments in use or contemplated are met.

For efficiency and simplicity, a single location for the calibration and intercomparison facility should be selected. The facility must be available to all aircraft used for reconnaissance and must have a rawinsonde station already in operation. The RFF at Miami meets these requirements and has laboratory facilities already established. A Calibration Branch at RFF with minimum manning and equipment in the beginning could start functioning quite soon.

Equipment and instruments already owned by the Instrumentation Branch at RFF should be pressed into service where possible. Manning of the Calibration Branch should include one professional person with experience in the use of meteorological instruments and two sub-professionals to carry out measurements and calculations. The tasks of the Calibration Branch would be (see Table III-2):

- 1) Development of calibration procedures and maintenance of standards;
- 2) Construction and operation of calibration facilities;
- 3) Testing, calibrating, and evaluating aircraft instruments;
- 4) Sampling and testing of sondes.

Sets of standard instruments, both laboratory and airborne types, should be procured so that meaningful intercomparisons can be made in terms of the best available secondary standards of measurements. Static laboratory measurements of each type of aircraft instrument used should be made under very carefully controlled conditions, so that the quantities measured, meteorological or electrical, can always be referred to NBS secondary standards. After satisfactory accomplishment of standards, these tertiary standards should be maintained continuously for comparisons. Data-recording equipment which can accommodate all of the instruments should be purchased.

As soon as practicable, the following pieces of calibration equipment should be purchased or constructed (if not already available to RFF):

- 1) An accurately controlled altitude chamber with precision pressure and temperature control;
- 2) A wind tunnel covering the entire subsonic region, with provisions for controllable humidity and introduction of liquid water for two-phase testing;
- 3) A black-body source of large area for simulation of sea surface conditions in the expected range;
- 4) A controlled static humidity chamber.

A routine plan for coordinated laboratory and flight tests of aircraft instruments should be formulated. This plan would provide detailed descriptions of the calibration techniques and procedures. The following points should be included:

TABLE III-2

HURRICANE RECONNAISSANCE - CENTRAL CALIBRATION FACILITY

<u>Tasks</u>	<u>Equipment</u>
Development of calibration procedures	Controlled altitude chamber for flight P + T simulation
Maintenance of suitable standards	
Construction, purchase, and operation of calibration equipment	Subsonic wind tunnel with two-phase water capability
Testing, calibration, and evaluation of all aircraft instruments	Large-area black-body for absolute radiation calibration
Sampling, testing, and standardization of sondes for use in hurricanes	Controlled humidity chamber Standard laboratory instruments and data recording

Location

Central location where laboratory and aircraft facilities already exist and rawinsonde station is nearby. Miami RFF location seems best choice.

Activities

Ground calibration and evaluation of removable instruments
 In-front calibrations compared to selected rawinsondes and dropsondes
 Selection, calibration, and comparison of rawinsondes and dropsondes
 Six-month calibration cycle for each aircraft
 Collaboration with aircraft meteorological officer for data reporting

- 1) Removal of temperature and dew-point sensors from aircraft for comparison with the maintained standards over their ranges. When the wind tunnel is available, the instruments will be exercised within it;
- 2) Removal of pressure-actuated instruments for static testing in the altitude chamber, including tests of temperature sensitivity;
- 3) Replacement of instruments for controlled calibration flights. These flights will be conducted in much the same manner as outlined by the Air Force in AWSM 105-1, but the rawinsondes used will be selected and calibrated by the Calibration Branch;
- 4) Simultaneous dropsonde measurements will be made for comparison with 3 above. The dropsondes will also be selected and calibrated by the Calibration Branch;
- 5) Sea surface temperatures will be measured in a region where buoy monitoring is available and can be calibrated;
- 6) Calibration data for all instruments will be analyzed and reported to the flight organization responsible for the aircraft. Each instrumented aircraft in the Atlantic area should be calibrated during a six-month period.

A program for radiosonde sampling and calibration should also be implemented so that the manufacturers' specifications can be tested independently, and calibrated sondes will be available for the testing of aircraft instruments. A number of samples from standard procurements of both rawinsondes and dropsondes will be purchased by the Calibration Branch. These numbers should be sufficient to satisfy sampling statistics, and having been calibrated by the Branch, will furnish a supply of well-calibrated instruments for its use.

The sample radiosondes will be carefully calibrated in the altitude and humidity chambers and recycled to determine their reliability. Satisfactory samples of each type of instrument calibrated will then be available for simultaneous flights on the aircraft and balloons in the aircraft calibration flights, and their laboratory calibrations will be used to calibrate the aircraft pressure altimeter. Cooperation of the Weather Service rawinsonde station at Miami will be necessary in this program.

A separate test program should be initiated to compare dropsondes and rawinsondes on the same balloon flights to see whether these instruments are compatible under the same air-flow conditions. The Calibration Branch would need sets of dropsonde data reduction equipment to carry out this program.

It is expected that a calibration effort of this type would have the immediate effect of pointing out gross inconsistencies between aircraft measurements now being made, and its long-range effect would be the growth of confidence in the reconnaissance techniques being employed by the three organizations involved. It is implicit in the concept that the meteorological officers of these organizations would participate in the calibrations and offer their advice and assistance in analyzing the results. A cooperative effort by all concerned would result in a much higher level of confidence in reconnaissance measurements and an enhanced feeling of participation in the joint program.

C. Near-Term Instrument Improvement Possibilities

1. Dropsondes

One of the instruments which was singled out by the users of reconnaissance information as having a serious deficiency was the dropsonde AN/AMT-13, which is alleged to read about 4 mb high when it reaches the sea surface. The reason for such a bias error is not known and hypotheses as to its origin are not convincing, even though it is of the same order as the rms

error for some of the sondes used. A significant improvement in the use of the sonde could be effected by a systematic investigation of this phenomenon, hopefully by laboratory simulation of flight conditions. The sonde calibration program, discussed under calibration facilities, might be the best way in which to investigate and resolve this problem. Dynamic flight conditions may have to be included in the simulation tests.

Improvement in the fundamental accuracy of radiosondes is also very desirable. The best radiosonde elements are reported to have pressure accuracies of ± 2 mb in actual use and it is very doubtful whether repeated flights of different expendable sondes (either dropped or balloon-launched) would have rms errors that small. Since improved quality control or element precision would raise the unit cost of the sondes, an alternative method of ground testing should be employed so that sondes can be individually field-calibrated and automatically corrected for individual instrument errors over the entire flight altitude range. The objective should be an error of ± 1 mb at all altitudes for each element flown, using ground calibration equipment that is simple to operate.

2. Wind Measurement

Wind measurement below the aircraft is not now being accomplished. Remote sensing of these winds is being proposed elsewhere in this report. However, techniques of direct wind sensing should also be considered for two reasons: (1) they would serve as corroborative data for the remote techniques, and (2) they would measure winds independently of the precipitation or aerosol content of the atmosphere below the aircraft.

a. Dropsonde Plus Hyperbolic Navigation (LOCATE): During the course of the study, we heard descriptions of three techniques still in the early stages of development. The first of these was the LOCATE dropsonde, which has been investigated by Beukers Laboratories, Inc. This system incorporates an expendable dropsonde, a modified AN/AMT-13, with a navigational receiver so that the aircraft receiving equipment can record both sounding data and dropsonde location when falling at a slower than normal rate (about 1000 feet per minute). The OMEGA navigational system, or LORAN-C if greater accuracy is desired, is used to track the sonde position. The on-board aircraft equipment extracts meteorological data, processes the navigational signals, and computes the wind speed and direction. Several drops have been made of prototype sondes.

b. Foam Balls: Beukers Laboratories have also proposed a "winds-only" system which would utilize small, plastic-foam balls that would float down at about 500 feet per minute, transmitting only altitude and geographical location. No prototypes have been flown, but this system shows considerable promise as an atmospheric wind measurement scheme.

c. An Aerodynamic System: Honeywell, Inc. has conducted a contract study with AFCRL over several years which has also culminated in the development of a wind-sonde. The technique employs an arrow-shaped, low-wind-drift sonde that falls through the atmosphere aerodynamically, being tilted away from the vertical by the relative wind. The resultant device uses an air-bearing gyroscope to measure vertical tilt angle and a magnetic field sensor to measure angular orientation around the roll axis. Prototypes have been dropped from balloons, but not from aircraft, and detailed testing of the device has not been performed.

All of these methods are aimed primarily at the normal meteorological wind measurement problem. Severe storm conditions, which include winds ranging up to 200 knots, strong horizontal and vertical shears, updrafts and downdrafts, introduce a great deal of uncertainty into

the problem of direct wind measurement. Any object that moves slowly enough so its drift velocity is representative of the wind field at that altitude is going to be violently perturbed by turbulent flow, whose scale is of the same order as the dimensions of the drifting device. If the device falls rapidly, as with the Honeywell windsonde, then these same perturbations will introduce noisy signals into the angle-sensing systems.

Considering the efforts so far expended and their past lack of application to severe storms, it does not seem desirable to recommend additional sonde wind measurement schemes for the hurricane environment. Remote sensing techniques probably represent the best long-term hope of mapping the wind field and should be implemented as soon as possible. Meanwhile, we are inclined to recommend early field tests of the Honeywell windsonde in drops from aircraft. If these drops are successful, we recommend subsequent field tests in the hurricane environment.

IV. IMPROVEMENT OF HURRICANE WARNING AND FORECASTING

The research programs outlined in the following four subsections have an immediate or potential bearing on data used or useful in forecasting and hurricane warning.

A. Satellite Data for Hurricane Forecasting and Research

1. Introduction

The platform which has received the greatest attention at this Summer Study has been the airplane, for reasons which have already been discussed. The airplane, however, suffers from the disadvantage of yielding instantaneous spatial coverage to the horizon only. If it is desired to obtain instantaneous coverage over areas which are hundreds or even thousands of miles on the side, and this is desired for reasons to be discussed below, then the satellite is the only satisfactory platform for this purpose.

The satellite, of course, suffers from some disadvantages. It can carry only a limited payload for reasonable cost. Once the satellite has been launched, calibration is difficult and maintenance is almost impossible. A low-altitude satellite does not view the region of interest continuously, and a synchronous satellite is spaced 20,000 miles from the earth, which significantly decreases received signal levels, and makes difficult the achievement of small-scale measurements.

2. Forecasting

The desire for broad-field-of-view coverage occurs in both areas — forecasting and research. In fact, satellite data are already being used for forecasting at the NHC. In the very early phases of a suspected hurricane, cyclonic motion with well-defined "eyes" have been observed by photography in the visible region of the spectrum. Hurricane reconnaissance airplanes are vectored to these eyes. These aircraft have at times flown through highly separated cloud formations without significant circulation and no hurricanes developed. However, at other times, similar satellite-derived patterns did lead to hurricane development. A broad overview of cloud cover may occasionally suggest nonexistent circulation patterns. It is important to further investigate the relation between cloud cover as observed at variable optical contrast levels and upper-air circulation. At present, satellite observations provide early indication of "suspicious disturbances," which can be investigated in detail by reconnaissance aircraft.

Later stages of the pre-hurricane phase are monitored by the satellite. The fully developed hurricane can be watched as it moves across the ocean, possibly towards land. The spiral arrays of cloud and rain bands are clearly observed, often with well-defined, sharp-edged cirrus shields. These cirrus clouds can be seen shearing off the edges of the brighter

overcast areas, an indication of upper anti-cyclonic flow. The hurricane's eye is apparently not observed in many pictures. However, Fujito has shown that with careful processing, the eye can often be brought out in a photograph. There is no reason why this could not be done in real time for presentation at the NHC. Of course, sophisticated data-processing will not bring out the eye if it contains a low-level cloud or is covered by a thick cirrus shield. Moreover, there are occasions when the inflow band is obscured by the cirrus shield. Visible photography cannot be used at night.

3. Infrared and Microwave Radiometry

Night photography of hurricanes can be done in the infrared, where advantage is taken of the difference in temperature between the warm sea surface and the cold cloud tops. When the eye is covered by or contains clouds, then visible and infrared instruments will not "see" the eye. For this case, the microwave region of the spectrum becomes useful. There are some special difficulties here in achieving adequate spatial resolution, due to the long wavelengths. If it is assumed that the eye is about 20 miles in diameter, then about 2-mile resolution is required to do adequate mapping for identification and positioning. At synchronous altitude, a radiometer operating at 1 cm requires a 100-m antenna. At a 500-mile satellite altitude, a 2.5-m antenna operating at 1 cm will provide the needed spatial resolution. At longer wavelengths, such as 5 cm, the antenna will be larger than the satellite and will have to be either a folded dish or an array which opens when the satellite is in orbit. Because microwave area detectors are not available, a scanning instrument is necessary.

The choice of wavelength is important. To look through the cloud deck (which is in or above the eye) down to the sea surface implies the use of long wavelengths. However, the wavelength must not be so long that radiation from the eye wall is not detected. The correct wavelength will yield maximum eye-wall contrast. This may require some investigation.

The above gives a cursory indication of how passive satellite measurements in the visible, infrared, and microwave portions of the spectrum could be used to obtain eye position data for hurricane forecasting. Additional forecasting information is available from these measurements.

Fritz and others at the National Environmental Satellite Center (NESC), using satellite photographs (in the visible portion of the spectrum) collected over a period of years, have classified tropical and subtropical disturbances in the pre-hurricane stages and hurricane categories. Stage A contains no curved cloud lines or bands. However, these do occur in Stage B, while in Stage C, there are well organized, curved cloud lines and bands with a well-defined center outside a dense cloud mass. The categories may run from 1 to 4, from cloud structures with poorly organized spiral bands with no visible eye, to cloud structures with a high degree of band concentricity with a round eye near the center of the central cloud mass.

The NESC people have also obtained from the above satellite pictures an empirical relationship, which can be used for forecasting, of maximum wind velocity versus cloud pattern diameter, using category number as a parameter and depending on the presence or absence of a visible eye. Since the measured cloud pattern diameter is a function of the instrument sensitivity, an appropriate intensity contour normalization is necessary in order to optimize this approach. The NESC people have obtained a similar relationship between maximum wind velocity and cloud pattern diameter for use at night. They did this by using the high-resolution infrared radiometer (HRIR) on Nimbus II to yield cloud data in the water vapor window. Again, an empirical relationship was obtained (which needs further verification through the collection and analysis of more data) between the maximum wind velocity and (for the infrared measurement) the ratio of cloud

canopy diameter and eye diameter. The microwave equivalent of the above determination of maximum wind velocity has not been attempted thus far.

B. Research/Feasibility Investigations

1. The Scintillation of Radiometric Data

The above method of determining maximum wind velocity is empirical and may prove not to be adequate in the face of new data. Another passive method would be desirable. The use of mean values of received power, only, has been discussed. However, it is conjectured that the scintillation spectrum of the received signal also contains information that is a measure of the wind velocity field in a particular spatial resolution cell. The radius from the storm center at which the maximum wind occurs should, in principle, be obtained in this manner. The desired accuracy of ± 1 n.mi is difficult but nonetheless, the possibility should be investigated. This hypothesis could be tested using appropriate Doppler filter-processing techniques on signals which have been received by radiometer broadband enough to follow the scintillations generated by a complex radiative transfer phenomenon in the resolution cell as radiation is generated within and transported through the cell. In this cell, the cloud medium is moving at a speed related to the mean wind velocity, with a velocity spectrum around the mean. Scintillations result from a convolution of the medium motion and the transported and generated radiation.

2. The Overall View

Radiometric "pictures" show the entire expanse of the hurricane, including the feeder band. This feeder band must be viewed continuously, along with the type of surface over which it passes. As Simpson has indicated, when the feeder band passes over warm ocean surfaces, the central hurricane pressure drops and the storm intensifies; when the feeder band passes over land, the pressure increases and the storm weakens. It may be desirable to monitor the feeder band continuously and satellite photography is an efficient method for performing this function at those wavelengths where it is not obscured by high cloud layers.

The "chimney," a vertical column adjacent to the eye and its wall, through which the moisture spirals up and out, has a cross-sectional area with dimensions of about 10 n. mi by 15 n. mi. It is heavily laden with moisture. The behavior of this chimney is obviously of interest from a research point of view. Moreover, it is felt that an empirical view of the radiometric data obtained from the chimney such as effective temperature and scintillation will improve hurricane forecasting. Observations should be made at different wavelengths. Because the moisture level is so high within this vertical column, long microwave wavelengths are needed to obtain data from the lower levels of the chimney.

3. Eye-Wall Height

The height of the eye wall, another indication of the intensity of the storm, is useful in forecasting. The HRIR aboard Nimbus I was used to obtain cloud height data on Hurricane Gladys in 1964. This was done by interpreting the received radiation as equivalent black-body temperatures for different positions near the eye wall. Geometric height above sea level was related to this temperature by means of radiosonde data taken four hours earlier in Bermuda. While the accuracy of this method is probably not within the required range (2 to 5 km), this possibility should be checked.

4. Side-Looking Satellite Measurements

A low-altitude satellite about 500 miles above the earth could, in principle, obtain a side look at the eye wall. It would have to look through clouds between the eye and the satellite. The latter implies a narrow-beam, long-wavelength, earth-limb-observing microwave radiometer

with a vertical scan capability.

At an altitude of 500 miles, the eye wall at the horizon will be at a range of approximately 2000 miles. If the eye wall is about 50,000 feet high, then a minimum vertical spatial resolution of 5000 feet is required. At an operating wavelength of 5 cm, the required antenna diameter is about 100 m, which is rather impractical. Even at 1 cm, the antenna size is about 20 m, which is also difficult to obtain. This approach does not appear to be practical unless a lower orbit can be used or new techniques are developed to deploy in orbit large, open-mesh antennas.

5. Sea Surface Temperature

The measurements discussed thus far do not involve quantitative analysis of absolute intensity (except for the stated desire to obtain effective temperatures in the chimney). Sea surface temperature is needed to an accuracy of 1°C for forecasting purposes, which does require a careful quantitative determination of absolute intensity. Two types of radiometric measurements have been used to obtain sea surface temperatures: infrared and microwave.

Measurements can be made during the day or at night in the 10 to 12μ band, but only in cloud-free areas. Therefore, clouds must be located by the use of other wavelengths to distinguish cloud-free areas. The medium-resolution infrared radiometer (MRIR) has been used to obtain daylight data in the 0.2- to 4μ band. These data have been used to compute albedo, which permits cloudy and clear areas to be separated, with a spatial resolution on the ground of 29 n. mi. The HRIR aboard Nimbus III provides 5-n. mi resolution in an 0.7- to 4.2μ band. This spatial resolution is probably inadequate to identify and separate the cloud radiation. This approach, useful only in daylight, can yield statistics of the spatial distribution of clouds. The ITOS-1 satellite, launched in early 1970, contains scanning radiometers which will measure earth albedo in the 0.53- to 0.73μ band, during the day, with higher calibration accuracy than obtained with previous TV camera systems and will yield 2-n. mi spatial resolution on the ground. It will also measure radiation emitted in the 10.5- to 12.5μ band with 4-n. mi resolution, thus improving the infrared temperature determination. Whether it will produce the 1°C accuracy will be determined when the data presently being gathered are analyzed.

In addition to the cloud problem, atmospheric attenuation in the infrared also makes absolute intensity (and therefore, temperature) measurements difficult. In order to make an accurate attenuation correction, it is necessary to know the water vapor content between the sea surface and the satellite. The use of generally available synoptic data from ocean areas is most likely not accurate enough for 1°C accuracy. It is probably necessary to make simultaneous spectroscopic measurements from the satellite.

These difficulties in interpreting the infrared data make microwave radiometry more attractive for the sea surface temperature determination. These data should be obtained at an angle of 20° from the vertical because at or near this angle of inclination, the average of the vertically and horizontally polarized microwave emissivity from the sea is nearly constant over a range of rms sea slopes varying from specular to 22° . This average obtained by using a circularly polarized antenna yields a radiant brightness which varies by only $\pm 0.3^{\circ}\text{K}$ over the total range of sea roughness mentioned above when viewed at 20° inclination. If the sea roughness in the neighborhood of a hurricane is greater than the maximum obtained with the above-described data, then the error will be higher. Whether this leads to a total error greater than 1°C is not known, but should be determined.

The true temperature of the sea is obtained from the measured radiant brightness by taking account of the temperature dependence of the sea water's dielectric constant. The

radiometric measurement should be made at wavelengths longer than 3 cm because of the decreasing dependence of measured temperature on true temperature at shorter wavelengths and because at shorter wavelengths, cloud radiation may confuse the result.

6. Moisture Content

The moisture content, in terms of the mixing ratio, is also desired for forecasting purposes with an accuracy of about 1.5 gm/kg. This could be done, in principle, by using many wavelengths to separate the resonant and nonresonant radiation in the microwave region, or by making infrared observations in the clear spaces between rain bands. Whether the desired accuracy in determining the mixing ratio is attainable by using passive radiometry is not known, but should be determined.

C. Research Requirements

The measurements described above were derived from the forecasters' direct requirements. However, there is also a strong interest in determining the mechanism of hurricane formation, intensification, and de-intensification for the purpose of storm modification.

1. Sea Surface

In the very early stages of hurricane formation, certain conditions must exist, some of which may be detectable from satellites, such as hot and humid air at sea level. Sea surface measurements can be made as described above, which will indicate whether the 25°C critical value has been exceeded.

2. Polar Fronts

A second condition which is favorable for hurricane formation is the presence of a polar front extending to latitudes less than 30°. This can and should be observed from a satellite by viewing the cloud structures coming from the north. Also, by determining the cloud top temperatures, the temperature ridge in the polar front can be detected.

3. Cyclonic Shear

The cyclonic shear in the cloud patterns might be obtained by cloud observations. It should be noted that there is a danger in interpreting cloud motion in terms of wind velocity. The observed cloud motion is the result of a complex velocity field on different scales. There is the droplet microscale, which will move with the micro-wind field for droplets which are about 1 μ or less in size. For larger drops, there will be an error in observed velocity. On a larger scale, there will be a vertical distribution of horizontal wind shear, which may or may not affect the velocity, measured by the satellite, of the effective center of gravity of the cloud. A careful investigation of what is actually being measured when motion is observed on different scales from a large cloud to small drops has apparently not been made on a quantitative basis (even, it seems, for the microwave radar case). This should be done as soon as possible.

It might be possible to obtain other information by cloud observations. For example, the active inter-tropical convergence zone at latitudes of about 5° is laden with clouds, and the possible occurrence of minimal wind shear might be detected by observing decreasing scintillations in the radiometer data. This is a conjecture which can only be verified by analyzing data from wideband radiometers. The mid-latitude upper trough might also be observed with these methods.

4. Jet Stream

The presence of an anti-cyclonic jet stream at lower latitudes is another indication of the possible birth of a hurricane. These jets occur at altitudes of about 40 kft and may be hundreds to perhaps a thousand miles in width, containing streaks which may be tens of miles wide. These

jet streams obviously cover such wide global areas that satellite observation is again ideal. Again, however, the same problem comes up - how to measure wind velocity in the jet stream from cloud data. This is obviously a basic problem with regard to the further use of and confidence in satellite data that must be solved by active techniques if passive techniques fail.

In any case, attempts have been made at NESG to locate jet streams from TIROS photographs. They felt that jet streams could be located in about eighty percent of the cases when clearly defined cloud characteristics occurred under viewing conditions which were favorable for their system at the time (1966). They found that the most definitive cloud characteristics are (1) an extensive cirrus shield having a sharply defined poleward edge (the data were obtained over the U. S.), often outlined by a shadow cast on lower cloud surfaces or on the earth, and (2) transverse banding in the cloud shield. The jet axis is located on the poleward cloud edge. It was found that cirrus streaks alone prove to be undependable detectors and there is a danger confusing frontal cloudiness with jet stream cloudiness. In fact, the greatest difficulty in this approach is that it relies largely on pattern recognition, which apparently fails at times. A study should be made to determine the best approach for jet stream location by more quantitative means. Perhaps the Riehl model should be used as a guide in a choice of optimum observables. In this model, the axis of the jet itself represents an abrupt boundary between cyclonic and anticyclonic shears with the consequent abrupt changes in the vertical motion across the boundary. Again, scintillations in radiometric data may give a measure of these shears.

5. Sea Surface Albedo

Finally, in investigating events which may trigger the formation of a hurricane, other measurements, conjectural at this time, should be considered. One is the effect of changes in cloud and ocean surface albedo. It is known, of course, that evaporation of moisture into the atmosphere is the primary source of hurricane energy. Thus, the amount of incident solar energy which is absorbed by the ocean and reflected by it is extremely important and will produce changes in observed albedo. These changes may be due to natural causes such as the presence of large areas of plankton or other living matter on the surface of the water or may be due to man-made causes such as oil spills.

The evaporated moisture will rise in the hurricane chimney and will condense at some altitude. The condensation region will depend, of course on local conditions. If the cloud albedo varies from one region to another, then it is possible that the local radiation balance will be such as to alter the conditions for condensation in these regions. Finally, with regard to condensation, it is generally agreed that solid particles which act as condensation centers are required to initiate the event.

6. Condensation Nuclei

A possible source of such condensation centers may be African dust. The concentration of dust in the trade winds passing over Barbados has been measured continuously since 1965, as reported by Prospero and Carlson. The average dust load has been found to be about $2.5 \mu\text{gm}/\text{m}^3$. It has been found that there is a marked seasonal periodicity in the transport with the average dust concentrations in the summer months. Also, the composition of the dust and the quantities transported are dependent on the meteorological conditions over Africa and the tropical North Atlantic Ocean. The dust is carried in air parcels at altitudes between 4 and 14 kft. These parcels travel behind disturbances known to emerge from Africa with an average frequency of one every three or four days. The slab-like parcels of African air have relatively

high potential temperature and mixing ratio and their dust content is of sufficiently high content to produce dense haze visible on satellite photographs. (This may account for disturbances reported by satellite which were not subsequently seen by investigating aircraft.) When proper differentiation is possible, the satellite can be used to investigate and to keep track of these dust clouds in an effort to determine their potential effect on hurricane initiation. If dust "seeding" is found significant, another avenue for hurricane modification may be opened, a statement which may also apply to surface and cloud albedo changes once sufficient data have been collected (possibly by satellite) and interpreted.

Finally, it should be noted that the hurricane modifications which have been performed thus far and are planned for the near future, along with others suggested in this report, should be monitored over a broad hurricane field. This implies satellite sensing of the type described above, along with certain spectroscopic measurements. Also, the measurements that have been discussed thus far are all passive. However, small microwave radars have been built and can be packaged for satellite use. The laser radar is further behind in this respect. Although the laser radar can make some very interesting Doppler measurements in the clear, cloud-free regions by scattering from aerosols, this must await the flights of laser radars on board airplanes.

D. Satellite Instrumentation

The above discussion did not include a survey of the potential of the present satellite instrumentation and hardware or the need for developing new equipment. However, there are two areas which must be especially noted in this respect: large antennas and sensitive detectors. The first has already been alluded to. It is necessary to develop means of opening and deploying large microwave antennas that are satellite-borne. These antennas should satisfy high surface tolerance requirements so that sidelobes are suppressed.

The second area involves the use of sensitive detectors, which must be cooled on satellites. The specific problem here is the cooling device, which must operate reliably for a period of years. Some form of improved thermo-electric or reliable closed-cycle cooler must be developed, a non-trivial problem. It is recommended that various cooling systems, appropriate for satellite use, be actively investigated.

In conclusion, it can be stated that NOAA and NASA, as indicated above, have already shown that satellite measurements can supply useful information to the hurricane forecaster and researcher. These measurements can be refined and new ones made to improve the forecaster even more, and to supply new information on hurricane mechanisms and control.

E. Recommendations for Satellite Measurements

1. Forecasting

Determine optimum means of defining cloud eye and its position from infrared and/or microwave data in real time;

Determine optimum means of obtaining maximum wind velocity from cloud diameter, and the error in the determination;

Determine the accuracy by which the wind velocity spectrum can be obtained from the radiometric intensity scintillations

Determine means of estimating changes in the strength of the hurricane as the feeder band passes over water and land;

Determine methods of measuring wind velocity and effective temperature in the chimney (or hot tower) with microwave radiometry;

Determine methods of measuring eye wall height using infrared and/or microwave radiometry. Determine whether the required accuracy is attainable using radiometry;

Determine whether infrared radiometry will obtain sea surface temperature to an accuracy of 1°C by properly accounting for the effects of clouds and atmospheric attenuation due to water vapor;

Determine whether microwave radiometry will obtain sea surface temperature to an accuracy of 1°C in the presence of large sea roughness;

Determine the optimum means of measuring the mixing ratio using infrared and/or microwave radiometry.

2. Research

Determine the best method of detecting from a satellite the presence of:

- Polar front extending to latitudes less than 30°;
- Cyclonic shear
- Active inter-tropical convergence zone at latitudes of about 5°;
- Minimal shear areas;
- Mid-latitude upper trough;
- Anti-cyclonic jet stream at lower latitudes.

Determine whether the observations of cloud motions on different spatial and temporal scales will yield accurate wind velocity fields by using passive and (if necessary) active techniques;

Study the effects of sea surface and cloud albedo changes on hurricane formation;

Study the effect of African-generated dust on hurricane formation;

Determine methods of obtaining satellite data from hurricane modification experiments;

Determine means of performing microwave and laser radar experiments from satellites;

Determine whether large microwave antennas can be placed on satellites;

Determine optimum cooling methods for detectors.

V. OBSERVATIONS FROM AIRCRAFT

A. Satellite Data Display in Reconnaissance Aircraft

The Improved TIROS Operational Satellite-1 (ITOS-1) carries, in addition to a scanning radiometer (for measurements of reflected radiation in the 0.52- to 0.73- μ region during the day and of emitted radiation in the 10.5- to 12.5- μ region at night), an Advanced Vidicon Camera (AVCS) with Automatic Picture Transmission (APT). Pictures from the AVCS are stored aboard the satellite before transmission to data-acquisition stations located in Alaska and Virginia; the pictures are subsequently relayed to the NESC in Suitland, Maryland.

The APT camera uses narrow-band transmission to inexpensive one-man receiving stations. The APT camera contains a high-persistence vidicon which gives a 600 x 800 scan-line image.

A modified AVCS-APT system might be useful to reconnaissance aircraft in severe storms.

B. Real-Time Video Signals from Aircraft

The development of a real-time pictorial representation of the events below the aircraft can be achieved at any wavelength by either ambient radiation (passive) or external illumination

(active). In the latter instance, practical illuminators will be limited to optical wavelengths of less than 13 microns. The signal generation can be produced by either a framing system, i. e., TV-like camera, or a strip camera, i. e., a scanning radiometer.

The utilization of a single camera provides a two-dimensional representation except where time-lapse pseudo-stereo can be produced or a stereo imagery can be provided by two cameras.¹ The stereo coverage is defined by the camera installation: (1) partial overlap along the longitudinal axis; or (2) total overlap. The aforementioned procedures have been utilized in aircraft and satellites.

Satellite experience has already indicated that two vidicon cameras are feasible (ESSA-9) and transmission of the data is straightforward. Similarly, one can perform the same without any difficulty from an aircraft. Again, signal transmission is independent of wavelength content.

The TV-like camera(s) for dawn-to-twilight operation can be constructed with current vidicons, including the RCA return-beam high resolution. A field of view of 40° will give about 0.28 milliradian resolution, which is comparable to an infrared scanner operating in the 8- to 13-micron region.

From an altitude of 60 kft, the ground coverage is about 7.2 mm and, of course, at lower altitudes, the coverage is proportionated less and the resolution greater. Mission planning will be required to optimize the TV camera since different field of view may be desired — a choice not readily available to the infrared system.

The storage and transmission of the data recorded can be varied significantly. In the NASA/ESSA satellites, APT utilizes a narrow-band transmission link to rather simple, inexpensive receiving stations. If continuous readout is required, then a wideband system is needed (≈ 1 MHz), which is now available in COMSAT TV transmission links. Otherwise, storage on magnetic tape and slow readout can be used.

An alternative scheme arrangement is to utilize the Princeton Electronic Products (PEP) silicon tube (electrical in/out), which can be produced in a 1200-TV-line format. This tube can be applied in an interesting fashion, namely storing four 525-TV-line pictures from several sensors, including radar, and then transmitting the results at a slow scan rate. The technique avoids resolution loss of a system employing a camera looking at a CRT display.

The preceding summary remarks show that current, off-the-shelf hardware either at visible or infrared wavelengths, in conjunction with storage tubes like the PEP device, can provide high resolution and wide coverage of the clouds and their structure in real time. Although this equipment is readily available, we question its utility in low-flying aircraft. It might, however, be a useful adjunct for a high-altitude reconnaissance plane, except that this job is probably better done from a satellite platform.

C. Hurricane Observations from a High-Flying Aircraft²

Workers at AFCRL overflew Hurricane Ginny (22 October 1963), taking photographic and radiometric data at about 15-second intervals. The U-2 aircraft was equipped with a Barnes infrared radiation thermometer, Model 14-311, which measures radiation in the interval 7.5 to 13.5 microns over a field of view of about $2^\circ \times 2^\circ$. Cloud photographs were taken with a Perkin-Elmer panoramic camera that has a field of view of 42° fore and aft by 180° perpendicular to the line of flight. Measurements were made at altitudes of 67,500, 50,000, and 38,000 feet, and a descent into the eye was made to 30,000 feet. Cloud tops at the eye wall were about 40,000 feet.

On September 20, 1964, an instrumented U-2 overflew at 66-kft altitude the southwest edge of Hurricane Gladys (29°N, 71°W), to observe the presence of ice. It should be noted that the data were not analyzed to ascertain whether the water vapor content was different at this time relative to a normal atmosphere. The value of future effort in this direction is not obvious until a more sophisticated model of a hurricane system is generated.

D. Passive Observations from Aircraft in the Ultraviolet, Visible, Infrared, and Microwave Regions of the Spectrum

Passive instrumentation over a range of electromagnetic wavelengths can provide data related to pressure, temperature, and molecular species and their distribution under specific atmospheric conditions and surface temperatures. From these measurements, secondary parameters may be derived, e. g., sea surface velocities, vertical motions, cloud velocities, etc. It should be noted that active measurements may be preferred in some instances to take advantage of the range-gating ability of the laser transmitter and sensing element. From aircraft it is possible to use cooled detectors impractical for application on satellites.

1. Ultraviolet

In the ultraviolet part of the spectrum, the most important specie is ozone (O₃). For a quiescent atmosphere, the distribution, except for seasonal changes, is relatively stationary and therefore, stratospheric vertical circulations associated with developing storms, e. g., hurricanes, result in increases or decreases of ozone. Variations in ozone content can be detected from an aircraft using a spectrometer in the region of 0.25 to 0.28 microns looking upward and performing measurements of solar transmission in the ultraviolet. Below 0.28 microns, ozone absorption is the dominant attenuation mechanism and a ten percent decrease in ozone results in about a 10⁻⁵ decrease in attenuation.

Since little is known about the ozone distribution in or about severe storms, e. g., hurricanes, research is needed to establish ozone distributions from sea level to the upper stratosphere (35 km) to establish if any correlation exists between this molecular specie with significant storm-warning parameters.

2. Visible

In the visible portion of the spectrum, we obtain pictures of the cloud formations. These are produced by reflected light; therefore, no information is obtained on any underlying cloud formations. Ice or water droplet clouds may have different albedos or, possibly, different effects on polarization. The determination of cloud-top heights using reflected solar radiation in the oxygen (O₂) absorption band at 0.76 microns has been attempted with only modest success. Scattering from within the cloud layer gave variable contribution. Theoretically, by using a dual-wavelength radiometer at 0.74 micron and 0.76 micron, a pressure profile in the vicinity of clouds may be established to an accuracy of 0.5 km in the lower troposphere.³

3. Infrared

In the infrared, we can hope to obtain significantly more data. For a cloudless atmosphere, radiometric measurements at a number of wavelengths in an absorption band, e. g., 14 μ CO₂, can provide through suitable inversion techniques a temperature profile of the sampled local vertical column of air. The error in this method for a particular point is about 2°C relative to radiosonde observations, except in the tropopause where the error is about 5°C. The error lies inherently in atmospheric variability, uncertainties in molecular parameters, and mathematical methodology. With non-cirrus clouds in the field of view, current methods cannot yield useful information unless a single layer with well-defined, clear areas exists. Cirrus clouds

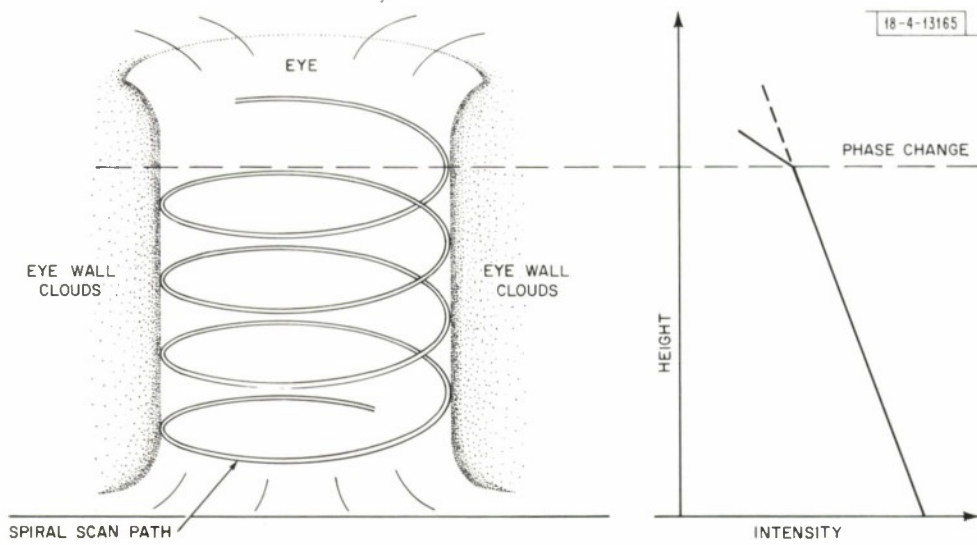


Fig. III-1. Possible passive indication of phase change.

introduce error in the inversion. Chahine⁴ has examined this limitation and has produced some useful results, but useful conditions are rarely found in a real atmosphere, particularly in the vicinity of storms. The second limitation has been examined by Houghton and Hunt⁵, who will attempt to eliminate experimentally this possible error from their inversion process. They propose to fly on Nimbus-E a dual-wavelength radiometer operating at 50 and 120 μ . From the difference in reflectivity properties at these wavelengths, ice/water cloud can be differentiated due to variation of ice properties at 50 and 120 μ . The latter result can then be used to correct the 14- μ radiance data for cirrus-type clouds.

Measurements in the 10.5- to 11.5- μ regions of the sea surface have provided sea surface temperatures with an accuracy of 2°C. Again, the errors are produced by variability in atmospheric and surface conditions.

At the shorter end of the spectrum, several items of possible interest may be obtained from spectroscopic measurements.

The absorption peaks of ice are shifted relative to the peaks for water vapor and liquid water. These effects have been observed with aircraft and satellite instrumentation.

The strength of the water vapor absorption bands increases with increasing wavelength from 0.85 to 2.7 microns; hence, radiometric measurements of reflected solar radiation at several wavelengths near the absorption peaks can yield cloud-top heights when viewed from above to an accuracy of 1 to 2 kms. This conclusion applies because the intensity of reflected radiation at these wavelengths is a function of particle concentration in such a way that only the exposed upper cloud layer can be probed.

Measurements of humidity below the sensor have been performed by observations in the 2.7- and 6.3-micron bands with good results. Evidently, above the platform, absorption measurements can yield integrated water vapor content to an accuracy of several percent. The limitation in accuracy is the effect of scattered radiation.

A calibrated radiometer mounted either on the top or bottom of the aircraft can scan the eye wall from below or above, respectively, to obtain radiometric temperatures as a function of height. Discontinuities in such temperature profiling can be interpreted as either super-cooled water and/or ice (see Fig. III-1).

Recent measurements utilizing stereo imagery with calibrated scanners have shown that several useful parameters can be obtained: (1) wind velocities from cloud movements; (2) if clouds at different heights are observed, then a temperature-versus-altitude profile can be established by looking at cloud emissivities; and (3) if needed, the vertical cloud surface temperature can be measured. In essence, by sophisticated data processing, a three-dimensional temperature field can be constructed with a resolution consistent with available cloud distribution.

4. Microwave

Passive microwave radiometers provide data similar to the data in the infrared in that they can probe the atmosphere utilizing the properties of either O₂ or H₂O; however, they have the added advantage of being useful in the presence of clouds and rain. An additional advantage is that a rotational line can be readily resolved; that is, the resolution is about 0.1 to 0.2 percent of the wavelength and the linewidth may be 10 percent of line wavelength; e.g., the 1.35-cm line is about 6 GHz wide and the resolution can be about 20 MHz. The theory of radiative transfer in the atmosphere at microwave frequencies and detailed results of USSR aircraft measurements are well documented.⁶

Microwave radiometers have already been flown on aircraft by Sperry Rand⁷ under an Air Force contract and Space General/NASA.⁸ In the latter instance, the instrument was an electrically scanning radiometer prototyped for aircraft use. Similarly, in the USSR, extensive aircraft flight measurements have been made, including one reported satellite flight.

The results of the several programs are now summarized:

a. Sperry Rand

- 1) Temperature sensing in a clear atmosphere using the O₂ band (49 to 60 GHz) revealed that the temperature at any given height could be determined by inversion with an average probable error of 2°C. The minimum error of 0.6°C occurred at the higher altitudes (50 kft) and the maximum error of 4°C occurred in the first few thousand feet. With refinements in methodology, the resultant errors could be halved.
- 2) Humidity profiles were not determined successfully because of the large variability in water vapor distribution.
- 3) Pressure profile measurements were attempted by combining temperature and aircraft altimeter data and using a hydrostatic equation which had included the virtual temperature. Pressure profiles could be obtained from 18 to 53 kft with a height resolution of 35 ft. In a hurricane environment with excessive moisture, it is doubtful that these errors would be larger since the virtual temperature may still be close to the dry-air temperature. However, the temperature observed with the microwave radiometer should be nearly the virtual temperature. Several observations could help to improve the accuracy of the measurement.

b. NASA

A radiometer operated at 19.35 GHz was used to study a variety of atmospheric features. This frequency is on the high side of the H₂O absorption band. The field of view of the scanner was 100° with an instantaneous field of 2.7°. It should be noted that an on-board facsimile recorder provided instantaneous readout. The results are enumerated below.

- 1) Measurements at 19.35 GHz are unaffected by atmospheric conditions and cloudiness except for clouds containing substantial amounts of precipitation.
- 2) High-altitude cirrus and low-altitude stratus of thickness up to 10,000 feet had little effect upon the observed water temperature in the North Pacific.
- 3) Towering cumuli with cloud top at 35,000 feet over the Gulf of Mexico containing cells of heavy precipitation were overflown and penetrated, producing an increase of 120°K above the water temperature of 140°K. Clouds containing less rainfall produced a smaller increase in brightness temperature. With appropriate calibration and correlation, the scanning microwave radiometer can map cold regions, separating precipitation from non-precipitating clouds and determine the amount of precipitation.

At 19.35 GHz, a temperature resolution of less than 1°C should be achievable; hence, surface temperatures in the eye can be mapped with a spatial resolution of 40 meters from an altitude of 35,000 feet.

c. USSR

The details, except for the wavelengths used and the respective antenna beamwidths, of the USSR satellite radiometers are not available. The wavelengths were 0.8, 1.35, 3.4, and

8.5 cms and the antenna beamwidths were 8° for the three shorter wavelengths and 15° for the longest wavelength. Ground resolution was about 10 kms. The 0.8-cm wavelength lies between the O_2 and H_2O lines, 1.35 cm lies in the H_2O pure rotation region, and 3.4 and 8.5 cms are relatively free of atmospheric effects. The results which are reported are as follows:

- 1) The 3.4- and 8.5-cm radiometers yielded sea surface temperatures to an accuracy of 1° to $2^\circ K$, as verified by subsatellite ground measurements.
- 2) From the 1.35-cm radiometer, integral water vapor measurements above the ocean to an accuracy of 0.2 gm/cm^2 were obtained. Note: Aircraft measurements indicated a maximum error of 10 percent.
- 3) From the 0.8- and 3.4-cms radiometers, the distributions of integral liquid water content of clouds above the oceans were obtained.
- 4) Zonal regions of storm winds were identified by anomalously high values of emissivity and brightness temperature and also by "water vapor" fronts.

The listed results from microwave radiometers are impressive. Additional cogent data can be obtained, e. g., wind velocities at the sea surface, using the same wavelengths but adding polarization observations.

Research on temperature, pressure, and humidity profiling should produce, if pursued adequately, applicable results when correlated at several frequencies. Polarization effects on intensities should separate liquid water from ice.

5. Summary

- 1) Ultraviolet: We see the need to study if and how the ozone distribution is affected by severe storms and to determine whether these variations can be correlated with needed observational or diagnostic parameters.
- 2) Visible:
 - a. We see little value in observations in this region except for documentary records of the clouds associated with the storm and a picture of the eye.
 - b. If the platform position is known, then the eye dimensions and location can be established.
 - c. If any additional information is available, research using a multi-spectral camera is required.
 - d. Data on oxygen using the band at 0.76μ is better obtained at other wavelengths.
- 3) Infrared:
 - a. Temperature profiles can be obtained in a clear atmosphere. If such profiling can be performed in a hurricane eye, more detailed information is required in two areas; namely, the overall stratification of cloud structure and the vertical distribution of CO_2 mixing ratio. The possibility of occurrence of abnormal CO_2 distribution in the eye should be examined. (See Fig. III-2.)
 - b. From multi-wavelength reflectivity measurements, ice or water clouds can be distinguished. If direct sunlight is available, the distribution of water droplets, in principle, determines the reflected emission profile.

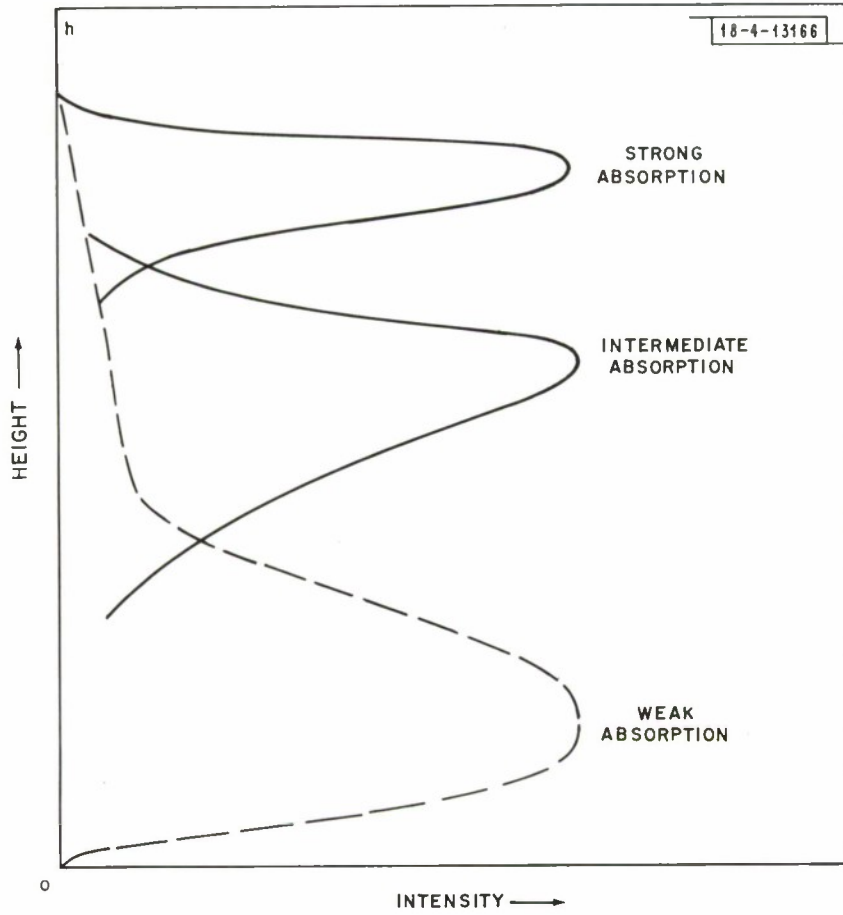


Fig. III-2. Temperature profiles from radiometric observations. Microwave 49-60 GHz (O_2); infrared 15 microns (CO_2 band). Accuracy required: $\pm 2^\circ C$.

- c. From radiometrically calibrated scanners, temperatures of cloud tops, cloud walls, and sea surface can be measured to an accuracy of 2°C .
 - d. A scanning radiometer may be used to map the hurricane wall vertically and to establish from discontinuities the boundaries between water and ice.
 - e. With a cooled detector system of high sensitivity and high resolution, the cloud field of the hurricane system may be monitored.
 - f. Stereo infrared imagery obtained below the cloud bases, i. e., at altitudes of less than 1500 feet, can yield simultaneously sea surface temperatures and detailed structure of the wave system. Resolution of wave heights of less than one foot should be readily obtainable.
 - g. Stereo infrared imagery may provide a temperature profile in broken cloud situations.
- 4) Microwave:
- a. Sea surface temperatures can be measured reliably even with non-precipitating clouds in the field of view.
 - b. Regions of precipitation can be separated from non-precipitation in the presence of clouds.
 - c. Rates of precipitation in excess of 5 mm/hr may be correlated with brightness temperature.
 - d. Integral water vapor and liquid water content can be determined to about 10 percent accuracy.
 - e. Wind velocities at the sea surface can be indicated from sea state measurements.

We can conclude that from a combination of select infrared and microwave measurements, one may obtain most if not all parameters of interest to hurricane detection and warning. Implementation of an early operational capability utilizing available instrumentation is recommended. An experimental research program is recommended to generate a second-generation capability to make possible the transition of "possible" method to operational instruments.

TABLE III-3

SUMMARY CHART OF MEASUREMENTS WITH RADIOMETRIC METHODS

<u>Sea Surface Temperature</u>	$\pm 2^{\circ}\text{C}$
In clear atmosphere, use 10.5- to 11.5-micron band	
In presence of clouds, use 3.4- and 8.5-cm wavelengths	
<u>Identifying Regions of Precipitation</u>	
Use 1.55-cm or 3.4- and 8.5-cm wavelengths	
<u>Precipitation Rate (5 mm/hr)</u>	
Use 1.55- or 1.0-cm wavelengths	
<u>Vertical Temperature Profile</u>	$\pm 2^{\circ}\text{C}$
In clear atmosphere, use 15-micron or 50 ± 5 GHz bands	
<u>Integral H₂O Vapor Content</u>	$\pm 0.2 \text{ gm/cm}^2$
Wavelengths 0.8, 1.35, and 3.4 cm	
<u>Integral Liquid Water Content of Clouds</u>	
Wavelengths 0.8 and 3.4 cm	
<u>Cloud Heights</u>	± 1 to 3 km
Wavelengths 0.85 to 2.8 microns	
<u>Possible Measurements</u>	
Pressure Profile	± 35 ft
Wind speed at sea surface	10%
Wave heights	1 ft (infrared stereo)

VI. NEW INSTRUMENTATION FOR IMPORTANT OBSERVABLES

A. Laser Doppler Wind Velocity Measurements

The laser-Doppler velocimeter has been extensively used in fluid-flow studies, especially for probing the atmosphere, vortex flows, laminar boundary layers, and rotating flows. In the rotating flow studies, which relate perhaps most directly to hurricane diagnostics, a large improvement was achieved in both spatial resolution and absolute accuracy, for measurements of individual velocity components. Although extensive measurements of laser scattering in the atmosphere have been reported, we are not aware of successful applications of the laser-Doppler velocimeter to an airborne platform.

The achievable spatial resolution and range are strictly determined by the laser source intensity and by the sensitivity of the detector element for a given atmosphere. Theoretical studies indicate that available, high-power, pulsed laser returns should be detectable at ranges of tens of km if only molecular scattering occurs. In the clear atmosphere with normal concentrations of aerosols, some reduction in range may be anticipated. In heavy fog or through dense clouds, the operational range is reduced to tens of feet. In rain, the achievable range will take intermediate values depending on rain intensity.

Using a CW laser source and a spectrum analyzer, time-averaged measurements of frequency shifts over short time intervals are feasible. For maximum range, the CW source should be replaced by a short-duration pulse, which may also be required for backscattering measurements where range-gating is desirable. With pulsed sources, an appropriate search of frequency shifts will have to be performed.

Although laser probing of the atmosphere is a very active current field of research, it appears desirable, nevertheless, to obtain early experience with airborne instruments in hurricane reconnaissance in view of the very great potential utility of an operational system for probing of the clear-air spaces within the eye and between the rain bands. For exploratory research, a tunable CO₂ laser source of the type used in trailing vortex experiments on C-47 aircraft may be useful. We review briefly the salient performance estimates for an instrument of the type used by Huffaker, et al.⁹

In a coaxial focused system using a 10-watt CW CO₂ laser, the transmitted radiation is focused at a range f_T . The backscattered light is measured (with a liquid-helium cooled, copper-doped germanium detector) and is homodyned with a reference fraction of the laser radiation. The power signal-to-noise ratio (SNR) is then given by the relation

$$\text{SNR} = \frac{1}{4} \frac{\eta n \sigma \lambda N}{\pi B} \left[\frac{\pi}{2} + \tan^{-1} \left(\frac{\pi R_T^2}{\lambda f_T} \right) \right] ,$$

where η = quantum efficiency of the detector, n = number density of scattering centers in the flow, σ = average scattering cross section of the scattering centers, λ = laser wavelength, N = number of photons emitted per second from the laser, B = electronic bandwidth, R_T = radius of the (transmitter and receiver) optical system. For an aperture with $R_T = 25$ cm, an axial resolution of about 20 meters (50 percent of peak power response) at a distance of 500 meters or 3.2 meters at 117 meters, one percent overall system efficiency, $n\sigma = 0.8 \times 10^{-3} (\text{km})^{-1}$ at 10.6μ (corresponding to clean continental air at sea level), the estimated values of SNR are about 150 per meter of length at a range of about 500 meters and about 25 per meter of length at a range of 1200 meters. The diameter of the focal volume lies between 0.4 and 2.8 cm with a

nominal value of 1.4 cm. Scanning was to be performed over the vertical plane with 60 range cells; the integration time during the elevation scan requires an angular resolution of 1 meter at the nominal range. For a 2-second frame time, 3000 data points are obtainable per second with a dwell time on each resolution element of 300 μ sec.

The experimental studies were actually performed from a movable truck with a 20-watt CW CO₂ laser at a range of 80 feet.

NASA-Huntsville is currently contracting a pulsed CO₂ laser system for clear-air turbulence measurements with pulsed peak power of 5 kw, 10-kc maximum linewidth, 2-, 4-, and 8- μ sec pulse widths, and a matched filter coherent detector. With a 12-inch aperture and integration over about 50 pulses, the SNR is estimated to be very large at a range of 10 n. mi in clear air with turbulence. The PRF is 10³ cps and the average laser power 20 watts. (See Table III-4.)

TABLE III-4
LASERS FOR USE IN A HIGH-ALTITUDE RECONNAISSANCE SYSTEM

- Purpose: (a) Measurement of three velocity components in clear-air spaces and in moderate rain
(b) Total and component-density measurements

Real-Time CW System

300-watt bistatic CW CO₂ laser, with movable (preferably continuously in two directions) source and detector mirrors mounted at extreme wing tips

Range: 12 km (with 0.3% system efficiency)

Axial resolution length: 20 m at 1.2 km, 200 m at 12 km

Beam Diameter: 24 cm at 12 km (20-microradian beamwidth)

Output: Real-time display of velocities with less than 1-sec averaging times

Problems: Stabilization of optical trains in bistatic system to required precision has not yet been accomplished

Real-Time Pulsed System

Use 5-kw maximum, monostatic, pulsed CO₂ laser of type currently being developed by NASA and Raytheon; PRF-1 kc: average power = 20 watts. With 2- μ sec pulses, achievable resolution length is 300 m. Stabilization of single sending and receiving unit on aircraft is presumably not a problem. Design optical train for sequential examination of five paths to obtain some redundancy in measurement of three velocity components. Reconstruct complete flow field from applicable symmetry considerations. Signal-to-noise output looks very favorable.

Problems: Real-time velocity displays have not yet been built, but there are no anticipated basic problems if weight and space limitations can be relaxed.

B. Laser Rayleigh and Raman Scattering (Density and Selected Particle Density Measurements)

In the clear atmosphere containing aerosols for which the aerosol concentration is definable, the Rayleigh return (i. e., the scattered intensity at the incident frequency) provides a direct measurement of local total density. In Raman scattering, the intensities measured at selected frequencies define the local densities for those chemical species for which the Raman intensities are being observed at well-defined, shifted frequencies. Theoretical studies of

achievable signal-to-noise ratios suggest that the experimental difficulties in studies of Rayleigh and Raman scattering are comparable.

Intensities in Rayleigh or Raman scattering have not yet been observed from airborne platforms. As with the laser-Doppler velocimeter, we are dealing with an active field of research in which significant progress should be achieved during the next five years. We regard the absolute intensity determinations required for local density measurements as more difficult to perform in the field than the frequency shifts that are involved in laser-Doppler velocimetry. However, the promise for hurricane diagnostics is again so significant that early flight experiments should be initiated.

C. Laser Pressure Sensor

Research in the laboratory utilizing Raman scattered radiation from a volume of air defined by the transmitter/receiver fields of view has been found to be a valid method to determine species concentration.

In principle, the volume is illuminated by a laser at a specific wavelength, e. g. , a ruby laser at 6943 Å, and each of the species radiate simultaneously at several permissible wavelengths different than the absorbed incident wavelength. The observed radiation will include the Rayleigh scattered component of the incident radiation.

The intensity of the radiation is directly proportional to the number density and, therefore, if the number density of O₂ and N₂ can be established, the pressure can be determined. It should be noted that other molecular species like CO₂ and H₂O can be determined. To accomplish this analysis, a multi-megawatt (~100 megawatt) laser is required since the available scattered light is small; that is, the observed signal at a specific wavelength is about 10⁻¹⁵ of the output power. Further, the signal is reduced about one order of magnitude for a similar reduction or pressure.

In practice, a Q-switched ruby laser with a one-joule output released in a 10-nanosec pulse can be utilized and air cooling is sufficient. The laser must be properly mounted in proximity to the receiver and yet minimize scattered light into the crew compartment.

The receiver will consist of several filtered photo-multipliers to monitor the Raman light and the Rayleigh scattered component. The latter will be used to eliminate the effect of any aerosols.

The overall accuracy of individual species measurement is less than ten percent.

As an instrument that is ultimately used to measure pressure, a calibration curve between measured intensity and air pressure would be preferred (see Fig. III-3).

D. Spectroscopic Temperature Measurements using Wave Number Spacing between Intensity Maxima in the Band Branches (for CO₂ and H₂O)

The wavenumber spacing between the observed maxima in vibration-rotation bands is temperature-dependent and may, therefore, be used in temperature determinations from radiometric scans without performing absolute or quantitative relative intensity measurements. We present here a zeroth-order theory which requires refinement before it is suitable for application to inhomogeneous temperature fields and to inversion for reconstruction of the temperature field. In the zeroth-order theory, we use asymptotic approximations for large rotational quantum numbers (j) even though the low-temperature fields in hurricanes will require some complication in analysis, which in this approximation is deleted.

For large values of j, the line-intensity distribution is determined by the factor

$$j \exp [-E(n_1; j)/kT] ,$$

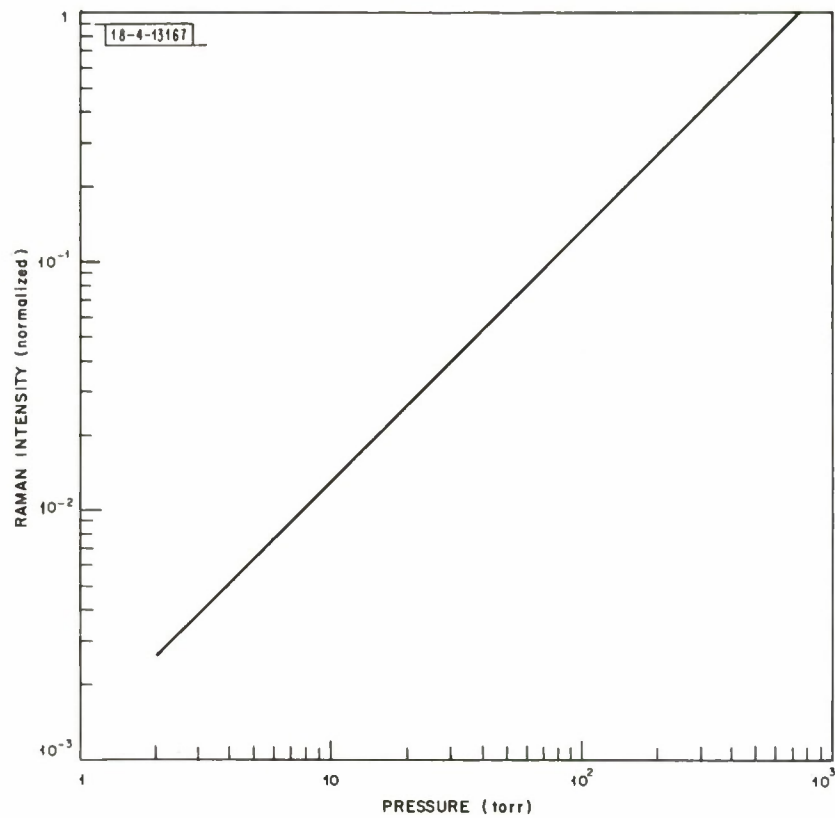


Fig. III-3. Pressure vs Raman intensity.

where $E(n_1; j)$ is the energy of the level characterized by the set of vibrational quantum numbers n_1 and the rotational quantum number j . Neglecting vibration-rotation interactions, it may now be shown that the line intensity reaches a relative maximum for the transitions $j^* \rightarrow j^* \pm 1$ if

$$j^* \approx (kT/2 hc B_e)^{\frac{1}{2}},$$

where B_e is the rotational constant (in cm^{-1}) if we set $hc/k \approx 1.4 \text{ cm}^{-1} \text{ } ^\circ\text{K}$ and T represents the temperature in $^\circ\text{K}$. The wavenumber spacing between intensity maxima now becomes approximately

$$\Delta\omega \approx \frac{2}{hc} [E(n_1; j^*) - E(n_1; 0)].$$

Again, neglecting vibration-rotation interactions, it may be shown that

$$\Delta\omega \approx 4 B_e j^* \approx 2 B_e (2 kT/hc B_e)^{\frac{1}{2}}.$$

It is interesting to observe that $\Delta\omega$ depends only on B_e in zeroth-order and is, therefore, the same for all of the vibration-rotation bands belonging to a given diatomic or linear (e.g., CO_2) molecule; the applicable value of B_e for an asymmetric-top molecule (e.g., H_2O) depends, however, on the band under study.

We ask to what precision it is necessary to measure $\Delta\omega$ in order to define the temperature to an accuracy of $\pm 1^\circ\text{C}$. For H_2O , $B_e \approx 12 \text{ cm}^{-1}$ while $B_e \approx 0.4 \text{ cm}^{-1}$ for CO_2 (for which every other rotational line is missing). Hence, we find the values listed in Table III-5 for $\Delta\omega$.

TABLE III-5
CALCULATED VALUES OF $\Delta\omega$ FOR CO_2 AND H_2O AT
THREE DIFFERENT TEMPERATURES
(Using $B_e = 12 \text{ cm}^{-1}$ for H_2O and $B_e = 0.4 \text{ cm}^{-1}$ for CO_2)

T ($^\circ\text{K}$)	Molecule	$\Delta\omega$ (cm^{-1})
300	CO_2	28
	H_2O	144
270	CO_2	26.8
	H_2O	136
240	CO_2	25.2
	H_2O	128

Reference to the data listed in Table III-5 shows that we require a precision in the determination of wavenumber spacings between band-branch maxima of about 0.05 cm^{-1} for CO_2 and about 0.2 cm^{-1} for H_2O in order to determine temperature with an accuracy of about $\pm 1^\circ\text{C}$. The specified accuracy should be easily achievable in flight measurements of emitted radiant energy.

The inversion problem for inhomogeneous temperature fields, following multiple traverses in different directions, will presumably be handled in a manner that is analogous to that used in the inversion of radiometric intensity measurements.

The spectroscopic technique described in this section merits careful study since it seems especially well suited to observations from moving platforms for which intensity calibrations are generally more difficult to perform than wavelength calibrations. It should be noted that the achievable wavelength precision may be considerably better than the spectral resolution of the instrument used.

VII. RESEARCH

A. Introduction

Introduction of effective measures for severe storm control will require intimate knowledge of the dynamical processes determining at least the large-scale structures and, possibly, also of the nature of the elusive perturbations that act as triggering mechanisms for the larger-scale motion. Recognition of this basic principle is evidently involved in the current hurricane-seeding studies. Total rotational energies in mature hurricanes are of the order of 10^{23} to 10^{24} ergs. These prodigious energies represent only about five percent of the total latent heat introduced into the hurricane. In view of the very large energies involved, it is apparent that mature-storm control will be feasible only if a redistribution of the total available energy can be affected by appropriate application of small-scale disturbances. Implementation of this idea is basic to the hurricane-seeding program.

In Project Stormfury, silver iodide is used to freeze supercooled water. According to experiments* performed with a computer program, the heat released by freezing introduces vertical motion which, in turn, is responsible for additional precipitation of liquid water. In numerical studies described by Dr. Gentry, the principal heat-releasing mechanism, which accounts for about 85 percent of the total supplementary energy addition, was found to be the precipitation of liquid water induced by vertical motion. The supplementary heat release, when it occurs at the appropriate locations, presumably smoothes the wind profiles by reducing the maximum wind speeds near the eye wall, while increasing the wind somewhat further out in such a manner that the total rotational energy of the hurricane is substantially preserved. Thus, the expectation of success in Project Stormfury is based on the assumption that appropriate seedant addition will decrease the maximum tangential (azimuthal) wind-velocity components. At the present time, no hurricane control program other than Project Stormfury is being pursued actively, nor are we aware of any promising proposals for hurricane control other than the seeding program.

Tornadoes, which are defined by much smaller scales and correspondingly lower integrated energies than hurricanes, are being observed as they are spawned by thunderstorms or by hurricane winds. There are, however, no active control attempts.

It is difficult to define fundamental experimental and theoretical studies that are of immediate relevance to the principal mission. By its very nature, there can be no assured promise in peripheral basic "risk" research. Yet, examination of the past long-term history

* Rosenthal reported during April 1970 at Miami that hurricanes recovered to their initial wind speeds when seeding was accomplished in the regions of maximum winds (i. e. , 15 to 30 km from the eye center). On the other hand, with peripheral seeding (30 to 60 km from the eye center), some decrease in wind speed was found to persist. These summary statements are based on the results of computer experiments.

of this type of peripheral research has clearly indicated enormous implications for the practical program, often in a manner that could not be foreseen by the people planning the basic research. For example, much of the basic research relating to large-scale rocket-engine development has turned out to be irrelevant. And yet in a subtle and ill-defined manner, this basic research led to the successful introduction of baffles and to the successful stabilization of our largest rocket boosters.

B. The Importance of Scale Studies

In meteorological studies, the field laboratory is the atmosphere and the important length scales correspond to tropospheric or large fractions of global dimensions. Nevertheless, real understanding of important similarity groups, derived from small-scale laboratory studies, may allow important generalizations and predictions. As an illustration of this statement, we consider the general problem of spin-down of rotational motion when the feeding processes are removed (as in a hurricane over land or in a tornado after the funnel has touched the ground and has become detached from the thunderhead). Laboratory studies using a Doppler-laser velocimeter on rotating flows in a finite cylindrical container at large Reynolds number (R) have shown that spin-down of the rotational motion occurs without disturbance of the rotational velocity profile, i. e., a perturbation theory may be used in which all terms smaller than $R^{-\frac{1}{2}}$ are neglected. In the language used by meteorologists, the cyclostrophic approximation applies during the initial phases of spin-down. In the language used by specialists in rotating flow, similarity obtains in the axial direction as in the theoretical models of von Kármán (1921) and Bödewadt (1940). Furthermore, the finite size of the cylindrical configuration turns out to be irrelevant insofar as the slow-down of rotational motion is concerned because the observed tangential velocity profiles during spin-down in small cylinders are completely described by a perturbation theory using as boundary conditions infinite-disk solutions in semi-infinite rotating fluids. The laboratory studies and the perturbation solution describing the laboratory studies show that the characteristic time for spin-down (t) required for the local tangential velocity component to decay to e^{-1} of its steady-state value is

$$t = h/\nu\omega^{\frac{1}{2}} \quad ,$$

where h is the height of the rotating column, ν is the kinematic viscosity, and ω is the initial rotational frequency. The origin of this equation, its laboratory verification, its derivation from a perturbation analysis for large Reynolds numbers, and the apparent applicability of infinite-cylinder boundary conditions to a finite cylindrical configuration, should give us some confidence that the equation may be applicable to hurricanes and tornadoes. We shall now verify this particular use of the above equation.

In both hurricanes and tornadoes, we use Brunt's estimate of a turbulent kinematic viscosity coefficient for air of $10^5 \text{ cm}^2/\text{sec}$. In a hurricane, we estimate the value of R from the relation

$$R = \omega h^2/\nu \sim 1.6 \times 10^4 \quad ,$$

while for a tornado,

$$R = \omega h^2/\nu \sim 8 \times 10^4$$

if we use 10 km and 1 km as typical heights for a hurricane and a tornado, respectively, and use corresponding mean azimuthal wind velocities of 75 mi/hr at a radial distance of 16 km

and 200 mi/hr at a radius of 500 feet, respectively. These calculated values of R are sufficiently large to justify the use of $t = h/(v\omega)^{\frac{1}{2}}$ for hurricanes and tornadoes. Using the specified wind speeds, we find that $\omega \approx 2 \times 10^{-3} \text{ sec}^{-1}$ and 1.1 sec^{-1} for the hurricane and tornado, respectively. The corresponding e-folding times for spin-down calculated from the referenced equation are 17 hours and 5 minutes, respectively, which fall within the expected ranges of values for observed hurricanes and tornadoes. Thus, for the relatively simple spin-down problem of rotating flows, the expected small-scale laboratory predictions appear to be reasonable. At the very least, this modest success suggests that further laboratory studies of spin-down will lead to suggestions for field applications that may conceivably turn out to be useful.

We cannot be certain that small-scale laboratory studies will contribute to our understanding of incipient spin-up, i. e. , to a description of precursor hurricanes or precursor tornadoes. Nevertheless, it again appears likely that the laboratory investigations in a subtle and unpredictable manner may suggest new and useful ideas for implementation in the larger laboratory that is the atmosphere.

C. Research Related to Hurricane Modification and Control

1. Model Building and Field Verification

Comprehensive numerical descriptions of hurricane models are being developed by Rosenthal, Ooyama, and others. These models are used in computer "experiments" in order to simulate the dynamical response of the real hurricane to modification by seeding. Work of this type has been of basic importance in attempts at verifying the efficacy of hurricane-seeding programs and has led some experts to conclude "with a 97 percent-plus confidence level" that seeding has been effective in reducing peak wind speed by fifteen to twenty-five or thirty percent. Peak wind-speed reductions of this magnitude are of considerable economic value since the energy (E) varies as the square of the speed and the loss in economic value roughly as $\exp(E)$.

The current computer "experiments" are not directly tied to separate field observables and, at the present time, make no quantitative use of the very detailed diagnostic information that is supplied by reconnaissance and surveillance flights and by satellite observations. One distinguished scientist has criticized the complete decoupling of the computer programs from immediate field observations as an essential deficiency. Thus, G. F. Carrier and his collaborators have stated after several years of quantitative study that the numerical computer programs are not yet adequate, that a more fruitful approach to understanding hurricane behavior might well begin with a description of the governing physical phenomena, and that there is as yet no overwhelming evidence for the efficacy of the hurricane-seeding program. On the other hand, the available experimental results also permit an optimistic interpretation of the seeding program.

The dichotomy of views on how to develop mathematical descriptions of hurricanes will no doubt be reconciled in time as the numerical programs become more elaborate and the physical approximations more realistic. In this connection, Dr. Myron Tribus, Assistant Secretary of Commerce, should be commended for his efforts at establishing constructive dialogues between that segment of the meteorological community involved in hurricane seeding and fluid dynamicists conversant with the component aspects (e. g. , rotating and boundary-layer flows) of this rich field.

Further work on model building, using the best efforts of all interested groups and leading to early integration of the finer details of current field data into the numerical programs is clearly required if significant advances are to be made in hurricane control.

D. Dynamic Meteorology and Computer Technology

The development of faster computers with much larger storage capacity and with multiple-access stations should be of considerable value in allowing broader-based and more sophisticated modeling of meteorological phenomena, in general, and of hurricanes, in particular.

E. Laboratory Studies

1. Instrument Performance in Highly Adverse Conditions

In reconnaissance and surveillance, the flight instruments and dropsondes are subjected to highly adverse field conditions that may provide radically different environments from those prevailing during calibration. Under these conditions, it is clearly desirable to develop a small supporting group charged with the responsibility of verification of claimed performance of measurement devices and with the development of new and improved instrumental facilities.

An example of promising effort in the field of new instrument development is provided by the introduction of absorption measurements in the Lyman- α region for the determination of total water content.

It would probably be desirable to fund, at selected academic institutions, instrument-development studies relating to the critical parameters needed in the description of hurricanes, tornadoes, and other severe storms. Alternatively, active cooperation could be solicited from a specially-qualified meteorological-instrumentation group at the NBS or in the NWS.

2. Search for Resonances in Coupling Axial Energy Addition into Azimuthal Energy

Hurricanes, tornadoes, water spouts, and fire storms are examples of natural phenomena in which relatively efficient energy-release coupling into rotational motion occurs. In principle, the energy-transfer processes are described by the Navier-Stokes equations, and by the conservation equations for energy and momentum, after imposition of appropriate boundary conditions. In practice, considerable physical insight is required in order to formulate a tractable mathematical problem. An outstanding example of the required physical knowledge is provided by the work of Charney and Eliassen on the influence of cumulus convection in the development of the pre-hurricane depression.

Because of the rich phenomenology of rotating flows and the universal importance of energy coupling into azimuthal motion, a basic laboratory study on the nature of these coupling mechanisms appears to be worthwhile. We may verify the practical importance of this work by the following observations. It is customarily stated that about five percent of the total latent energy of evaporation finds its way into azimuthal motion. Yet the hurricane-seeding program is based on the idea that supplementary energy release at the proper location will decrease the peak wind speeds associated with tangential motion. According to the results of computer "experiments," the desired effect is produced by a very small supplementary energy release. In fact, using Gentry's numbers (April 1970), we may state that a hurricane seeding experiment involved the use of 208 rocket cannisters yielding 120 g of Ag I each, each gram of which precipitated 10^{12} to 10^{13} ice nuclei (under laboratory conditions) in such a way that induced motion produced augmentation of energy release by water condensation by an additional factor of about 85/15. Assuming that the ice crystals have a diameter of about 2μ , the supplementary energy release is about 10^{-8} of the hurricane energy in rotational motion and about 5×10^{-10} of the total latent energy in the hurricane.

The stated sequence of events clearly shows that we need greater physical insight into the coupling processes between heat release and rotational motion.

3. Control of Crystallization and Condensation of Water through the Use of Optimal Seedants

The number of seedants currently used in field applications is relatively small. Although there is an exceedingly rich literature on nucleation phenomenology, the particular problems involved in condensing and crystallizing water over wide controlled ranges of temperature and pressure may well deserve further support in laboratory studies, particularly if proper simulation is achieved of the fluid motion.

4. Studies on Vortex Stability and Vortex Disintegration

Hurricane seeding and spatial redistribution of energy release provide the only active means for control that currently are used. It is not certain that additional research and better understanding will lead to improved methods for effective utilization of the energy stored in a hurricane or tornado in their self-destruction. Nevertheless, the class of phenomena of destructive rotating flows is sufficiently large and of sufficient economic value to justify risk research without immediately foreseeable returns.

Vortex flows require well-defined boundary conditions for maintenance of stability. In principle, these flows destroy themselves when new boundary conditions are imposed. Perhaps a more detailed understanding of unsteady vortex flows will lead to suggestions for new techniques in storm control. Perhaps basic studies directed at this objective will amplify and support the view that seeding is the only feasible attack in achieving hurricane control. In either case, research in this area would appear to be justified.

A graphic illustration of the self-destruction of a vortex flow, after imposition of new boundary conditions, is provided by an example described by Zalovcik, which has been studied at NASA.

5. Controlled Boundary-Layer Growth Preceding Vortex Motion

There appear to be field observations of periodic detachment and reattachment of tornado funnels from the ground. It is unknown whether or not this phenomenon is determined by the bottom-terrain configuration and by interactions between the terrain and the base of the tornado funnel.

The basic problem of the influence of boundary-layer configuration on vortex motion has not been studied and its study may not have a practical impact on tornado, hurricane, or fire-storm control. Nevertheless, this is an area of basic research that should form a part of an integrated adjunct research program relating to deepened understanding of vortex flows.

6. Convective Growth of Large-Scale Atmospheric Motion

The problem of convective growth has been extensively studied, both by fluid dynamicists and by meteorologists. An interdisciplinary status evaluation might prove fruitful, particularly if care is taken to include people conversant with radiation gas dynamics.

Theoretical simulation studies, using techniques developed in combustion theory, may prove of value in understanding the coupling between energy release and fluid motion.

7. Identification of Governing Similarity Parameters in Dynamic Meteorology

Dynamic meteorology is a mature discipline and an especially challenging area of research because of the difficulties involved in performing meaningful, controlled, small-scale experiments and the great demands in interdisciplinary training required for expertise in quantitative analytical descriptions. As in other mature fields of pure and applied science, the experts in meteorology use esoteric language that may be highly confusing to the non-specialist. At the same time, it is apparent that the central field is fluid mechanics and that the central

problems are, therefore, of a type in which highly sophisticated analytical work has been done by non-meteorologists.

A useful mission in broadening our understanding of large-scale phenomena could probably be accomplished by preparation of a readable survey on "governing similarity parameters in meteorological problems."

8. Actual Speeds in Two-Phase Flows (Water Droplets, Ice, Snow, Sondes, etc.)

The central physical assumption in the interpretation of Doppler-radar measurements in two-phase flows relates to the hypothesis that local droplet velocities correspond to local wind velocities. This assumption, and the precise conditions under which it is justified, should be carefully defined. Early work¹⁰ on velocity lags in two-phase flow has been augmented by numerous recently-published papers. The times required for droplets to accelerate to the gas velocity are proportional to the square of the droplet radius and, hence, increase rapidly with droplet size. It is conceivable that some velocity lags occur during heavy rains in the complex flow fields that develop in hurricanes. This problem requires further study, as does the corresponding problem relating to the motion of ice and snow.

For rapidly-falling sondes in inhomogeneous flow fields, it is clearly necessary to estimate aerodynamic transfer functions in order to define local sonde velocities relative to moving air. Definition and application of the aerodynamic transfer function should replace the assumption that the sondes move at the wind velocity.

9. Controlled Introduction of New Boundary Conditions in Vortex Motion

The motivation for this work has been fully discussed under Section VII, C. The supplementary studies proposed here deal with the conceptual development of techniques for imposing new boundary conditions on large-scale atmospheric disturbances.

Interaction between Rotating Flows and Complex Structures; Modeling of Expected Wind Gusts as a Function of the Local Environment

Very little experimental or theoretical work has been done on the complex interactions between large-scale rotating flows and city structures. Inadequate model experiments of this type on fire storms have suggested that these interactions determine the extent and nature of the damage. Analogous and more elaborate studies should be performed in modeling the interactions between hurricanes or tornadoes and ground structures. Perhaps these model experiments will lead to a better understanding of how cities should be designed in order to withstand tornadic and hurricane winds and accompanying short-duration gusts.

Design of Cities to Minimize Losses under Tornadic and Hurricane Conditions

Environmental design and city planning might well form a component of the research suggested in Section VII.

F. Diagnostic Techniques Involving the Use of (a) Nonreactive Chemical Seedants (e. g., SF₆) and (b) Reactive Chemical Seedants

Preliminary attempts at mapping large-scale circulation near and within a hurricane have been made by injection of SF₆ at high altitudes. The compound SF₆ is nearly ideal for tracer studies because tracers should be chemically inert under atmospheric conditions and, furthermore, SF₆ permits quantitative tracer analysis with extremely small concentrations. The field tests indicate feasibility for this type of investigation although no detailed results were obtained. Apparently, some SF₆ was found in spatial regions, where it should not have been. Supplementary tests on SF₆ dispersal in hurricanes are planned and if successful, should provide valuable insight into the nature of the large-scale hurricane circulation patterns.

In addition to inert-material injection (e. g., SF_6), some thought might be given to the possibility of augmenting the diagnostic studies with injection of reactive chemicals such as NO, in which case, distribution of the injectant could be studied in clear air by spectroscopic means (by observing continuum radiation associated with oxidation of NO) without the need for direct sampling of the atmosphere.

G. Simultaneous Measurements of H_2O (c), H_2O (l), H_2O (g), and of Ice-Particle-Size and Liquid-Water-Drop-Size Distributions

Accurate simultaneous measurement of the concentrations of crystalline, liquid, and gaseous water in air, together with quantitative information on particle- and drop-size distributions, is an important fundamental problem in cloud physics in which improvements in methodology and advanced instrument development are required.

In principle, quantitative absorption measurements at properly chosen wavelengths should provide information on total water content, on liquid-water content, on ice content, on effective scattering cross sections, and on particle- and droplet-size distributions. A great deal of experimental work has been done on the measurement of drop-size distributions in sprays by using multiple scattering techniques at a variety of wavelengths with both coherent and incoherent radiation. The magnitudes of the infrared absorption coefficients of liquid water absorption bands and of ice are sensitive functions of the concentrations of temperature-dependent, hydrogen-bonded structures.

It appears likely that a research program directed at the objective of determining phase concentrations, particle- and droplet-size distributions of water by the use of ultraviolet, visible, infrared, and microwave sensors, will lead to more reliable analytical experimental procedures than are currently available.

H. Remote Sensing of the Nature of the Sea State

Both radar and laser techniques have been used to measure the effects of sea-state variations. The distribution of radial velocities of scatterers produces a corresponding distribution of Doppler radar velocities, which results in broadening of the clutter spectrum. The scatterers may be either individual wavelets or wind-blown spray, but a rather strong correlation exists between the sea state and the bandwidth of the clutter spectrum at the lower range of sea-state classifications. Use of the radar techniques suggested elsewhere in this study (see the Radar and Radiometer Panel Report) should include direct sensing of the sea state, and correlations at higher sea-state ranges should be sought. The variation of clutter return with frequency should also be measured.

Visible laser beams have also been used¹¹ to make measurements of sea profile from an aircraft by comparing the phase of a received beam with that of a sinusoidally-modulated, transmitted beam. Functioning at a low altitude (200 feet), such a device has measured wave profiles where the peak-to-trough heights were of the order of 10 feet, and an accuracy of one inch in ripple detection is claimed for the technique. Development of this technique for operation from a hurricane reconnaissance platform would require the investigation of other wavelength regions and increased wave-profile range to match the needs of the hurricane forecaster. As with the radar techniques, it should be possible to adapt equipment simultaneously being used for wind measurements to the task of direct sea-surface sensing. In the case of the laser beam, a change in the modulation technique might be required, but the optical and signal-processing equipment could be quite similar in form.

VIII. SOME THOUGHTS ON TORNADO FORECASTING AND WARNING

A. Satellite and Radar Observations

It has been observed that tornadoes are very likely to occur in regions of the Midwest, where a low-pressure center occurs. This low-pressure center is in a relatively large area, where there is an encounter between (1) an eastward moving mass of cool, dry air; (2) strong southerly winds carrying very moist air from the Gulf of Mexico; and (3) a band of strong, jet stream winds emanating from the Southwest. However, the occurrence of a tornado will be in a small portion of that area in a position which cannot be predicted. Also, the time of occurrence cannot be predicted with any accuracy.

ATS-III photographs have detected (as in the Lubbock tornado) clouds two to three miles in diameter, in which a front between the dry air to the Northwest and the moist air to the Southeast can readily be seen as a cumulus line separating the dark area to the Northwest from the grey area. Jet streams have been located and recorded on Tiros satellite photographs. Thus, it is evident that the basic conditions necessary to give birth to a tornado area can be detected by satellite. It has also been noted that a square- or diamond-shaped cloud is visible in these satellite photographs. This cloud can be of the order of 100 x 200 miles in size, and tornadoes are often spawned under such clouds located in areas discussed above. The "anvil" cloud has been studied by Fujita, who observed cloud displacements on ATS-III satellite photographs and measured cloud velocities and mass outflow from the thunderstorm complex.

The satellite photographs noted above have been taken in the visible region of the spectrum. Such data can be obtained during the day, but infrared photography should be used at night for both forecasting and research. This, of course, does not solve the problem of looking through the precipitation-laden thunderstorm cloud complex to obtain data on the very small tornado itself. The microwave region of the spectrum would be useful if the radiative intensity characteristics (emissivity versus wavelength, scintillations, polarization, etc.) of the tornado were different from those of the surrounding storm.

It would appear that since the tornado is very small spatially that once the region has been pinpointed by satellite, some other platform would be more appropriate for both forecasting and research. The platform would be an airplane, helicopter, trailer-truck, or ground-based; the specific choice could only be made after a system and costing study has been done. This should be initiated.

The measurements discussed thus far are passive. However, microwave radars have long been used for tornado study, and the "hooks" sometimes seen on radar displays are well known. Doppler spectra can be obtained using these radars. However, the beamwidth of a microwave radar is relatively large compared to that of a laser radar. Since the tornado diameter may only be a few hundred feet, when viewed from a distance of about five miles, a beam of milliradian size would yield interesting data. A laser Doppler radar would have such a beam and is therefore a useful tool for tornado research.

Probing the tornado in this manner would yield information on the flow pattern in the vortex region. This is very important in order to determine why the tornado moves in certain trajectories and why it "skips" off the ground at times. The former is needed for forecasting and the latter might be a beginning in learning what the boundary-layer flow is like near the ground under different conditions, in order to do tornado modification in such a way as to keep the funnel off the ground when it is in or near populated areas. It is clear that more research is needed in these areas and this is strongly recommended.

B. Volunteer Wardens and Short-Term Warning

The problem of tornado warning is much more difficult to solve than that of hurricane warnings. Not only is forecasting of individual storms impossible at present, but even the detection and tracking of a storm are extremely inefficient. Throughout the panel discussions of tornadoes, we found that no unique "signature" has been identified except the visual sighting of a funnel cloud by an observer. Even in this case, it is certain that many funnel clouds are reported which do not actually occur, and of course, many of the real funnels are unreported until they strike an inhabited area.

Thus, we have a short-term warning problem that exists after the meteorological warning has been issued for an area of approximately 25,000 square miles. Radars in the area will search it for suspicious-looking echoes, but these have not been able so far to yield consistent sightings of specific storms. Research is clearly needed — this will be alluded to later.

The most obvious short-term approach is to increase the use of that segment of our population which has time available and is looking for significant activity of social benefit, i. e. , retired persons and unemployed adolescents. By devising a proper approach, the NWS could solicit a very large force of "storm wardens," who would attend a short but effective training course in storm identification and receive an official title and insignia of some sort. They should also be equipped with wide-angle binoculars, a weather-net radio, storm identification literature and guides, and any other equipment deemed useful. By choosing observation areas systematically and designating warden posts, each town and city in the tornado areas could be covered on its periphery and in depth, if necessary. Regular shifts would be designated so that no period would be uncovered in case an alert were called. Such networks functioned very well for air-raid warnings in Europe and even in the U. S. (although the latter were not needed). The most important factor is to endow the "storm warden" with sufficient prestige and confidence to introduce considerable accuracy and objectivity into the reports.

C. Corollary Contributions to Tornado Forecasting and Warning

In the longer term, an adequate warning service will begin to use the fruits of tornado research, with all of the tools modern technology can bring to bear. Upgrading of NWS radars to include methods of velocity measurement, use of larger radar antennas, increased use of satellite data, both visible and infrared, — all have a role to play in understanding tornado genesis, growth, and dissipation. Some of these techniques may also lead to new warning systems for specific storms, which can feed much more accurate data to the corps of wardens and the NWS stations that integrate them.

IX. CONCLUSION

This has been a review of the study done by the Research and Novel Measurements Panel. Almost all our effort went into the discussion of current, promising, and research instrumentation. Emphasis was on hurricanes, only one form of severe and hazardous storm. We didn't attempt to tackle the very difficult job of computer modeling, computer simulation, or physical modeling of the real hurricane. This is perhaps an appropriate subject for another summer study.

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SECTION IV

REPORT OF THE RADAR AND RADIOMETRY PANEL

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Airborne Severe Storm Surveillance Summer Study

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I. INTRODUCTION

The overall weather observing system must rely heavily upon both airborne and ground-based radars for hazard detection, mapping, and quantitative measurements. This report deals with the radar subsystems in terms of the required observations and outlines the basic radar approaches to each. We discuss improvements to present observing techniques which can be implemented without major alterations of either the radars or the aircraft, those which can reasonably be accomplished within one year (or by the next hurricane season), and an ultimate system without restrictions on the type of aircraft and with minimum limitations on overall cost of either the vehicles or the instrumentation. Intermediate systems, in which tradeoffs are made to accomplish the major objectives with existing aircraft and with more limited funds, are described and also research and development required to demonstrate the feasibility of not-yet-proven techniques. We define some special-purpose observational systems for research. Finally, the appendices treat a variety of the radar and radiometry problems in greater detail.

II. REQUIREMENTS AND BASIC APPROACHES

Three vital parameters to be observed in a hurricane are:

- (1) Location of the eye and its path;
- (2) Central pressure; and
- (3) Maximum wind.

Next in importance are:

- (4) Eye diameter;
- (5) Radius of maximum winds; and
- (6) The radial profile of wind with distance from the eye.

Of somewhat lesser importance is precipitation intensity, especially in the wall cloud, which is directly related to both the rate of release of latent heat, which drives the storm, and to the updraft strength, which is a measure of the strength of convergence into the core of the storm. More directly, the precipitation intensity is required for flood warnings to coastal and inland regions in the storm's path. Finally, the height of the eye wall and the vertical profile of the horizontal wind as a function of distance from the eye are required to determine the three-dimensional storm structure. These are the primary measurements to which operational radars and their associated processing systems should be dedicated. However, useful auxiliary information should not be discarded if it can be recovered at relatively modest cost.

Just as maximum winds can be derived from a measurement of minimum central pressure,¹ it should be noted that the radar measurement of maximum winds described in the following sections will permit the deduction of minimum pressure.

Implicit in all the above requirements is that the information be made available to the NHC promptly. NHC wants radar pictures every half-hour. In addition, in order to increase the confidence of both the forecaster and the public, it seems necessary to observe both eye positions and maximum winds as frequently as possible, hopefully once an hour, and more frequently as the storm approaches landfall. It is in the crucial 12- to 24-hour period prior to landfall when the first warnings for evacuation and hazard protection must be made. Clearly, reports of eye positions, maximum winds, and flood-producing rainfall made at

6-hour intervals are inadequate. This is especially true when either the path or the intensity is changing rapidly. With 3- to 6-hour intervals between observations, as is presently the case, the forecaster is prone to doubt observations which show sharp deviations from the previous trend. This would not be so if variations were confirmed in a continuous sequence of observations at half- to one-hour intervals.

Because storms threatening land will often be within range of sensitive ground-based radars during the critical 12- to 24-hour period prior to landfall, and because such radars can readily make the required observations with greater accuracy and continuity than can airborne systems, we place great emphasis on the use of coastal and island radars. Existing land-based radars can be used much more effectively than they are now without major modification or cost. In addition, improved radars with Doppler velocity measuring capability and data-processing and communications facilities are required.

Airborne radar systems exhibit a disappointingly wide gap between existing capabilities and the needs. Indeed, the Navy decision to abandon the C-121 aircraft in favor of the P-3 has required reduction in the antenna size of the APS-20 radar from 17 to 12 feet and elimination of the APS-45 height finder, thus greatly weakening the already limited capability. While the condition of the aging C-121 evidently forced this compromise, the deleterious effects on the reconnaissance program are regrettable.

To avoid such compromises in the future, we propose a long-range program which permits growth in three stages:

- (1) Immediate improvements to present reconnaissance radars prior to the next hurricane season;
- (2) Enhanced capability for the intermediate time period, involving continued use of present-day airframes; and
- (3) Development of a full-capability reconnaissance system of the 1980's.

In planning the growth program, we consider the ultimate required performance and major system components needed to achieve that level of performance.

III. THE RECONNAISSANCE SYSTEM OF THE 1980's

A. Location, Navigation, and Hazard Avoidance Radar

Since the reconnaissance aircraft must locate and navigate to the target storm area, there is an absolute requirement for a forward-looking search radar. Moreover, the need to traverse dangerous storms during the mission and in the terminal areas requires a hazard avoidance system. This implies the need for a continuous picture of the storm area at least in the 180° forward sector. The need to map great distances of heavy rainfall dictates wavelengths of 5.5 cm or longer (see Appendix A). The resolving of significant storm elements or gaps two to four nautical miles in size at ranges of about 150 n.mi requires a horizontal radar beamwidth under 2° . (Although wider beams may be tolerable for navigation and hazard avoidance, storm mapping and measurement demand a smaller beam.)

B. Mapping and Measurement Radar (MAMER)

The precise location of the eye, the measurement of the radial profile of winds, the mapping of reflectivity and/or rainfall quantitatively requires a narrow-beam radar operating at a long enough wavelength to be substantially free of attenuation. Appendix A indicates that neither X- or C-bands are suitable for this purpose, but experience with the APS-20 and WSR-57 10-cm radars in hurricane mapping strongly suggests that horizontal beamwidths greater than 2° are unacceptable. Similarly, vertical beamwidths greater than 2° or 3°

cannot be tolerated, both for reasons of Doppler spreading under conditions of large wind shear and aircraft motion, and because of beamwidth averaging and sea-clutter interference (Appendix B) in quantitative reflectivity measurement. Except for "Guppy-like" modifications, current aircraft size considerations limit antenna dimensions to ten to twelve feet, both horizontally and vertically. We are therefore forced to the shortest wavelength in the allocated S-band region, or 9 cm. Quantitative Doppler and reflectivity measurements and minimal sea-clutter interference also require very low sidelobes.

For general storm mapping, a region out to 250 miles should be displayed. A PRF less than 330 pps would give this range unambiguously. Quantitative velocity and reflectivity will be meaningful only to ranges of 100 to 150 n.mi. An unambiguous velocity range of about 30 ms^{-1} (i.e., ~ 60 knots) is required, where radial speeds in excess of $\pm 15 \text{ ms}^{-1}$ will be folded, but these ambiguities can be resolved by the on-board meteorologist through the use of a combination of displays; range-velocity (constant azimuth), azimuth-velocity (constant range), and velocity versus radial distance from the storm eye, and the continuity of radial speed components in azimuth and/or range, starting at a region where the radial speed is known to be in the first unambiguous velocity interval. The Doppler spread in any one pulse volume, thus, must not exceed the unambiguous velocity range. In extreme cases, e.g., large vertical wind shear, a 30-ms^{-1} velocity range may be exceeded, and the true mean Doppler velocity may be lost. However, this is expected to be a relatively rare event. A 30-ms^{-1} range is therefore thought to be adequate and sets the Doppler mode PRF at 667 pps, which has a maximum unambiguous range of 125 n.mi. Two PRF's are required, one for general mapping to 250-n.mi range, the other for Doppler measurements.

If the vertical beamwidth is less than 2° , this radar can be used for height-finding, but with limited accuracy. Further details of the mapping and measurement radar are presented later.

C. Height-Finding Radar

Present Navy WC-121 aircraft have an APS-45 (3.2-cm) height-finding radar (1.2° vertical by 3.1° horizontal beamwidths), which provides useful vertical cross sections of storm heights in general and the height of the eye wall in particular. The availability of a 9-cm search radar with vertical beamwidth of 2° or less, capable of scanning in elevation, would lessen the need of an independent height finder. Should a 2° vertical beamwidth prove too large, an X-band coaxial horn could be added to the basic search radar system to provide a $2/3^\circ$ beam in both dimensions. The vertically pointing radar described below also provides superb height information in a vertical cross section along the flight path.

D. Winds Below (Above) Aircraft Radar (WIBAR)

Until we have a 9-cm coherent, scanning Doppler with narrow beamwidth capable of velocity measurements anywhere in the field of view, we must anticipate either overflight of the hurricane or penetration. In addition, the need for winds as a function of height either below or above the aircraft, or both, will require much greater vertical resolution than is available with the 2° beamwidth search system, even when the latter becomes operational. Thus, we anticipate the need for a downward- and/or upward-looking Doppler radar capable of horizontal wind measurements at intervals of approximately 1000 ft.

The technique proposed to meet this requirement is a modification of the Velocity-Azimuth Display (VAD) wind measurement technique of Lhermitte and Atlas (1961)² and extended by Browning and Wexler (1968).³ This method has been used extensively and with

great success on ground-based Doppler radars to measure horizontal winds and convergence as a function of height. In essence, it involves scanning the beam through a cone in space and measuring Doppler velocity versus beam azimuth at a multiplicity of ranges and corresponding heights. In aircraft use, the single scanning beam would be replaced by a time-shared four-beam system with two beams tilted off-vertical fore and aft and two others port and starboard.

Appendix C-A shows that the largest source of errors in the four-beam WIBAR system is the inhomogeneity in the vertical velocity of the target scatterers from beam to beam. This and the need to have detectable scatterers in the four beams (essentially) simultaneously dictates that the beams not be tilted more than about 15° from the nadir. This tilt provides a compromise between the desired homogeneity of the sampled region and the larger tilt angles, which would be more sensitive to horizontal wind motions.

The need to penetrate great intensities of precipitation over a depth of 18,000 ft. from the melting level down to the surface in the hurricane eye wall (two-way losses in excess of 60 dB) appears to preclude the use of X-band wavelengths (see Appendix A), unless one is willing to accept the loss of wind data in the eye wall below heights of about 1000 ft. On the other hand, Doppler velocity spreading and sidelobe distortions of the spectrum in regions of non-uniform reflectivity are magnified in proportion to the beamwidth, which increases with wavelength for a fixed-size antenna. Thus, one would like to compromise with acceptable rainfall attenuation and not excessive beamwidths on the short-wavelength side of C-band. Finally, there are persuasive cost reduction arguments to consider a 9-cm WIBAR system, which would be virtually free of rainfall attenuation and also permit the time-sharing of the transmitter and receiver of the mapping and measurement radar.

Considering the various conflicting demands on the WIBAR system, we are inclined to recommend an independent, short-wavelength, C-band system in the long term, and a 9-cm time-shared radar for the intermediate term.

It is to be noted that the WIBAR system will also provide Doppler information on the sea return. We are confident that this will furnish greatly improved Doppler navigation data, if only because the signals from the sea surface are range-gated and not contaminated by weather clutter, as in present CW or interrupted CW Doppler navigators. However, a better navigation system would be Omega, Loran-C, inertial or combination inertial/Omega, so that the navigation function of the WIBAR radar should be considered only as a backup.

Once we learn more about the Doppler spectrum of sea return as a function of azimuth, elevation angle, and wind speed, we can reasonably hope that the WIBAR system may also measure sea state and possibly surface wind speeds. However, these must now be considered as research problems.

E. Vertically Pointing Doppler Radar

Measurement of updraft and downdraft velocities would be most valuable operationally in the eye-wall region and for research purposes elsewhere in the hurricane. In thunderstorm, hailstorm, and tornado research, there is also a critical need for a draft measurement radar system which can overfly the storms without hazard and return for sequential observations. Lhermitte (1970)⁴ has discussed the utility and design of such a radar, and also treats the measurement of raindrop-size spectra and turbulence. This system could also measure the height of the melting level as indicated by a reflectivity maximum (i. e., bright band) and a Doppler velocity transition from snow to rainfall speeds. If operated at C- or S-

band wavelengths, penetration would be adequate to provide a reflectivity cross section in the vertical plane along the flight path with excellent indication of storm tops and bases.

While a fully instrumented, vertical-beam radar (with power time-shared from the WIBAR system) is recommended for the long-term reconnaissance system, useful though less precise information on updrafts and the bright band is available from the WIBAR radar for the intermediate term. Storm top data is also obtainable. Accordingly, the intermediate reconnaissance system need not have a vertical-beam Doppler radar.

IV. INTERIM APPROACHES

A. Dual-Beam Pseudo-Doppler Wind Radar

In the transition period to the availability of any fully coherent Doppler wind measuring radar, the urgent need for wind data can be met by the use of the incoherent (pseudo-Doppler) dual-beam technique of Atlas and Wexler,⁵ as elucidated by Lob⁶ and Glover and Bishop.⁷ A simplified approach for the required measurements has been described by Atlas and Srivastava.⁸ While the accuracy to be expected is less than that from a fully coherent Doppler, dual-beam modifications can be made to existing incoherent airborne and ground-based radars. It is recommended that the dual-beam modifications be made to the APS-20 (10-cm) and AVQ-30 (5.6-cm) airborne radars and to the WSR-57 ground-based radars. The dual-beam approach should also be considered for the APN-59 3-cm weather radar, if combined with a modification permitting downward tilting of at least 45° from the horizontal.

In the case of the WSR-50 10-cm ground-based weather radars, we have every reason to expect useful measurements of hurricane wind speeds as a function of radius from the eye by means of the dual-beam approach. Thus, there is some urgency to implement the method on all coastal radars. In addition, when the two beams are made to overlap by about a half-beamwidth, the method should provide reliable tornado detection. Since the WSR-57 can be expected to be in operation for at least another 15 years, and operational coherent Doppler radars are not yet on the horizon, we strongly recommend the use of the dual-beam technique for tornado detection and hurricane wind measurement.

B. Echo Motion Velocity Measurement

A Moving Target Indication (MTI) technique known for years – the so-called area MTI or change detection MTI – has been implemented by Fujita¹² for the measurement of wind velocities. The equivalent of a time-lapse motion picture is made by projecting six to ten successive display photographs taken at two-to ten-minute intervals in an endless loop. When the photographs contain discrete identifiable echo elements, an analyst can derive vector velocity from the synthesized and speeded-up motion. The method is highly recommended for immediate use on all coastal FAA and National Weather Service radars.

In the case of airborne weather radars such as the APS-20 and AVQ-30, the approach is somewhat complicated by relative aircraft motion. The aircraft navigator might be used to provide a fixed latitude and longitude display along with a true North reference. If not, the hurricane eye can be used as the reference during a 30- to 60-minute velocity measurement period. (This is the approach used by Fujita on photographic records of the APS-20 display in Hurricane Debbie, 1969)

In order to facilitate the identification of conservative and thus trackable echo elements, the display photographed (or video-recorded) should indicate echo maxima. A "maxima" display is easily implemented by straightforward electronic differentiation of the received signals.

Until coherent Doppler or pseudo-Doppler techniques are available, we strongly recommend the implementation of the echo-motion velocity measurement technique for use by an on-board analyst.

V. MICROWAVE RADIOMETERS

A. Vertical Temperature Profiling

Present hurricane reconnaissance operations rely upon a dropsonde to obtain a vertical profile of temperature and humidity in the eye and a measure of central pressure. The feasibility of remotely sounding the temperature profile in (essentially) clear regions by a microwave radiometer in the 54-GHz oxygen absorption band is discussed elsewhere. The technique has been used successfully from the ground in an upward-looking mode⁹ and has been proposed by Staelin (1969)¹⁰ for use on a satellite. The principal hazard to successful airborne radiometry in the eye region appears to be the possible presence of absorbing water clouds in the lower 5000 to 6000 regions. If the clouds are sufficiently thin or have low water content, the method should permit temperature profiling with vertical resolution of about 3000 ft and temperature accuracies of about 1 to 2° C. Integration of the vertical temperature profile should then permit computation of surface pressure. Continuous profiles across the eye should also provide the location of the pressure eye.

In the immediate future, this approach must be considered as a strong candidate for remote temperature profiling and determination of central pressure. We recommend that research and feasibility testing be conducted on the microwave radiometric temperature-profiling method before it is considered for operational use.

B. Sea-Surface Temperature Mapping

Since sea-surface temperature plays a strong role in the genesis of hurricanes and in predicting their intensification or decay, there is both an operational and research requirement for measurements of this parameter. Fortunately, the areas of interest are often in the clear or nearly clear, where dense clouds and rain will provide minimal interference with the microwave radiometer. Measurement from higher altitudes with an infrared radiometer is not considered applicable because of interference from even thin water clouds. The approach is straightforward and well proven. A scanning microwave radiometer at 3-cm wavelength with a scanning angle of $\pm 60^\circ$ to port and starboard would permit the mapping of a swath about 23 n. mi wide, centered on the aircraft track from a height of 40,000 ft.

We recommend the use of a scanning microwave radiometer in the 2-to 4-cm band to map sea-surface temperatures.

VI. AUXILIARY SUBSYSTEMS AND TECHNIQUES

A. Chaff¹¹

The use of time-released chaff to dispense a series of chaff packages at 2000-to 5000 ft intervals below the aircraft in echo-free regions outside the rain bands and within the eye would permit the on-board mapping and velocity measuring systems to determine winds in these regions. This would be especially valuable for determination of the wind eye, even with present-day airborne radars. Thus, the use of chaff as an auxiliary tracer is recommended.

B. Dropsonde wind and sounding system

The need for temperature and humidity soundings below aircraft levels in regions where remote radiometric techniques fail, for wind data where precipitation tracers are absent, and for the measurement of central pressure, sets the requirement for a modified dropsonde system such as that developed and successfully tested by Beukers Laboratories. Dispersal of

approximately ten such packages at about 10-mile intervals on the radial traverse through the eye would provide exceedingly valuable data which is not now available. Moreover, except for wind data in regions of detectable precipitation or chaff, we cannot anticipate any other method of obtaining vertical temperature profiles in regions of dense clouds or precipitation.

The major remaining problem in the Beukers system is the simultaneous location and telemetry from a multiplicity of sondes. But this is clearly within the state of the art.

It is important to note that this technique will provide basic meteorological data in other reconnaissance missions not involved with hurricanes or precipitation.

We recommend the Beukers Laboratorie's dropsonde wind and sounding system for temperature, humidity, and wind soundings below aircraft.

VII. IMPROVEMENTS TO CURRENT SYSTEMS

A. Simple Modifications

We list here possible modifications to existing systems that could be made rapidly and at relatively small cost. The individual changes can be made in a year or less, but the whole group might take years.

1. Range Normalization / Compensation

Radar returns vary by 40 to 60 dB in signal strength with range. This variation contains no useful information, but increases the difficulty of presenting or quantifying the radar information. A simple technique called Sensitivity Time Control (STC) in which receiver or display gain is varied in time (range) has been used for years. For precision quantitative use, step changes with calibrated attenuators in steps of 10 to 20 dB may be sufficient if much additional quantitative processing is done before display.

2. Amplitude Compression / Wide Dynamic Range Receivers

Typical oscilloscope displays have dynamic ranges of 10 to 20 dB between saturation and the minimum discernible signal. When oversaturated, additional problems can occur. Displays for many radars are designed to be optimum for minimum target detection, a design of little utility for simultaneous measurement or display of very large and very small targets, as one has with weather radars. Even with $1/R^2$ sensitivity time control, weather echoes vary by 40 to 80 dB, particularly in the heavy rains of hurricanes. Modern radars routinely use "logarithmic" or other wide dynamic range receivers in which large signal variations are compressed to a range commensurate with display capabilities or processing and measurement techniques. For quantitative measurements, it may be desirable to use a more sophisticated receiver.

3. Special Receiver Processing and Displays

Signal information other than amplitude might be used to lessen the need for dynamic range. For example, contours or maximum signal regions and their location derived from derivatives or thresholds regardless of signal strength may be had, in the range dimension only, with simple circuits. More comprehensive information would require storage and possibly some digital logic.

4. Position and Angle References

To register successive radar observations to a ground location and reference direction, absolute references are needed only to about ± 1 mile (1σ) and ± 5 milliradians (1σ) (i. e., 1 mile at 200 m). Relative references ought to be on the order of ten times better over assumed observation intervals from 10 to 1000 seconds. Inertial and/or radio navigation reference systems are readily able to meet such standards except for the extremely

small velocities (i. e., 200 meters in 1000 seconds is 0.2 m/sec.) A cut-off of about 1 m/sec appears realistic.

5. Calibration and Standardization

The data gathered by a weather-mapping radar should be normalized to cross-section density to the extent feasible. Absolute cross sections may not be needed to much better than about ± 3 dB, and considerable effort will be needed to calibrate conventional radars any better even by frequent use of standard targets such as calibration spheres. Special radars may be expected to hold a 1-dB calibration. Test and precursor signals recorded with the data should make it possible to maintain relative cross section over many hours to about 1 dB. It must also be recognized that in making Doppler spectrum measurements, pulse-to-pulse amplitude variations (much smaller than 1 dB) create instrumental noise which might be removed by measurement and subtraction or by discrimination of the single-sideband Doppler shift.

The ultimate goal of presentation of weather radar signals normalized to cross-section density is limited, at least for real-time quick-fix displays by several more difficult problems. These are:

6. Aircraft Displays and Photography

Given the improvements in radar data quality outlined above, aircraft displays of the resultant data in real time should have greatly improved qualitative and quantitative utility to pilots, navigators, and meteorologists. Particularly if only qualitative use is to be made of the data, it will be desirable to provide these displays and to provide scope photography for later analysis.

7. Video Recording and Transmission

Full-bandwidth recording (1 MHz or more) of wide-dynamic range radar data with its necessary references can be made on magnetic tape. Even without additional processing, such data should be transmittable on 1 to 10-kHz circuits using existing slowdown techniques on the basis of one picture every 15 minutes (900 sec) gathered in about 9 sec (100:1 slow-down). A simple tape loop, coherent reference, and machine slow-down procedure should be adequate for transmission of a fully quantified picture both for high-quality real-time presentation and for immediate quantitative analysis.

Less quantitative data for even narrower-band transmission could be obtained by video scope photography. Data compression and display problems will be further complicated if data from many elevation beam positions must be combined or multiplexed for display and for transmission efficiency. A compromise in range resolution consistent with average angle resolution (i. e., 3 to 5 miles) can be made in order to reduce data rates, but this might well limit the performance of velocity measuring techniques.

8. Noncoherent MTI Wind Velocity Measurement

The dual-beam noncoherent MTI technique for determining winds from beats between rain and surface echoes in noncoherent radars can almost certainly be implemented in existing radars. Some care will be necessary in data registration and in removing instrumental data fluctuations. Otherwise, the technique will be limited to the range dimension where the samples compared are essentially simultaneous and generated in common. With appropriate instrumental care, two- and three-dimensional velocities may be measurable.

9. Time-Lapse Velocity Measurements (Change Detection MTI)

It has been reported that persistent, observable weather structures exist and travel

with their surrounding air masses with sufficiently high probability that two- and three-dimensional wind velocities can be adequately measured by time-lapse comparisons. The radar data quality improvement outlined above and, in particular, the provisions of high-quality position and angle references over times as long as 1000 seconds and in velocity to about 1 m/sec should make it possible to implement these techniques in near real time in the aircraft and on the ground. It may be necessary, however, to use several sets of time separations over the range of wind velocities and resolution cell sizes, for instance, 1-, 2-, 5-, and 10-minute lapse times.

VIII. DATA COMMUNICATIONS

Only a small fraction (1%) of the available radar and other data can be used effectively in near real time on the ground. This implies that communications bandwidths of the order of 1 to 10 kHz plus the use of simple data storage and time expansion, e. g., a 100:1 slow-down video recorder, can handle the real-time data. Modern coded communications techniques are available that can maintain high data quality for such transmissions so that the data quality improvements outlined above will be maintained in ground presentation.

Where line-of-sight or satellite path transmission is feasible, no major technical problem seems to exist in providing near-real-time ground data of high quality and adequate data rate. Line of sight should exist within at least 200 miles of landfall or path along a coast. The remaining data for post-storm analysis can be recorded on tape.

When it is necessary to communicate beyond line of sight with high quality, and when more complex processing of larger amounts of data are desired for ground presentation, the problem is more difficult. To further reduce the quantity of, but retain the quality of, associative storage with multiple pulse averaging, Doppler processing, time-lapse processing might be used, but unfortunately, none of these seem appropriate for the short term. The possibility of data processing on the ground served by a wideband 10- to 100-kc high-quality, line-of-sight link should be investigated seriously.

For communication beyond the horizon, HF radio may be adequate when data expansions of about 1000:1 are used and data selected to allow high-quality pictures every few hours. Even this data rate may be preferable to waiting for the aircraft to return to base.

If lower data quality is acceptable, scope photography and facsimile transmission or slowed TV transmission could be done via HF links. Scope photography compensates, in part, for the loss of quantitative data because of the multiple-pulse integration achieved. This alternative may in the short run be superior to other methods.

IX. IMPROVED UTILIZATION OF GROUND RADARS

The application of advanced techniques, with the exception of time-lapse measurements, for determining rain echo motion from airborne radar, seems on the whole to be outside the category of immediate improvements to the existing radar equipment. These techniques should be easier to apply to ground-based radars for evaluation in severe storm situations.

A single radar located on the U. S. coast might reasonably expect to get interesting hurricane data once every several years. A tornado alley radar might do better (say, once a year). To increase experience frequency, more radars might be modified, or alternatively, mobile equipments might be used. Mobile units may not have merit for tornado studies, but an S-band radar with a 20-foot or larger antenna that can be set up in four to eight hours could be very useful for hurricane studies.

The mobile radar must use range normalization, amplitude compression, calibration, positional accuracy modifications, special signal processing, etc. With this system, time-lapse detection should be easily done.

The ground radars may be coherent or it may be feasible to modify them for true coherence without extreme difficulty. Transmitter coherence, an expensive design, is by no means necessary, and, in fact, might limit discrimination against signals from an ambiguous range interval. A coherent oscillator operating at a frequency close to or related to that of the incoherent transmitted signal can be used instead. The transmitted phase and also the target range and phase can be read and stored relative to the coherent oscillator. The appropriate transmitted phase can then be subtracted even though several radar pulses may have been transmitted in the intervening time. All of this can be done in digital form or data can be stored for diagnostic processing.

X. FIXED AND TRANSPORTABLE GROUND-BASED RADARS

Doppler techniques for measuring hurricane winds, described in this report largely in the context of airborne measurements, can also be used for ground-based measurements. In fact, few of the difficulties encountered in the airborne system, such as limited antenna aperture, compensation for aircraft velocity, etc., would be encountered with a ground-based system. The one disadvantage of a ground-based system relative to an airborne system for hurricane use is that it is not likely to be near a hurricane, except if the hurricane passes near or over a coastal region where the ground system is located. There are a considerable number of coastal WSR-57 radars and FAA radars such that probably all hurricanes striking the U. S. would be visible by one or more of these stations for about twelve to nineteen hours before landfall. However, there is reason to believe that the necessary modifications of WSR-57 radars for Fujita noncoherent Doppler processing would not be unreasonably difficult. Tornado detection would be enhanced by such a method.

We propose the development of a fleet of about five weather radars capable of sophisticated Doppler processing of hurricane winds, which are transportable by air and are also self-propelled. These radars could be flown to the coastal area threatened by a hurricane, driven over highways to the most advantageous viewing position (perhaps several hundred miles from the airport of delivery), and be set up rapidly (mainly assembling a large foldable antenna of the order of 30 feet in diameter). These radars should have their own power sources, perhaps turbines, their own data-processing facilities, and good facilities for communicating data back to NHC. Hurricane-proof radomes or, alternatively, occasionally, expendable antenna dishes should be considered.

The quality of measurements of these transportable coastal radars should be such as to give, in the last ten hours before landfall, an essentially complete picture of the hurricane winds, turbulence, rainfall, and possibly sea state. It is recognized that ten hours is too short a warning to provide time for maximum preparation of property to withstand hurricane winds, but the good information on winds would be extremely useful nonetheless. In fact, such information might most usefully be employed to aid in decreasing the area under alert as soon as possible, freeing emergency facilities for use where they will be more needed, or freeing them from the expense of being on alert status.

To resolve wind direction ambiguities, at least two and preferably three radars should observe each hurricane. If one wished to account for the possibility of simultaneous landfall of two hurricanes, five of these transportable stations would be needed.

Insofar as the area hit by a hurricane may well be without good communications for some time after the catastrophe, some consideration should be given as to whether the transportable radar site could serve as a communications terminal after the storm. It would to some extent be a "hardened facility" in any case.

XI. A UNIFIED APPROACH TO UPGRADING PRESENT AIRCRAFT RADARS

The acquisition, reduction, and transmission of reconnaissance data with the present fleet of military aircraft is complicated by the variety of navigational, radar, communications, and meteorological equipment in use. One way of expediting the handling of both the on-board use and remote transmission of data is to provide a small programmable digital computer and input-output equipment required to digitize the airborne sensors to process the data, to display the results, and to generate records suitable for transmission to NHC. Computer displays will be provided for the observer to monitor the processed radar data and the computed results of dropsonde, D-value, and other meteorological observations. The digital computer has a reasonable growth potential to accommodate changes in sensors or in the data requirements for transmission to NHC. The "minicomputers" currently offered by industry have an almost unlimited "add on" capability.

Standardized analog circuit packages or modules will be used to supplement the existing functional components of the radar to ensure that the features, such as wide dynamic range, sensitivity time control, power monitors, etc., currently not available, can be incorporated in any aircraft used for weather reconnaissance. It is recommended that a power splitter be used to extract an IF signal at a point in the present IF chain that does not degrade the performance of the system; i. e., after the signal has been amplified to overcome the noise contributions of the mixer and first stage. A wide-dynamic-range, multiple-gain amplifier or a logarithmic amplifier can be used for obtaining a dynamic range of greater than 70 dB. If multiple channels, each having a different gain, are used, a multiplexer will be required to commutate each channel into a high-speed A- to-D converter. On the order of 100 range gates spaced two n. mi apart will be sampled during each PRF interval. Analog techniques are available if spatial smoothing is desired prior to digitizing. A digital integrator will be used to accumulate the amplitude values obtained in each range sample for 25 to 500 radar pulses, after which the data accumulated in the integrator will be read into the storage in the computer memory, together with a time lag and such parameters as the position of the antenna, aircraft heading and position, and the parameters logged to indicate the radar performance. The noise temperature of the radar, the peak output power, and other pertinent quantities derived from monitoring circuits in the radar will be used to normalize the data in the subsequent processing.

After accumulating the data from an azimuth or an elevation scan, the computer will perform the transformations needed to reformat the data in geographic coordinates. A storage display will provide the meteorological observer with a contoured display which can be used as a check on the system performance, as well as for navigational and meteorological purposes. A suitable storage medium such as a magnetic or a perforated paper tape will be used for permanent storage of the radar data. Radio transmission of the data to NHC can be accomplished by one of the many digital data techniques which are available.

In addition to processing the radar data, the computer can readily handle the acquisition and reduction of the data developed from dropsondes, thermometers, barometers, liquid water content, altimeters, and other sensors. The use of the integrator to reduce the bandwidth of

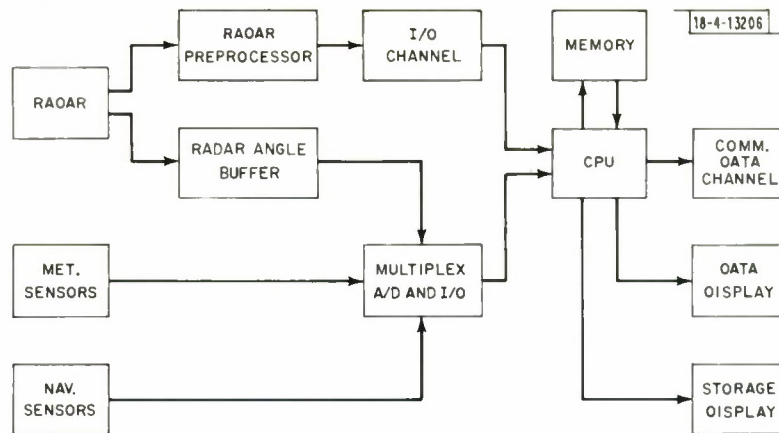


Fig. IV-1. Radar digital processing conceptual block diagram.

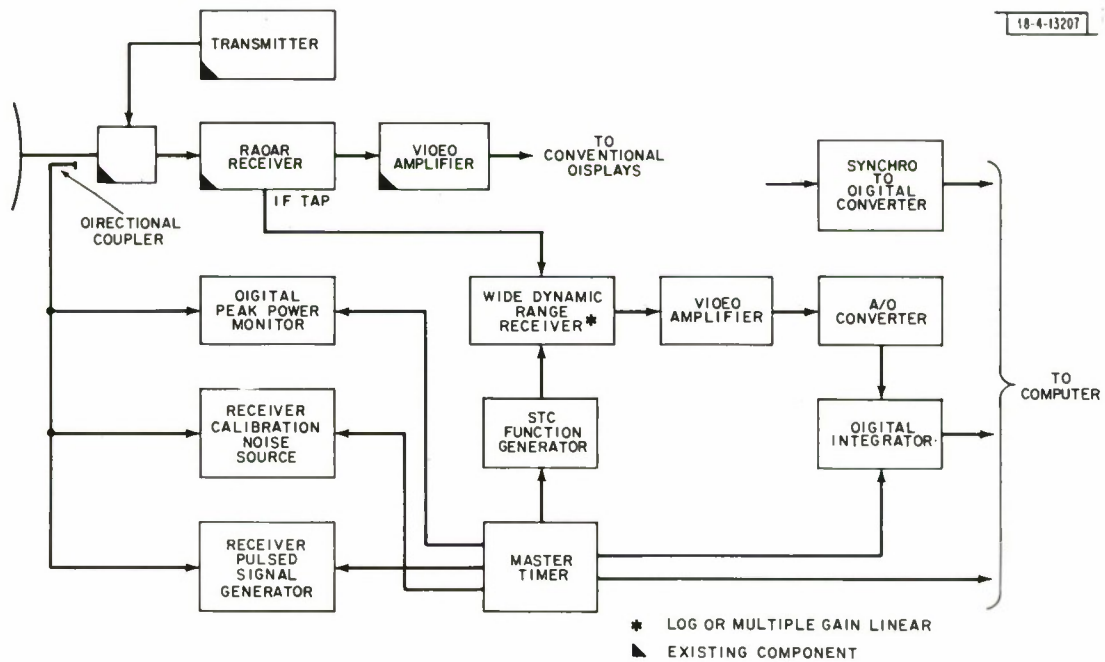


Fig. IV-2. Implementation of radar-digital processing interface.

the radar data ensures that the acquisition of other data can be maintained without interruption.

The detailing of the system requires extensive knowledge of the interfaces of the radars and the sensors used in each aircraft. A gross block diagram, Fig. IV-1, outlines the main features of the digital processing system. The universal radar coupling package, which incorporates the improved dynamic range receiver and system calibration equipment is described in Fig. IV-2.

Conceptually, the integration of all the radar upgrading into a unified package is attractive because it will ensure that the cross calibration of radar sensors of the same type, which is now uncertain, will be accomplished in a systematic way. The processing of the data by an airborne computer to produce the radar maps sent to NHC will further eliminate some of the variability experienced in the present system. In addition to these advantages, the radar system performance will be monitored continuously, and degradation in the transmitter power or receiver sensitivity will be reported and accounted for in the analysis of the radar signals.

The task of upgrading the radars of reconnaissance aircraft will be expedited by the use of a common package which can be interfaced with any of the existing equipment. Compatible coupling devices for the RF, video, timing, and servo signals are readily available. By combining all of the new equipment in one package with a suitable power source, it should be possible to realize considerable economy over the costs that would be incurred in making custom modifications of the existing equipment.

The radar interface to the computer will be contained in the new package. A digital integrator will relieve the computer of the requirement of handling wide-bandwidth video signals. The data rate will average about 100 four- or five-bit words at a rate on the order of 10 cycles per second; therefore, the computer can be used continuously for data logging, computing, and display generation.

XII. DISCUSSION OF LOCATION, NAVIGATION, AND HAZARD-AVOIDANCE RADAR

The three jobs envisioned for this radar are: (1) to aid in locating the center of the storm and in aligning the flight path with respect to it; (2) to produce a PPI map indicative of the spatial distribution of rainfall intensity, which is also useful in deriving the horizontal wind field; and (3) to provide Doppler measurements of the radial component of wind as evidenced by the motion of precipitation. The range requirement, together with the attenuation properties of precipitation force the choice of an S-band radar (or nearby frequency). At higher frequencies, the attenuation becomes prohibitive, while at lower frequencies, the beam which can be produced becomes too broad to discern important features (the eye) at great distance. Nine- to ten-cm wavelength seems the best choice. The examples given assume 9 cm.

A. Antenna

The two possibilities which seem most promising are: (1) a 12-foot circular dish mounted in the nose of a modified WC-130 aircraft, providing a 2° beam with coverage in front of the aircraft to 90° to either side; or (2) an array in a somewhat less modified nose, providing coverage from 45° to the right of forward to 45° to the left of forward, supplemented by two similar arrays, one on either side of the tail, to provide a total of 270° of coverage, also with a 2° beam. Both are expensive, reflecting the basic conflict between a narrow beam and good penetration ability.

The following discussion concentrates on the 180° coverage dish.

B. Locating the Storm Center

The radar is pulsed at 333 pulses/sec. This provides an unambiguous range of 250 n. mi. The actual range performance will be substantially less due either to the masking of precipitation by sea return or to the curvature of the earth. Which of these two factors comes into play depends on the aircraft altitude and on the strength of the precipitation return at the range at which sea clutter becomes important. As will be seen below, a 12-second scan is envisioned. Doppler processing is going to require a PRF higher than 333 pps. A possible system for satisfying the navigator's need and the Doppler need is to use a PRF suited for navigation on some scans and a PRF suited for Doppler on other scans. Another scheme worthy of consideration is based on using several nearby frequencies to separate range ambiguities while permitting Doppler processing at a high effective PRF.

The 2° beam should permit resolving a seven-mile eye at 200-n. mi range if not masked by sea return. For a storm intense enough to have such a small eye, the spiral rain bands should be well enough defined to further aid the definition of the center of the storm.

Sea clutter at short range due to reflection by the sea seen by antenna sidelobes can be a major problem. The downward sidelobes of the antenna must be well controlled, even at the expense of some increase in the upward-looking sidelobes. The sidelobes whose angle from the horizontal is substantial, say beyond 30°, should be less important since they can be eliminated by range-gating (this is, however, dependent on flight altitude).

The 180° horizontal scan limits the display of the eye to only the first half of each traverse of the storm.

The navigation display should be a PPI presentation with range normalization. A scope face larger than presently used would probably be helpful.

Within about 100 n. mi of the eye, doppler measurements will be made, calling for a higher pulse repetition frequency, and thus, a shorter unambiguous range. The navigator should see the shorter-range PPI map, which can be made using the higher PRF, rather than none at all. It is to be noted that if an array is used to steer the beam, it is possible to time-share between a low PRF scan for a long-range navigation display and a higher PRF for Doppler measurements.

C. Rainfall Mapping

In either the long-range or short-range mode, the information which is displayed for the navigator should also be available to the meteorologist as a quantized, contoured display on a large screen. Smaller scopes slaved to the meteorologist's scope should be automatically photographed at a regular rate for research, and photographed with Polaroid film for on-board wind analysis, using the Fujita technique described below. The contour display should indicate 3- to 5-dB differences in rainfall rate. It is expected that the dish could rotate at five revolutions per minute. This rate is appropriate for the Doppler measurements, as will be seen. The meteorologist's scope must have an indication (such as a grid) of the fixed ground position. This is necessary to permit precise alignment of photographs at successive time instants, needed for the Fujita technique. The automatic camera recording a frame about once every two minutes is for research use. At a minimum, each frame should have enough identifying numbers to correlate that frame with other research data recorded on the flight.

The meteorologist's scope should be able to display other information under control of a computer. One possibility is to get better than 180° coverage by using reflectivity information remembered from previous portions of the flight path, but present behind the aircraft. This

could also be used to augment the 180° coverage for the navigator. A possible variation of this is to use the information from range gates describing a swath not too far in front of the aircraft and perpendicular to the flight path to provide one scan every twelve seconds, of a reflectivity map to either side of the flight path for the entire flight. This could be recorded on a strip chart or other hard-copy device (e. g. , facsimile) for use after the flight.

D. Winds from the Fujita Technique

The Fujita technique¹¹ attempts to derive wind velocities by tracking the motion of recognizable features of the storm, such as areas of especially intense precipitation. Polaroid pictures taken about two minutes apart can be placed (carefully aligned) on a rotatable drum (preferable to a rotating table because it uses less space) and illuminated stroboscopically. The intense rain-generating cells will appear to move as the drum rotates. If the alignment of the pictures compensates for the different aircraft position at the time of each picture (the reason for the grid mentioned above), the motions of the rain cells should represent the winds in which they occur. The wind vectors can be marked on a transparent overlay, or indicated by other means. This technique should require considerable practice and, though actually demonstrated, must still be considered research. If proven useful in practice, it should be replaced by an improved system based on a TV-type display of equally-spaced PPI frames, saved on a disk, electronically aligned, with some means of electronically overlaying the estimates of wind velocity. The winds measured by this technique will at least serve as a check on the Doppler measurements. If the Doppler techniques prove to be unsatisfactory for any reason, this provides a backup.

E. Doppler Winds

At a given instant, radar Doppler measurements only indicate velocities projected on a vector radial to the aircraft. Actual wind velocities can be estimated using either radial components toward several different centers (when the aircraft has moved a substantial distance) or by assuming that velocities are constant in a region large enough to be seen by two radial beams at an angle with one another, as in the downward-looking VAD technique, or by using a priori knowledge of the wind direction to deduce velocity from the radial component measured. Except for the third category of decision, we expect that it is best to transmit the radial wind field to NHC at intervals and allow interpretations to be made there. However, along a range-azimuth locus for which the rainbands are observed to be along the direction of the aircraft, Doppler velocities may be approximately equated to the actual velocities.

For Doppler measurements, the PRF is increased to 667 pulses per second. For this PRF, ranges greater than 125 n. mi appear "aliased." There are several reasons why signals from these ranges need not be too disturbing. First of all, there is the decreasing signal received from greater range. Second, the strongest echoes are those near the center of the storm, and it is when the aircraft is near the storm center that the Doppler mode is especially valuable. A third, probably not significant, protection is that at ranges beyond 100 miles, the 2° beam will be wide enough to be larger than at least some of the "targets," which thus scatter only part of the beam energy.

The Doppler velocity ambiguity of a 9-cm radar at 667 PPS is 30 m/sec. This implies that some hurricane wind velocities will span several complete velocity ranges. The ambiguities must be resolved if useful information is to be obtained. The continuity of the atmosphere is an important clue in resolving ambiguities. Also, velocities which can be assumed perpendicular to the radius to the aircraft may be assumed small and, hence, in the unambiguous velocity

range. It is necessary to account for the aircraft velocity component in deriving wind velocities.

We believe the ambiguities should be resolved by a computer program running in an on-board computer. It is also possible to do the signal processing needed to extract Doppler in the on-board computer. There will be situations in which there is not enough information available to resolve velocity ambiguities. One such situation occurs when the 2° beam is broad enough to encompass a volume in which the wind shear is too great to permit a well-defined spectral peak. It is even possible that two distinct velocity peaks could occur, separated by as much as or more than 30 m/sec. It is also possible that two regions where the winds differ by more than 30 m/sec in radial component are separated by a region free of precipitation. This would make it impossible to use the continuity of the atmosphere to resolve ambiguity.

A third problem will arise when a sharp peak of velocity due to a sidelobe of our aliased range gate overwhelms the broad velocity peak associated with a region of turbulent wind.

For these reasons, consideration should be given to a system perhaps using a higher PRF with hopped frequencies, to increase the unambiguous velocity range as much as possible.

There are several system configurations which could be adopted for the signal-processing task. One, which computes Doppler in real time on the fly, requires a feasible but expensive special-purpose fast Fourier transform device. However, it is not necessary to compute a velocity map every twelve seconds. Another configuration involves saving the complete sampled bipolar video from a twelve-second scan on a disk (digital) to be processed during many subsequent scans. Assuming about 90 range gates by 90 azimuth gates (about 1.3 n. mi and 2°), a disk to hold the 36 samples (see below) per range gate is not excessive. The data rate into the disk (a datum about every 25 μ sec) could be difficult, but can easily be overcome by using the on-board computer as a buffer for the disk, saving about one-third of the range gates for each azimuth (or some smaller fraction) and accumulating the entire picture in the course of several scans. A third possibility, which avoids the disk, is to save and compute the Doppler for about 400 to 500 gates per scan, covering all the gates in about 16 to 20 scans.

At 5 rpm, the antenna covers a 2° beam in 1/15 second, or 44 pulse times. For rapid computation of a discrete Fourier transform, the best highly composite number near 44 is 36. Thus, 36 consecutive samples of the bipolar video for each range gate would be saved for each Doppler velocity computation. This permits a resolution of about 1.5 kts, which is comparable to the spread to be expected due to air speed (Doppler spread due to finite beamwidth, and due to rotation of the dish at 5 rpm).

Our own preference is for choosing, on each twelve-second scan, to save in a computer the sampled bipolar video for 90 azimuths, for gates number n , $n + 30$, $n + 60$, and special, where "n" advances by 1 each scan for 30 scans, covering the whole 90 ranges in that six-minute interval, and where "special" is a function of azimuth determined by the meteorologist so as to form a locus which crosses the rain bands where the velocities may be presumed to be directly toward or away from the aircraft. The Doppler velocities computed for the three constant range arcs per sweep would be used to construct a radial velocity map. The Doppler velocities computed for the special range-azimuth locus should be displayed to the meteorologist (on still another display) so that he can get a good idea of the profile of wind velocity versus radius from the center of the storm.

Using a simple, fast Fourier transform algorithm, a 36-point discrete Fourier transform program requires about 180 complex multiplications and associated operations. There are

moderate-sized computers available today which can perform these basic operations in 50 μ sec, so that a complete 36-point DFT on 360 gates would consume 3.25 seconds on such a computer. Allowing for other operations, such as data acquisition, windows, complex magnitude, computing velocity averages, resolving ambiguities, formatting displays, etc., it appears that such a computer could have time to spare in a twelve-second scan. Some additional time could be saved by omitting Doppler computation where the reflectivity is below some threshold.

Storage of 360 gates \times 36 points for computation and for the 8100 radial velocities comprising the entire wind velocity "map" are each moderate amounts of memory, not really requiring storage beyond a computer memory. However, the likelihood is that a moderate-size disk could profitably serve a number of functions, especially regarding the maintenance of meteorological radar displays, so that it would be a recommended part of the computer system. The vibrational environment of the airplane may be a severe problem with regard to a disk storage system.

F. Vertical Wind Profiles

If the dish has some ability to tilt in the vertical dimension, there is a distance in front of the aircraft (about 50 miles) for which Doppler processing can give information about the variation of wind with altitude. Beyond 100 n. mi, the beam sees virtually the whole storm, and this is impossible. Nearer than 20 miles, the required tilt of the antenna may be excessive, especially for high-altitude flight.

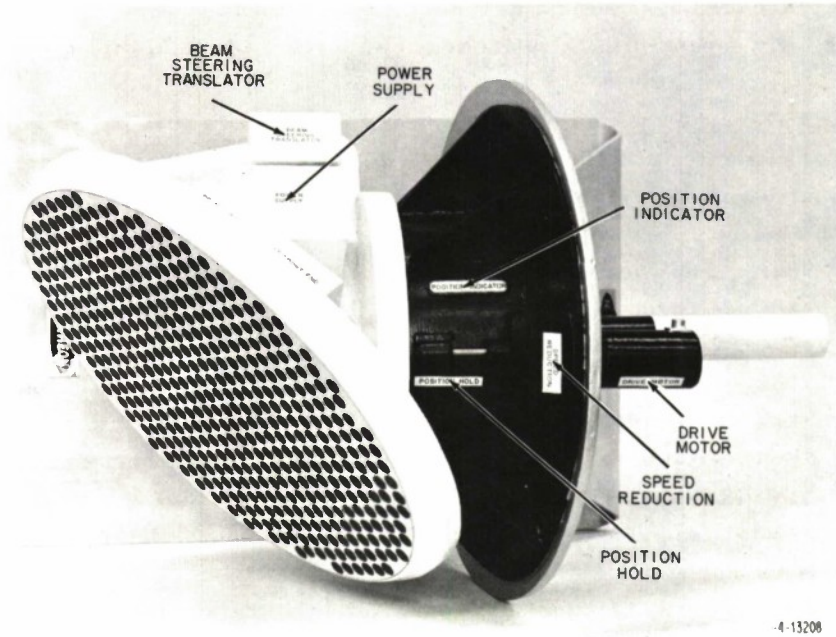
G. Implementation

1. Near-Term: For the near term, the AVQ-30C radar will be the navigation radar. Reflectivity data from this radar is too corrupted to be an indication of rain intensity, which is useful. However, the navigator can be presented with a convenient screen, and it (the picture) should also be available to the on-board meteorologist.
2. Mid-Term: Facilities for transmitting the scope picture to NHC and for using the Fujita velocity technique on board should be added.
3. Far-Term: This includes modification of the aircraft to carry an S-band radar with a large enough dish to be useful.

XIII. AIRBORNE ARRAY RADARS FOR WEATHER SURVEILLANCE

Demonstrated technology enables us to build a variety of airborne array radars at wavelengths from the 25- to the 1-cm bands, and arrays having numbers of elements of 5000 or more and having sensitivities (average power-aperture area product) 20 dB greater than any of today's airborne radars. The basic reason that this technology has not been widely applied is that both initial unit and final unit costs are much higher than for conventional radars, even though they are still modest compared with aircraft development and operating costs. Justification of both the increased performance and higher cost of airborne array radars has been lacking and it is not clear that airborne weather surveillance is likely to justify such development. Nevertheless, airborne array radars are likely to be developed for other purposes in the next five to ten years and may be inexpensive enough to use for weather reconnaissance experiments in the near future or to use operationally a few years hence.

One multi-function airborne array, jointly funded by the Air Force (Wright Field) and Raytheon (MSD) operates at 1-cm wavelength, has a fixed nose-mounted array, and employs flexible high/low frequency pulse Doppler waveforms. Commercial development costs for a modest airborne array radar such as this (without most of the normal government contracting



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Fig. IV-3. Mock-up airborne array.

restraints) are in the \$5-10 million category. A first-of-a-kind, large, airborne array radar having 10 to 100 kW average power and 200 to 400 ft² aperture area in the L- and S-bands would probably cost \$20-\$40 million for very large radars. A laboratory such as Lincoln, which is already highly competent in phased-array technology should also be able to design and build individual array radars at a fraction of these costs, using the many available subsystems such as transmitters, computers, receivers, displays, etc., together with developed technology from earlier array radar programs.

There are substantial potential advantages for an array radar solution for the airborne weather reconnaissance problem.

A. Aperture Size

Weather radar has historically chosen high microwave frequencies in order to minimize radar antenna size, weight, and cost. This approach is appropriate for some weather-avoidance, isolated, low systems, but is inappropriate for observation of large-scale, high-rain-intensity weather phenomena such as hurricanes or for extensive and severe frontal storm systems. Even at C-band (5 GHz), the attenuation over a 200-km path with 16 mm/hr average rain would be about 40 dB. It is clearly necessary to use at least S-band wavelengths to penetrate severe storms, and to have the possibility of making quantitative measurements. The aperture size at 3 GHz to provide barely useful angular resolution at 200 to 400 km, to say nothing of the desired resolution, requires a large aperture. A 2° beam about the maximum acceptable width (10 km @ 300 km) would require about a 10-foot aperture. A 0.5° azimuth beam would be far better at these long ranges. The required 40-foot aperture is reasonable as a fixed side- or top/bottom-mounted array on some types of aircraft at the sacrifice of forward coverage. A radar like this with 10 kW or more average power (100 joules/sample energy) will detect a 1 m² target with 15-dB signal-to-noise ratio (one sample) at about 200 km. Assuming an 8 × 10¹⁰ m³ resolution cell at 400 km, the radar should very adequately detect rains as light as 1 mm/hr ($\eta_v = 6 \times 10^{-14} r^{1.6} \lambda^{-4} (m^{-1}) r (mm/hr), \lambda(m)$). This sensitivity is likely greater than necessary so that a pulse of only 10 joules/sample could be used.

A 10-foot-diameter aperture can be mounted in many locations, including the nose of large aircraft. Let us now compare S-band reflector alternatives and the advantages of an array solution.

B. Multiple-Function Adaptability

If a ten-foot aperture is acceptable for all sensor purposes and a nose-mounted radome of compatible size and length can be installed on the aircraft with due consideration of aerodynamics, weight and balance, structural, and visibility, this location will provide radar visibility in all directions except the rear quadrant. It can thus serve for both the wide-angle surveillance function, as well as the other radar sensor functions which may be desired. Even a reflector antenna radar in a nose radome can view up to 45° aft of broadside and in all directions around the aircraft axis, with a circular aperture only slightly less than the radome diameter. The price is an extraordinarily long radome.



Nose Coverage

Utilizing array scanning to $\pm 60^\circ$ from the aperture axis, mechanical scanning can be reduced to a one-gimbal axis, yet maintain coverage at all angles except approximately the rear quadrant. A Raytheon antenna design configuration of this type is shown. It can be scaled to a 10-foot S-band aperture. A pair of fixed faces in the nose oriented about 30° from the nose and from vertical could also maintain horizontal azimuth coverage 20 to 30° aft of 90° and view the region around the nadir as well as dead ahead.

The three desired weather reconnaissance functions, broad area surveillance, near-vertical wind layer velocity measurement, and pilot/navigator assistance, can all be done at S-band (3 GHz) with the 10-foot aperture size and sensitivity needed to perform the surveillance function. The use of the array beam steering allows rapid compensation for aircraft motion to be performed electrically at a large reduction of the size and weight required for mechanical compensation. Most search and beam-sharing functions can also be done electrically, limiting the use of mechanical motion to relatively slow function or coverage sector changes.

XIV COMMUNICATIONS

A. Communication Needs

There are three kinds of communications requirements for which recommendations are made. There should be two-way voice communication between NHC and the aircraft. There should be provision for timely one-way transmission of two- and three-dimensional field quantities such as radar maps, from aircraft to NHC. Finally, there should be provision for one-way transmission of point- and profile-type data, such as temperature at flight level.

B. Satellite Relay

We must expect distances of more than a thousand nautical miles between NHC and the aircraft, as a routine matter. Since HF radio is subject to fading and interference due to the frequent variations in the state of the ionosphere, a reliable communications link should make use of a satellite relay. This should use a frequency between about 100 and 500 MHz, based on considerations of available signal-to-noise ratio with a nearly omnidirectional antenna. One satellite could provide a communications relay for the entire Atlantic and Caribbean hurricane surveillance area.

A synchronous satellite is 27,000 miles high. Antenna pointing is not economical from a moving aircraft. However, a synchronous satellite will remain at least about 60° in elevation over an area 4000 miles in diameter. The aircraft could be provided with an upward-looking antenna with about a 70° beamwidth. This should see the satellite from all reconnaissance locations without the need for pointing, provided the aircraft remains in level flight or nearly so. The satellite's high elevation angle also provides a protection against multipath problems.

Until a multipurpose military communications satellite is available at the proper station, LES-6 could be used.

C. Data Rate

Using a vocoder, which is a speech bandwidth compression device, intelligible all-digital speech can be transmitted at 2400 bits per second. This is compatible with satellite bandwidths, — that is, a satellite relay can provide a few 2400-bit-per-second channels. We are talking about one channel each way. With digital communication, the clarity of the received speech no longer depends on the distance between sender and receiver. However, our fundamental reasons for going digital are based on the desire to transmit not only speech but a wide variety of different types of data as well.

D. Reasons for Voice Communication

Almost all voice communication could be replaced by teletype communication, except for the human factors. In fact, we can well imagine that the voice path from NHC to aircraft – but not from aircraft to NHC – could be a teletype link. However, on the aircraft, the teletype introduces an additional source of delay and confusion between NHC and the data. Further, we need the voice rate for other data, as we shall see.

Effective instantaneous communication is needed for (a) fastest possible transmission of high-priority data; (b) requests for explanations, additional data, revision of flight plans; (c) verification of questionable data, and discussion; and (d) communication of unexpected phenomena or difficulties.

E. Vocoder Properties and Requirements

A vocoder achieves bandwidth compression by measuring speech parameters, transmitting them, and synthesizing artificial speech from the received parameters. There is no use made of the "silent" periods of the speech. Nor is any use made of the fact that one of the parameters, the laryngeal frequency, is itself "silent" for much of the time during active speech. Thus, a considerable amount of digital data can be transmitted over a vocoder speech channel, if it can afford to wait for these silent periods.

It is important to emphasize some special requirements placed on an airborne vocoder system. Extraction of the laryngeal frequency is classically a difficult problem and aircraft noise will make it an impossible problem unless (a) a noise-cancelling dynamic microphone is used on the aircraft, and (b) a high-quality pitch detector is used.

There is no reason why one need be limited to the use of existing HY-2 vocoders for this communications task.

In testing a vocoder system for the purpose envisioned here, one should use phonetically balanced (P-B) word lists to determine system intelligibility, rather than the more popular sentence intelligibility tests. This is because in reading data lists, context will be of rather little help in determining what was said.

F. Data to be Transmitted by Voice

Some data which should be voice-transmitted include the fix of the storm center, and whether it is a radar center, pressure center, or wind center, the central pressure and whether it is at altitude or from a dropsonde, the maximum winds, location of maximum winds, eye diameter, peculiarities of eye geometry, height of the eye-wall cloud and of other significant cloud structures, and presence of tornadoes, gustiness, turbulence.

G. Computer Formatting of Field Quantities and Profiles

Almost all of the sensor data requires some computer processing, even if in the case of some sensors this processing consists of little more than assembling observations taken over a period of time. In the case of radar data, there is Doppler processing, removal of ambiguities, signal averaging, and quite a few other steps. Furthermore, data must be sent back to NHC with different priorities. For example, sea-surface temperature measurements would not be as important as profile of wind along flight path. We propose that a computer format all these data and transmit them with appropriate identifying prefixes to NHC computers, which will sort them, save them in archival stores, display them to NHC personnel, and make the data available to other computers.

Passing the data through computers has other advantages. One is that modest data compression can be attempted. A data set collected along a line (range gates from a radar, airplane

wind speeds, etc.) may be expected to show more low-frequency components than high, and if probabilistic coding is employed (fewer bits for the likely values than for the unlikely values), it is not unreasonable to assume that 3:1 reductions in total number of bits might be achieved.

Note that the present aircraft procedures call for exactly this technique — with all profile data, only "significant levels," meaning those for which there is a change in slope, are radioed back to NHC.

H. Transmission Time of Typical Data

We consider a radar reflectivity map made with the 2^0 beam, 1-1/3 n. mi range resolution, and 250-n. mi range. With 2^4 gray levels, the picture will require 68,400 bits, or 29 seconds of transmission time, assuming no compression.

The radial component of winds with the same resolution for 2^7 velocities and 125-n. mi range requires 56,700 bits, and 24 seconds transmission time. Both of these quantities should be transmitted about every half-hour.

The downward-looking Doppler velocities as a function of altitude every 1000 feet and every 3 seconds with 7 bits/meas. over 45,000 feet require 105 bits per second during the course of the measurement.

Most of the meteorological variables like temperature and pressure need to be measured only once in five miles, representing a minute or more of flight, and show little change from one measurement to the next. Thus, the data rates associated with these data will be miniscule, representing perhaps a few seconds of transmission time in a half-hour. The sea-surface temperature is a field measurement (roughly a 5-mi x 5-mi grid), but again, the variation from one observation to the next should be minimal so that the data rate associated with this parameter is extremely small. The same comment applies to radiometric profile measurements in clean air.

I. NHC Use of Data

Obviously, a computer is required at NHC to receive, decode, and present all the data. In addition, a number of annoying quirks must be removed from the data. Several data will have been measured by more than one sensor, and the data must be compared. Some data will come from repeated measurements by the same sensor, and these data give clues to the variability of the storm. An important problem is the profile data collected over periods of an hour or more, so that meteorological parameters at one end of the track may have changed significantly from the measured values by the time measurements are made at the other end of the track.

Computers at NHC should ultimately employ experimental hurricane models able to use real-time, real-world data. None of the existing models (other than track forecasts) use real-world data. It is likely that effective models will require computing power not available at NHC. For this, the "network of computers" concept will ultimately provide a possible solution.

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APPENDIX A

Limitations on the Choice of Parameters Imposed by Rain Attenuation

A. Basic Considerations

In choosing the appropriate frequency for airborne weather radars, a compromise must be made between the better resolution and sensitivity obtainable at high frequencies, and the loss of signal due to rain attenuation, an effect which can become severe at high frequencies.

The requirements for a horizontally viewing radar are that the resolution be good enough to depict the eye and eye wall while the aircraft is still well outside the storm, at a range of approximately 200 km. For quantitative measurements of precipitation water, the attenuation should not exceed 2 to 3 dB. For locating the eye and navigation, it is necessary that the precipitation all around the eye be clearly detectable.

For a vertically-pointing radar, precipitation should be detectable from the height of the plane (9 to 10 km) down to one or at most 2 km above the surface. For Doppler measurements, a signal-to-noise ratio of 15 dB is desirable.

B. Attenuation as a Function of Frequency and Rainfall Rate

Computations of attenuation at various frequencies have been made by R. K. Crane (TN 1970-5, Lincoln Laboratory, M.I.T.) from drop-size distributions measured in Miami, Florida. The general frequency dependence is summarized in Table IVA-I. Attenuation in dB km⁻¹ one-way is given by $A = \alpha R^r$ where R is the rainfall rate in mm hr⁻¹.

Table IVA-I

Parameters in Attenuation Formula for Various Frequencies

<u>Freq. (GHz)</u>	<u>α</u>	<u>r</u>	<u>RMS error</u>
2.80	.000407	1.00	9%
6.00	.00342	1.17	
8.00	.00677	1.12	29%
9.30	.0104	1.12	27%

Values in Table IVA-I are somewhat higher than those presented by Atlas (Advances in Geophysics, Vol. 10), which were based on earlier and less extensive drop-size measurements. Crane's values are used in these computations because the Miami data are considered more representative of hurricane precipitation. Measured values of attenuation by precipitation are often higher than computed ones (for example, see Nathanson, 1969, Radar Design Principles, page 197). This result may be attributed to an underestimate of the precipitation rates in the experiments, as the most intense rain often occurs in cells of small dimensions which may be inadequately sampled by the gauges.

C. Hurricane Model

A hurricane model described by J. Simpson ("Hurricane Modification Experiments," Proc. Hurricane Symp., Am. Soc. for Oceanography, Publ No. 1. 71-81, 1966) suggests a precipitation-free eye 10 to 20 km in diameter, bounded by a wall containing several large rain cells with diameters of about 5 km and rainfall intensity as great as 150 mm hr⁻¹. There is also heavy general rain, about 10 mm hr⁻¹ in the eye wall region but outside of the intense cells. (Observations have been made of 25 to 50 mm/hr even outside the convective cells.) The spiral band structure extends outward from this center to about 150 km. The bands are roughly 30 km in breadth with rain rates of 2 or 3 mm hr⁻¹. Within the spiral bands are a

number of small convective cells (1 to 2 km in diameter) with rainfall rates on the order of 50 mm hr⁻¹.

A radar viewing horizontally might have to penetrate four or five rain bands altogether, as well as the eye wall on both sides of the eye.

D. Computations of Attenuation at Different Frequencies

The frequencies listed in Table IVA-II are in various bands available for government airborne radar operations. The attenuation values are computed from the formula $A = \alpha R^{1.1}$, the values of α being obtained from those in Table IVA-I by logarithmic interpolation.

Table IVA-II
Attenuation Coefficient for Selected Frequencies and Rainfall Rates

Freq. GHz	λ cm	R(mm hr ⁻¹):	A (dB km ⁻¹ , one-way)			
			150	50	10	2
2.8	10.7		0.12	3.6×10^{-2}	6.2×10^{-3}	9.6×10^{-4}
3.2	9.4		0.19	5.6×10^{-2}	9.8×10^{-3}	1.5×10^{-3}
4.2	7.1		0.37	1.1×10^{-1}	2.0×10^{-2}	3.0×10^{-3}
5.3	5.7		0.68	2.0×10^{-1}	3.5×10^{-2}	5.4×10^{-3}
8.8	3.4		2.5	7.5×10^{-1}	1.3×10^{-1}	2.0×10^{-2}
9.4	3.2		3.0	8.5×10^{-1}	1.4×10^{-1}	2.2×10^{-2}

If it is assumed that a horizontal radar beam has to pass through one of the intense cells in the eye wall and through five outer spiral bands, the distances it must travel through rainfall of various intensities are roughly those in Table IVA-III. The associated attenuation is also tabulated.

Table IVA-III
Two-Way Attenuation in dB through Various Parts of the Model Hurricane

Portion:		Eye Wall		Spiral Bands	
Freq.	Distance (km):	Cells	Other	Cells	Other
GHz	R (mm hr ⁻¹):	150	10	50	2
2.8		2.4	.12	.36	.29
3.2		3.8	.20	.56	.75
4.2		7.4	.40	1.1	.90
5.3		13.6	.70	2.0	1.6
8.8		50	2.6	7.5	6.0
9.4		60	2.8	8.5	6.6

It is clear that at any frequency, attenuation in the intense eye wall cells exceeds that in any other portion of the storm. Since the eye and eye wall are the most significant regions, this portion must be penetrated for any useful observation. For quantitative measurements of the precipitation water content, an S-band radar is imperative. For detecting the position of the eye, C-band should be adequate since there should be sufficient heavy precipitation beyond the eye to be detectable even with 15 or 20 dB of attenuation. Computations in the previous study (Lincoln Laboratory TN 1970-5) showed that the AVQ-30C radar could

detect precipitation with a Z-value of $40 \text{ mm}^6 \text{ m}^{-3}$ at a range of 180 km if there is no attenuation. With 20 dB of attenuation, the reflectivity would need to be 100 times as large, or 4×10^3 . This corresponds to a rainfall rate of 6 mm hr^{-1} . The AVQ-30C has a transmitter peak power of 75 kw and a beamwidth of 5.2° between half-power points. A C-band radar with greater gain or more power would detect lighter rainfall with the same amount of attenuation.

With 50 to 60 dB of attenuation, an X-band radar would probably not be able to detect the eye from outside the hurricane.

The results of these computations are in agreement with those obtained by the ASD Hurricane Model Computations.

For the radar which points at 15° off the vertical, the required range is the same as the flight altitude. We assume this to be 30,000 ft, or 9 km. Two-way attenuation for 9 km and also values of the radar reflectivity factor Z are in Table IVA-IV, for X- and C-band frequencies. The relation $Z = 380 R^{1.24}$, as computed from the Miami raindrop data, is used.

Table IVA-IV
Radar Reflectivity Factor Z ($\text{mm}^6 \text{ m}^{-3}$) and Two-Way Attenuation
for 9-km Path in Various Rainfall Rates

<u>R (mm hr^{-1})</u>	<u>10 Log Z</u>	<u>Attenuation</u>	
		<u>9.5 GHz</u>	<u>5.3 GHz</u>
150	52.7	54	12
50	46.8	15.3	3.6
10	39.3	1.5	0.6
2	30.6	0.4	0.01

The reflectivity values increase by 22 dB from the light to the heaviest rain. The 12 dB of attenuation at 5.3 GHz would certainly not interfere with detection at such a short range. At 9.5 GHz, the signal from the heaviest rain would be 28 dB weaker than that from the light rain because of the large amount of attenuation. Since the maximum winds occur in the eye wall region, the VAD radar must be able to observe this region. If an X-band radar is used, it must have sufficient power to accommodate these large amounts of attenuation.

E. Limitations Imposed by Resolution

The effects of attenuation become increasingly severe as the wavelength becomes shorter. However, since the size of the dish which can be mounted on an aircraft is limited, any advantage associated with a longer wavelength is paid for by the broader beamwidth associated with it.

Table IVA-V shows the beamwidth between half-power points for parabolic antennas with 12- and 16-foot diameters. Figure IVA-1 gives the breadth of the beam as a function of range.

Table IVA-V

Beamwidths between Half-Power Points for Parabolic Antennas
with 12- and 16-Foot Diameters

Wavelength	3.2 cm		5.7 cm		8 cm		9 cm		10 cm	
Frequency	9.5 GHz		5.3 GHz		3.75 GHz		3.33 GHz		3.0 GHz	
Antenna Diameter	16 ft	12 ft	16 ft	12 ft	16 ft	12 ft	16 ft	12 ft	16 ft	12 ft
Half-Power Beamwidth	0.45°	0.6°	0.8°	1.1°	1.1°	1.5°	1.3°	1.7°	1.4°	1.9°
Gain (55% Efficiency)	51 dB	49 dB	46 dB	44 dB	43 dB	41 dB	42 dB	40.5 dB	41 dB	39 dB

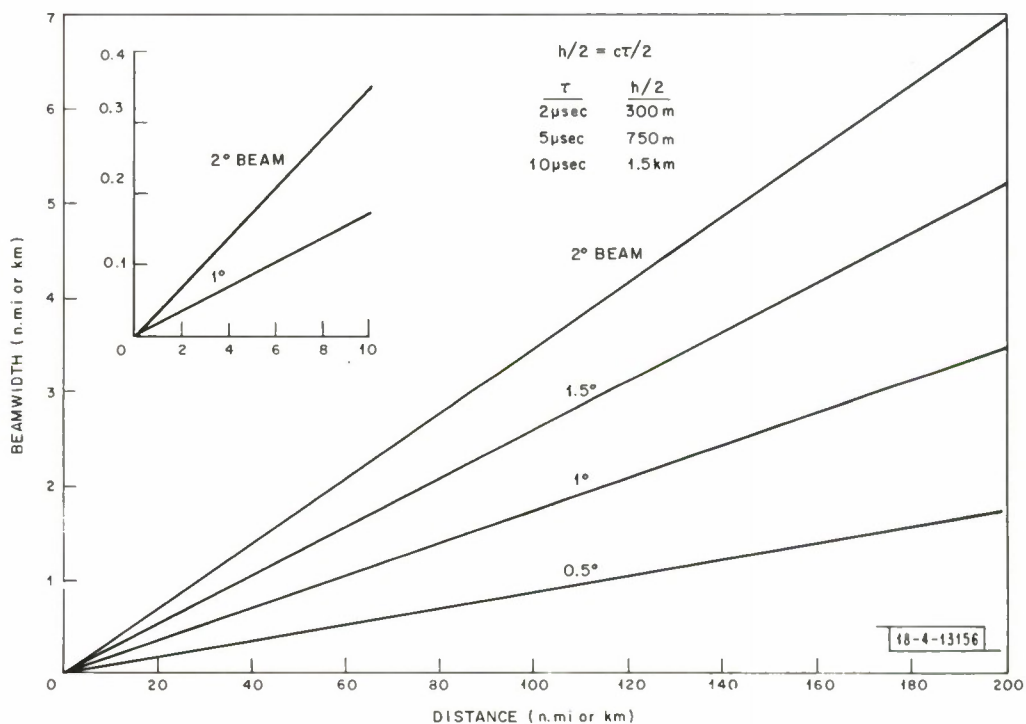


Fig. IVA-1. Breadth of beam as a function of range.

APPENDIX B

Sea Clutter

Airborne weather radars will detect signals scattered both by rain and by the sea surface. The relative magnitude of the rain and sea scattered returns may be estimated when the frequency, beamwidth, antenna height, and antenna pointing angles are known. The scattering cross section for rain is given by

$$\sigma_R = R^2 \frac{c\tau}{2} \int_0^\pi \int_0^{2\pi} g^2(\theta, \varphi) \beta_R(\theta, \varphi, R) \sin \theta d\theta d\varphi \quad ,$$

where

- σ_R = scattering cross section due to rain
- $g(\theta, \varphi)$ = relative gain function of the antenna
- $\beta_R(\theta, \varphi, R)$ = backscatter cross section per unit volume of rain
- c = velocity of light
- τ = pulse length
- R = range to center of resolution cell.

For a Gaussian-shaped antenna beam symmetrical about the pointing direction and for β_R constant over the beamwidth of the antenna,

$$\sigma_R = R^2 \pi c \tau \beta_R \int_0^\pi e^{-2\alpha\theta^2} \sin \theta d\theta \quad .$$

For an antenna with a half-power beamwidth less than 5° ,

$$\sigma_R \approx \frac{R^2 \pi c \tau \beta_R}{2} \int_0^\pi e^{-2\alpha\theta^2} d\theta^2 = \frac{R^2 \pi c \tau \beta_R}{4\alpha} \quad .$$

Now, $\alpha = \frac{4 \ln 2}{\theta_h^2}$, where θ_h is the half-power beamwidth

and

$$\sigma_R = \frac{R^2 \pi c \tau \beta_R \theta_h^2}{16 \ln 2} \quad .$$

For rain, β_R is related to the meteorological parameter Z , for frequencies below 10 GHz by

$$\beta_R = \frac{\pi^5 Z |K^2|}{\lambda^4}$$

where

- Z = sum of the 6th power of the drop diameters for all drops in the unit volume
- λ = wavelength
- $|K^2|$ = is a factor related to the dielectric properties of water and is approximately unity.

Using these relationships,

$$\sigma_R \approx \frac{R^2 \pi^6 c \tau \theta_h^2 Z}{16 \ln 2 \lambda^4} \quad .$$

The scattering cross section for sea clutter, is found from the per-unit area scattering cross section of the sea surface integrated over the area viewed by the radar and weighted by the antenna pattern of the radar. For a pulsed radar operating near grazing incidence to the sea surface, the effective scattering area is given by the intersection of the surface and the volume defined by the beamwidth and pulse length.

$$\sigma_s \approx \frac{c\tau}{2 \sin \psi} \int_0^{\infty} g^2(y) \eta(y) dy$$

where

- ψ is the angle between the direction of propagation of the incident wave and local vertical at the sea surface
- η is the scattering cross section per unit area
- y is the distance along the surface normal to the direction of propagation of the incident wave.

The sea clutter is maximized when the antenna is pointed at the surface such that the peak of the beam intersects the surface in the range interval of interest. In this case, $y = R\theta$ and

$$\sigma_s' \approx \frac{Rc\tau\eta}{2 \sin \psi} \int_0^{\infty} e^{-2\alpha\theta^2} d\theta,$$

where η is assumed constant over the beamwidth and earth curvature effects are ignored. Under these assumptions,

$$\sigma_s' \approx \frac{Rc\tau\eta}{4 \sin \psi} \sqrt{\frac{\pi}{2\alpha}} = \frac{Rc\tau\eta\theta_h}{8 \sin \psi} \sqrt{\frac{\pi}{2 \ln 2}}.$$

The worst case rain-to-sea-clutter scattering cross-section ratio is given by

$$\frac{\sigma_R}{\sigma_s'} = \frac{R^2 \pi^6 c \tau \theta_h^2 Z 8 \sin \psi}{16 \ln 2 \lambda^4 \sqrt{\frac{\pi}{2 \ln 2}} R c \tau \eta \theta_h} \approx \frac{R \theta_h \pi^5}{\lambda^4} \sqrt{\frac{\pi}{2 \ln 2}} \left(\frac{Z}{\eta} \right) = \frac{R \theta_h}{\lambda^4} \frac{Z}{\eta} (4.7 \times 10^2)$$

near grazing incidence where $\sin \psi \approx 1$. For Z in mm^6/m^3 , η in m^2/m^2 , R in km, d in cm, and a fixed aperture of diameter D in m,

$$\theta_h \approx \frac{\lambda}{D} \times 10^{-2}$$

and

$$\frac{\sigma_R}{\sigma_s'} = \left(\frac{R}{D\lambda^3} \frac{Z}{\eta} \right) 4.7 \times 10^{-9}.$$

In logarithmic form,

$$10 \log_{10} \left(\frac{\sigma_R}{\sigma_s'} \right) = 10 \log_{10} R + 10 \log_{10} Z - 10 \log_{10} D - 30 \log_{10} \lambda - 10 \log_{10} \eta - 83.$$

To evaluate, the value of η must be found from experimental data. Nathanson (1969) has tabulated η by frequency band for angles near grazing incidence. These values have been

tabulated as a function of grazing incidence. The angle of incidence $\gamma = \frac{\pi}{2} - \psi$ is given by (for a 4/3 earth)

$$\gamma \approx \frac{h}{R} - \frac{R}{1.7 \times 10^4}$$

or

$$R = \left[\sqrt{\left(\frac{1.7 \times 10^4 \gamma}{2} \right)^2 + 1.7 \times 10^4 h} - \frac{1.7 \times 10^4 \gamma}{2} \right]$$

where h = height of aircraft and h and R in km .

Using an aperture of 3.6 m diameter ($12'$), and the data from Nathanson for surface reflectivity values at 3, 5.6, and 9.3 GHz, the Z value for a 10-dB rain-to-sea-clutter cross section ratio is given in Table IVB-I

The values are computed from

$$z_s = (\log_{10} Z)_{3 \text{ GHz}} = 12.9 - \log_{10} R - \eta_s(\gamma)$$

$$z_c = (\log_{10} Z)_{5.6 \text{ GHz}} = 12.1 - \log_{10} R - \eta_c(\gamma)$$

$$z_x = (\log_{10} Z)_{9.3 \text{ GHz}} = 11.4 - \log_{10} R - \eta_x(\gamma)$$

The tabulated data shows that, for a high sea state and horizontal polarization, a Z value of better than 10^5 (a rain rate of 60 mm/hr) is required to provide a 10-dB rain-to-sea-clutter ratio for an antenna depression angle of 2.6° and an aircraft height of 30 kft. By elevating the antenna, the rain-to-sea-clutter ratio is improved or the Z value required for a 10-dB rain-to-sea-clutter ratio is reduced. By elevating the antenna by 2° relative to the depression angle in Table IVB-I, the minimum Z value would be reduced to 10^2 or below at each of the frequencies. As a first-order model, the improvement in rain-to-sea-clutter ratio would go as twice the ratio of one-way main lobe to side lobe gain in the direction of the surface at the range of interest.

For grazing angles larger than 3° , the backscatter cross section per unit area does not increase significantly. For ranges in to about 20 km of the radar, the model used above remains valid and the only change in the rain-to-sea-clutter ratio comes about because of the range dependence of the ratio. From this, it is seen that the Z value for a 10-dB ratio and distance greater than 20 km are the order $Z = 10^9$. Using the approximation that the sea clutter is reduced by the main lobe, side lobe ratio, an antenna with main lobe, side lobe ratios the order of 30 dB in the direction of the sea surface would require a Z the order of 10^3 to have a 10-dB rain-to-sea-clutter ratio.

At the near grazing incidence angles, the sea clutter return is only weakly polarization-dependent and the results given above may, to first approximation, be used for vertical polarization as well with less than an order of magnitude error at a sea state of one and less than a 1-dB error at a sea state of 5. At the low sea states, the sea clutter return is higher for vertical polarization than for horizontal polarization.

TABLE IVB-1

Z-Value for 10-dB Rain-to-Sea-Clutter Ratio

$z = \log_{10} Z, Z \text{ in } \text{mm}^6/\text{m}^3$		Sea State 1 Hor.		Sea State 5 Hor.		Pol.				
deg.	Depression Angle deg.	z_s	z_c	z_s	z_c	Pol.				
	h					z_x				
	R km					z_x				
.1	1.5	10k'	3km	210	2.6	2.3	2.0	5.3	5.0	4.9
.3	1.5	10k'		185	3.2	2.7	2.5	6.2	5.7	5.2
1	1.8	10k'		120	4.3	4.4	4.2	6.6	6.5	6.0
3	3.3	10k'		50	5.3	5.0	4.9	8.5	7.0	6.5
.1	2.2	20k'	6km	305	2.4	2.1	1.8	5.1	4.8	4.7
.3	2.2	20k'		277	3.1	2.6	2.4	6.1	5.6	5.1
1	2.4	20k'		202	4.1	4.2	4.0	6.4	6.3	5.8
3	3.7	20k'		100	5.0	4.7	4.6	8.2	6.7	6.2
.1	2.6	30k'	9km	376	2.3	2.0	1.7	5.0	4.7	4.6
.3	2.7	30k'		348	3.0	2.5	2.3	6.0	5.5	5.0
1	2.9	30k'		278	4.0	4.1	3.9	6.3	6.2	5.7
3	3.9	30k'		144	4.8	4.5	4.4	8.0	6.5	6.0

APPENDIX C

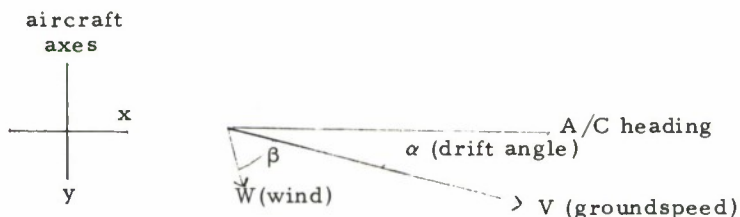
Multi-Beam Winds Below/Above Radars (VAD - Velocity Azimuth Display Doppler Systems)

A. An Error Analysis

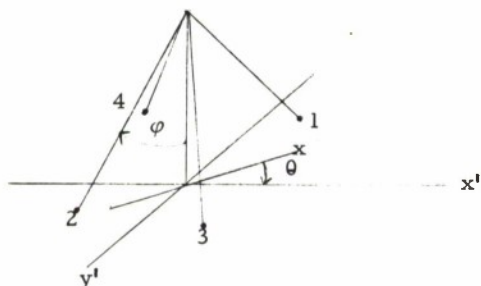
Three configurations of multi-beam down-looking radars are considered. Two use four beams; one maintains beam orientation with respect to the ground-speed vector, the other is not gimbaled in azimuth. The third makes use of three beams and is included only to show the limiting effect of updraft for this configuration.

Analysis of the first-mentioned four-beam radar is the most general and therefore is presented in detail. The symmetry shown has been chosen on the basis of minimizing updraft effects during the data-reduction process.

The geometry of the wind and groundspeed vectors and the heading is shown below.



The four beams are symmetrically displaced from the vertical by the angle φ . The primed axes are stabilized in azimuth to an angle θ from the unprimed axes as well as to the vertical with small verticality errors in pitch (ΔP) and roll (ΔR).



In addition to these pitch and roll errors, there are uncertainties in ground speed (ΔV), drift angle ($\Delta \alpha$), and in the updrafts at the points of measurement (U_1 to U_4).

The relationship between the primed and unprimed axes is

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta & -\Delta P \\ -\sin \theta & \cos \theta & \Delta R \\ \Delta P \cos \theta + \Delta R \sin \theta & \Delta P \sin \theta - \Delta R \cos \theta & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (1)$$

Denoting the measured mean Doppler velocity for the beams by B_1 to B_4 , the sensitive directions are

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} \sin \varphi \sin 45 & -\sin \varphi \sin 45 & \cos \varphi \\ -\sin \varphi \sin 45 & \sin \varphi \sin 45 & \cos \varphi \\ \sin \varphi \sin 45 & \sin \varphi \sin 45 & \cos \varphi \\ -\sin \varphi \sin 45 & -\sin \varphi \sin 45 & \cos \varphi \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} \quad (2)$$

The wind, groundspeed, and updraft vectors, signed according to the way they are sensed by the Doppler radar, are

$$\begin{bmatrix} -V \\ -W \\ U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} -V \cos \alpha & -V \sin \alpha & 0 \\ -W \cos \beta & -W \sin \beta & 0 \\ 0 & 0 & U_1 \\ 0 & 0 & U_2 \\ 0 & 0 & U_3 \\ 0 & 0 & U_4 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (3)$$

For the case of the beam azimuth slaved to the groundspeed vector, $\theta = \alpha$, and Eq. (3) becomes

$$\begin{bmatrix} -V \\ -W \\ U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} -V & 0 & -V\Delta P \\ -W \cos(\beta - \alpha) & W \sin(\beta - \alpha) & -W\Delta P \cos(\beta - \alpha) \\ -U_1\Delta P & U_1\Delta R & U_1 \\ -U_2\Delta P & U_2\Delta R & U_2 \\ -U_3\Delta P & U_3\Delta R & U_3 \\ -U_4\Delta P & U_4\Delta R & U_4 \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

The total sensed Doppler shift is the sum of the components of W , V , and the appropriate U on each beam. These components are formed by taking the dot products using Eqs. (2) and (4). To simplify the notation, let $\tilde{B}_1 = \underline{B}_1 \cdot (-\underline{W} \underline{-V} \underline{U}_1)$, etc.

$$\begin{aligned} \tilde{B}_1 &= -V \sin \varphi \sin 45 - W \sin \varphi \sin(\beta - \alpha + 45) - V\Delta P \cos \varphi - W\Delta P \cos \varphi \cos(\beta - \alpha) \\ &\quad - U_1 (\Delta P + \Delta R) \sin \varphi \sin 45 + U_1 \cos \varphi \end{aligned} \quad (5)$$

$$\begin{aligned} \tilde{B}_2 &= V \sin \varphi \sin 45 + W \sin \varphi \sin(\beta - \alpha + 45) - V\Delta P \cos \varphi - W\Delta P \cos \varphi \cos(\beta - \alpha) \\ &\quad - U_2 (\Delta P + \Delta R) \sin \varphi \sin 45 + U_2 \cos \varphi \end{aligned} \quad (6)$$

$$\begin{aligned} \tilde{B}_3 &= -V \sin \varphi \sin 45 + W \sin \varphi \sin(\beta - \alpha - 45) - V\Delta P \cos \varphi - W\Delta P \cos \varphi \cos(\beta - \alpha) \\ &\quad - U_3 (\Delta P + \Delta R) \sin \varphi \sin 45 + U_3 \cos \varphi \end{aligned} \quad (7)$$

$$\begin{aligned} \tilde{B}_4 &= V \sin \varphi \sin 45 - W \sin \varphi \sin(\beta - \alpha - 45) - V\Delta P \cos \varphi - W\Delta P \cos \varphi \cos(\beta - \alpha) \\ &\quad - U_4 (\Delta P + \Delta R) \sin \varphi \sin 45 + U_4 \cos \varphi \end{aligned} \quad (8)$$

The solution for W and β , given V and α , involves the combination of these equations. Neglecting for the moment the error terms in Eqs. (5) to (8), and letting W_m and β_m be the estimated parameters,

$$W_m \sin(\beta_m - \alpha + 45) = \frac{\tilde{B}_2 - \tilde{B}_1}{2 \sin \varphi} - V \sin 45 = k_1 \quad (9)$$

$$W_m \sin(\beta_m - \alpha - 45) = \frac{\tilde{B}_3 - \tilde{B}_4}{2 \sin \varphi} + V \sin 45 = k_2 \quad (10)$$

Then

$$k_1 + k_2 = \sqrt{2} W_m \sin(\beta_m - \alpha) \quad (11)$$

$$k_1 - k_2 = \sqrt{2} W_m \cos(\beta_m - \alpha) \quad (12)$$

$$W_m = \sqrt{k_1^2 + k_2^2} \quad (13)$$

The solution for β_m makes use of Eq. (11) or Eq. (12), whichever is smaller.

To evaluate the effect of error terms in Eqs. (5) through (8), let $W_m = W + \Delta W$, $\beta_m = \beta + \Delta\beta$, and include the additional errors ΔV and $\Delta\alpha$.

$$\begin{aligned} k_1 &= (W + \Delta W) \sin(\beta + \Delta\beta - \alpha - \Delta\alpha + 45) = \frac{\tilde{B}_2 - \tilde{B}_1}{2 \sin \varphi} - (V + \Delta V) \sin 45 \\ &= V \sin 45 + W \sin(\beta - \alpha + 45) - \frac{(U_2 - U_1)}{2} (\Delta P + \Delta R) \sin 45 \\ &\quad + (U_2 - U_1) \frac{\cot \varphi}{2} - (V + \Delta V) \sin 45 \end{aligned} \quad (14)$$

Then

$$\begin{aligned} \Delta W \sin(\beta - \alpha + 45) + W \Delta\beta \cos(\beta - \alpha + 45) &= - \frac{(U_2 - U_1)}{2} (\Delta P + \Delta R) \sin 45 \\ &\quad + (U_2 - U_1) \frac{\cot \varphi}{2} - \Delta V \sin 45 + W \Delta\alpha \cos(\beta - \alpha + 45) \end{aligned} \quad (15)$$

Similarly for the k_2 relationship

$$\begin{aligned} \Delta W \sin(\beta - \alpha - 45) + W \Delta\beta \cos(\beta - \alpha - 45) &= - \frac{(U_3 - U_4)}{2} (\Delta P + \Delta R) \sin 45 \\ &\quad + (U_3 - U_4) \frac{\cot \varphi}{2} + \Delta V \sin 45 + W \Delta\alpha \cos(\beta - \alpha - 45) \end{aligned} \quad (16)$$

The solution is

$$\begin{aligned} \Delta W &= [(U_2 - U_1) \cos(\beta - \alpha - 45) - (U_3 - U_4) \cos(\beta - \alpha + 45)] \frac{\cot \varphi}{2} \\ &\quad - [(U_2 - U_1) \cos(\beta - \alpha - 45) - (U_3 - U_4) \cos(\beta - \alpha + 45)] \frac{(\Delta P + \Delta R)}{\sqrt{2}} \\ &\quad - \Delta V \cos(\beta - \alpha) \end{aligned} \quad (17)$$

$$\begin{aligned} \Delta\beta = & [(U_3 - U_4) \sin (\beta - \alpha + 45) - (U_2 - U_1) \sin (\beta - \alpha - 45)] \frac{\cot \varphi}{2W} \\ & - [(U_3 - U_4) \sin (\beta - \alpha + 45) - (U_2 - U_1) \sin (\beta - \alpha - 45)] \frac{(\Delta P + \Delta R)}{W\sqrt{2}} \\ & + \frac{\Delta V}{W} \sin (\beta - \alpha) + \Delta\alpha \end{aligned} \quad (18)$$

Note the strong dependence (through $\cot \varphi$) on the differences in updraft. For $\varphi = 15^\circ$, the maximum sensitivity is two knots for each knot of updraft difference ($U_2 - U_1$ or $U_3 - U_4$). For $\Delta P, \Delta R = .5^\circ$, the sensitivity to each of these is only one-half knot for a 100-knot difference in U_1 and U_2 or U_3 and U_4 .

A similar analysis can be made for the case where the antenna is fixed to the aircraft in azimuth ($\theta = 0$). The wind component expressions are

$$W \sin (\beta - 45) = \frac{B_1 - B_2}{2 \sin \varphi} - V \sin (\alpha - 45) = k_1 \quad (19)$$

$$W \sin (\beta + 45) = \frac{B_4 - B_3}{2 \sin \varphi} - V \sin (\alpha - 45) = k_2 \quad (20)$$

$$W = \sqrt{k_1^2 + k_2^2} \quad (21)$$

The errors in estimating the wind vector become

$$\begin{aligned} \Delta W = & [(U_4 - U_3) \cos (\beta - 45) - (U_1 - U_2) \cos (\beta + 45)] \frac{\cot \varphi}{2} \\ & + [(U_1 - U_2) \cos (\beta + 45) + (U_4 - U_3) \cos (\beta - 45)] \frac{(\Delta P + \Delta R)}{\sqrt{2}} \\ & - \Delta V \cos (\alpha - \beta) \end{aligned} \quad (22)$$

$$\begin{aligned} \Delta\beta = & [(U_1 - U_2) \sin (\beta + 45) - (U_4 - U_3) \sin (\beta - 45)] \frac{\cot \varphi}{2W} \\ & - [(U_1 - U_2) \sin (\beta + 45) + (U_4 - U_3) \sin (\beta - 45)] \frac{(\Delta P + \Delta R)}{W\sqrt{2}} \\ & - \frac{V}{W} \Delta\alpha \sin (\alpha - \beta) \end{aligned} \quad (23)$$

Again, the magnification of updraft differences due to the $\cot \varphi$ factor appears. In addition for this case, if the wind is low, a small heading error propagates a very large angular error in estimating β .

Finally, the case of a three-beam antenna slaved in azimuth to the groundspeed vector is presented to demonstrate the biasing effect of a uniform updraft when an odd number of beams is chosen.

Two beams look forward symmetrically to each side of \underline{V} and the third looks backward along \underline{V} . The equations are

$$W \sin (\beta - \alpha) = \frac{B_1 - B_2}{\sin \varphi} = k_1 \quad (24)$$

$$W \cos (\beta - \alpha) = \frac{B_3}{\sin \varphi} - V = k_2 \quad (25)$$

$$W = \sqrt{k_1^2 + k_2^2} \quad (26)$$

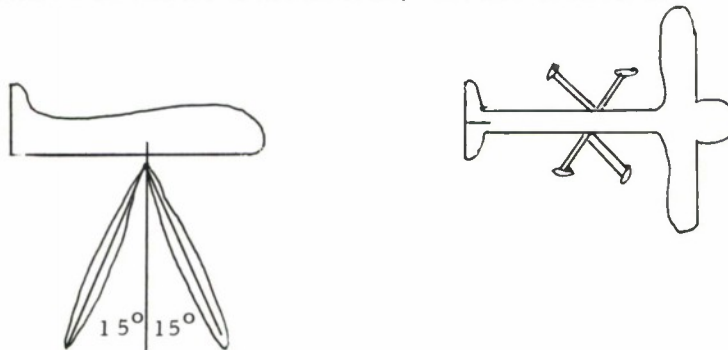
$$\begin{aligned} \Delta W = & [(U_1 - U_2) \sin (\beta - \alpha) + U_3 \cos (\beta - \alpha)] \cot \varphi \\ & + (U_2 - U_1) \Delta P \cos 30 \sin (\beta - \alpha) + U_3 \Delta P \cos (\beta - \alpha) \\ & + (U_1 + U_2) \Delta R \sin 30 \sin (\beta - \alpha) - V \Delta P \cot \varphi \cos (\beta - \alpha) \\ & + V \Delta R \cot \varphi \sin 2\alpha \cos (\beta - \alpha) - W \Delta P \cot \varphi \cos^2 (\beta - \alpha) \\ & + W \Delta R \cot \varphi \sin (\beta - \alpha) \cos (\beta - \alpha) + \Delta V \end{aligned}$$

The error principally depends on U_3 which is amplified by as much as a factor of 4 for $\varphi = 15^\circ$. Also, for the three-beam case only, pitch and roll stabilization errors, coupling groundspeed, contribute significantly; full cancellation of these errors is lost by choosing an odd number of beams.

B. Antenna Design Factors

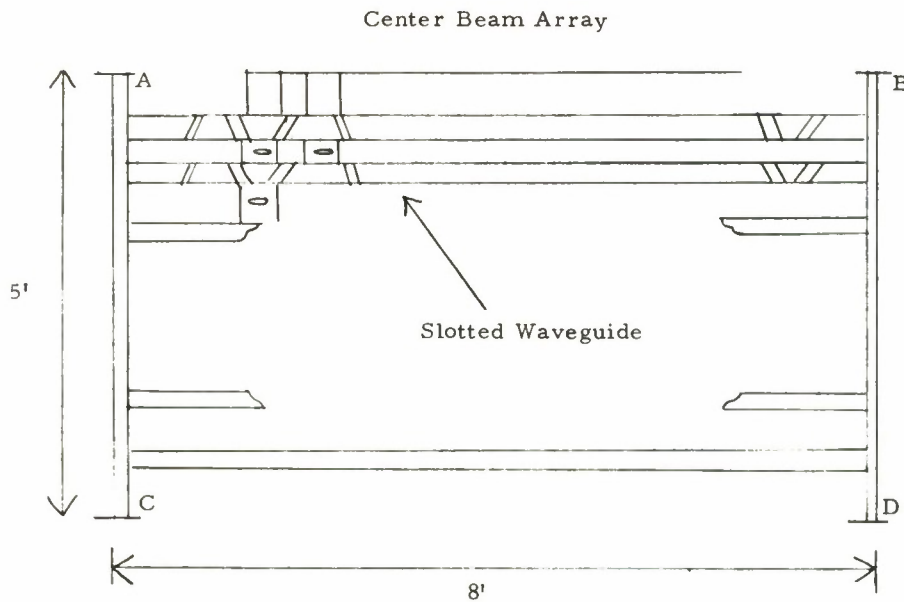
X-Band (3.2-cm) Four-Beam Array with Center Beam

An antenna is required which will generate four beams at about 15 degrees of normal and positioned fore and aft of the aircraft, directed downward.



An antenna of this sort has been developed.* It consisted of an array of slotted waveguides, as shown below.

*J. R. Miller and R. J. Forman, "A Planar Slot Array with Four Independent Beams," PGAP, AP-14, 5, 560-566 (September 1966).



The waveguides AC and BD distribute energy from ports A, B, C, or D to the horizontal slotted waveguides through coupling holes located in the broad wall of the waveguides AC and BD.

The relative excitation vertically is controlled by the size of the coupling holes and the phase distribution is determined by the phase velocity in waveguides AC and BD.

The phase progression can be made to increase or to decrease from the top to the bottom of the array by using either ports A, B, or C, D.

The horizontal slotted waveguides form what is known as nonresonant arrays. They radiate a beam off the normal dependent on the relative phase velocity of the horizontal waveguide.

In any case, by properly choosing the waveguide dimensions of the vertical and horizontal waveguides, the radiated beam can be positioned where desired. The four ports provide, simultaneously, identically positioned beams in the other quadrants.

This array may be mounted on the outside of the aircraft covered by a radome or used through an opening such as a bomb bay. In general, it will require mechanical stabilization.

To indicate up/down-drafts in a storm, a vertical Doppler radar would employ a center beam looking directly downward. Probably the simplest way to obtain this is to provide another array directly behind the above array and radiating through the space between the horizontal waveguide. Such interleaved arrays have also been constructed (see IEEE Phased Array 1970 Symposium Record). A portion of such an array is also shown in the figure. As the main beam here is desired to be normal to the array, this additional array is made resonant; that is, the slots are located at half-guide wavelength intervals.

The combined array will be about 4" to 5" thick and about 5' x 8' to give a HPBW of about $1^\circ \times 2^\circ$.

As this array has been developed, it is estimated that another can be built for about \$150,000 — and that it will require about nine months construction and testing time.

C. Antenna Configuration Considerations

Let us base any antenna configuration on the following general requirements:

Frequency of Operation	≈ 9.4 GHz
Wavelength	3.2 cm (1.26 in)
Half-Power Beamwidth (HPBW)	1° to 2°
Square, or	122 cm (48 in) min.
Round	153 cm (60 in) max.
Rectangular	153 cm x 244 cm
Power-Handling Capacity	≈ 300 kw peak ≈ 1 kw average
Space Available	≈ 153 cm x 153 cm x 244 cm

The antenna must be capable of radiating five pencil beams, four of which point along the surface of a cone (included angle $\approx 30^\circ$), whose apex is located at the airplane and whose base is centered on the nadir position of the aircraft on the earth. These four beams are equi-spaced azimuthally; the fifth beam points along the axis of the cone. Consideration should be given to positioning the four beams on the surface of the cone with more than one azimuthal orientation.

We will consider three basic configurations in the order of increasing complexity of their electrical design. A three-dimensional Luneberg lens is perhaps the easiest, most straightforward configuration, and a two-dimensional slotted waveguide array is an example of a more complicated configuration. Intermediate to these configurations, we will consider a cylindrical "Luneberg" lens illuminated by a slotted waveguide "line feed;" a hybrid of the previous two systems.

Luneberg Lens

The lens is a sphere whose index of refraction, n , varies as $n = \sqrt{\epsilon} = 1.4r/a$ where ϵ = the relative dielectric constant, r is the radial distance from the center of the sphere, and a is the radius of the sphere. These devices are available commercially in diameters as large as 122 cm (4 ft), and when they are used in a microwave antenna, the radiation pattern usually has a first sidelobe level of ≈ 22 dB. They are often constructed of a polystyrene foam loaded with metal filings; a 4-ft-diameter lens might weigh ≈ 100 lb. Because of its spherical symmetry, the performance of the device is invariant with beam direction; the latter is determined by a line joining the center of the feed horn and the center of the lens (see Fig. IVC-1). Feed horns #1 and #2 are shown, indicating the manner in which beams with 180° azimuthal separation can be obtained. Feed horns #3 and #4 are shown to indicate the manner in which the second pair of oppositely-directed beams are obtained. Feed horn #5 generates the "on axis" beam. The arrangement of feed horns could be an integral assembly (i. e., a feed cluster) connected to an RF switching circuit; the entire feed could be moved along the surface of the sphere to compensate for the roll, pitch, and yaw of the airplane. In particular, it is not necessary to move the lens to skew or squint the antenna beams. The switch system (Fig. IVC-2) is a conventional corporate structure configuration with a ferrite three-port switch at each junction.

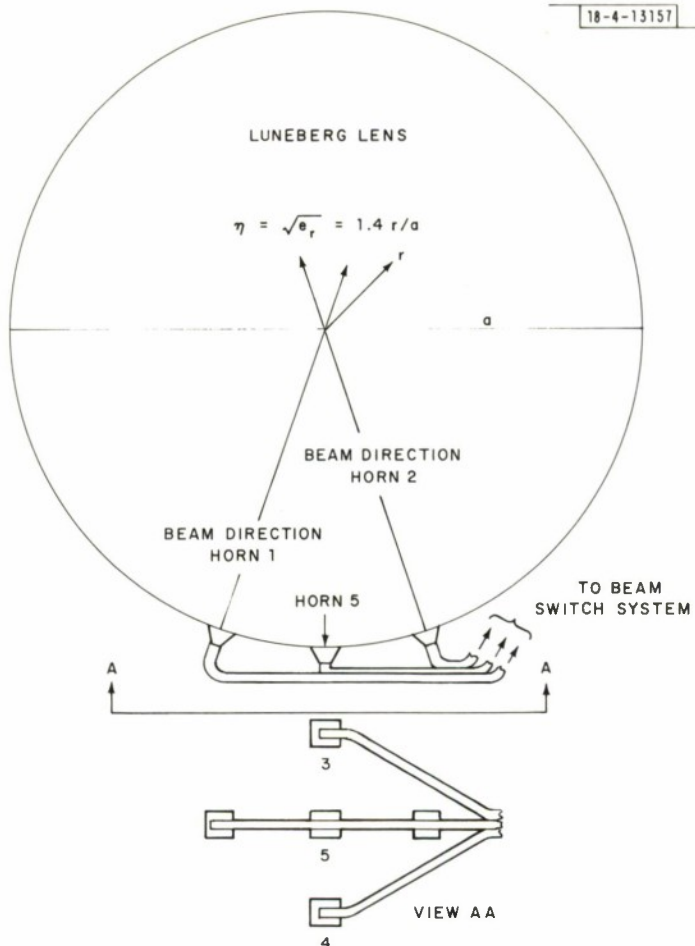


Fig. IV C-1. Proposed Luneberg Lens antenna.

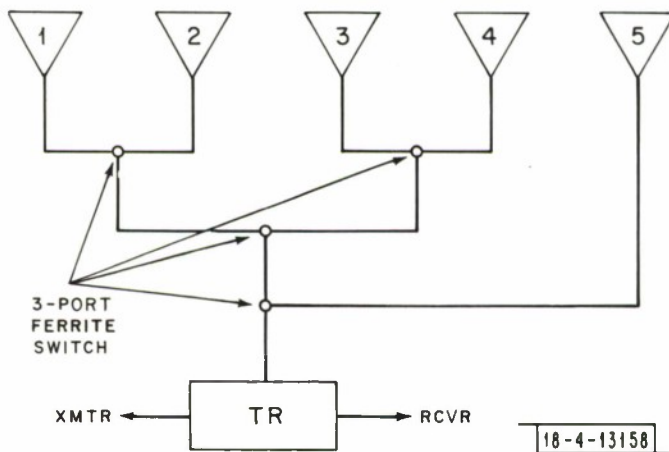


Fig. IV C-2. Proposed switch system.

Let us list the estimated performance characteristics of a 4-ft and 5-ft-diameter lens and consider the disadvantages of the system:

	Diameter	
	122 cm (4 ft)	153 cm (5 ft)
Half-Power Beamwidth	1.83°	1.45°
Directivity	39 dB	41 dB
Losses		
Lens	.3 dB	.4 dB
Switch	.4 dB	.4 dB
Gain	38.3 dB	40.2 dB
Sidelobe Level	≈ 22 dB	≈ 22 dB
Estimated Cost	≈ \$25,000	≈ \$35,000

The loss in the lens is estimated on the basis that it is constructed of unloaded polystyrene foam of varying density. The switch system loss is based on commercially available three-port circulators which have a 0.1-dB insertion loss and ≈30-dB isolation. Although the sidelobe level can in principle be reduced by altering the feed-horn radiation pattern, the method of manufacturing the lens is usually the principal factor which determines the sidelobe level. That is, the variable index of refraction is approximated by ≈ ten spherical homogeneous shells; this quantized approximation introduces a phase error over the radiating aperture of the lens, reducing its gain and raising the sidelobes to the value stated.

This device is basically simple; it is relatively easy to design, its performance is not sensitive to mutual coupling between the feeds, and the beam configuration is relatively easy to alter.

The major disadvantages of the lens are:

- 1) Development of a special material will be required to render the device capable of handling the average radiated power;
- 2) A much larger volume than that required by the two-dimensional planar array will be needed;
- 3) Special care must be taken to maintain its configuration if the air pressure of its immediate environment changes.

Cylindrical "Luneberg" Lens

A hybrid arrangement of the foregoing antenna and a two-dimensional planar array is obtained if the lens is a right circular cylinder having the same radial variation of the index of refraction in the plane perpendicular to the axis of the cylinder. This lens converges the illuminating energy only in the plane perpendicular to the axis of the cylinder; a line-source feed is used to illuminate the lens and to form the beam in the plane containing the axis of the cylinder. The lens performs generally as described previously. The line source might consist of a slotted waveguide array designed to radiate a single beam either scanned ≈ 15° from the broadside direction or near the broadside direction. A broadside beam is undesirable because the device does not present a reasonable input impedance when the radiated beams point within 1/2 HPBW of the broadside direction.

Let us consider the slotted waveguide in more detail. The slots can be cut in either the broad or narrow walls of the waveguide; however, it will be shown later that the narrow wall slotted waveguide is preferred for the configurations being proposed here. If the slots are

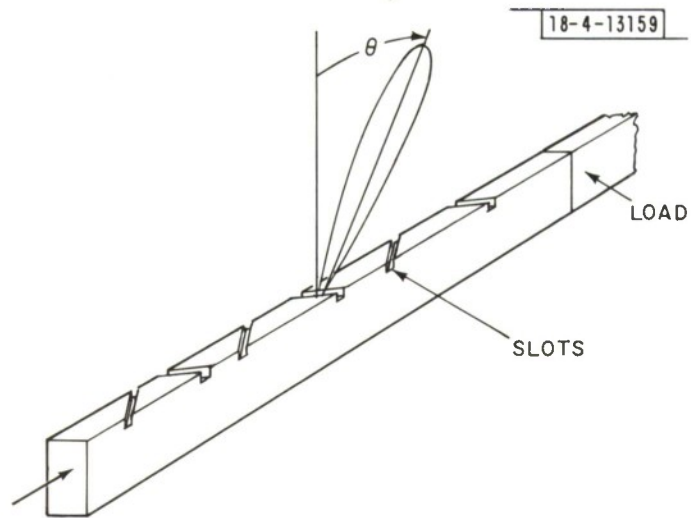


Fig. IV C-3. Slotted waveguide array.

spaced every half free-space wavelength λ along the guide axis, the angle θ between the radiated beam axis and the direction normal to the axis of the waveguide is given by

$$\theta = \cos^{-1} \left[1 - \left(\frac{\lambda}{2w} \right)^2 \right]^{1/2}, \quad (1)$$

where w is inside broad dimension of the waveguide cross section. In practice, the inter-element spacing is usually somewhat greater than $\lambda/2$; this has the effect of reducing θ for a given λ . The transmission line appearance of the device indicates that whenever the slots are spaced $\lambda_g/2$ (λ_g = guide wavelength), the slots appear to be connected in parallel. Indeed, under this condition, the input admittance $Y_{in} \approx Y_s N$ where Y_s is the admittance of a single slot and N = the number of slots. This "resonance condition occurs when the beam radiates in the broadside direction. Scanning the beam one or more HPBW from the broadside direction reduces the input VSWR to less than 1.2 (for the arrays being considered here). When the antenna is designed to radiate the beam normal to the waveguide axis, it is called a "resonant array;" otherwise, it is called a "traveling wave array."

The radiation pattern shape is controlled by adjusting the coupling of the slot to the wave (or waves) traveling in the waveguide. The axial spacing is determined in accordance with the desired beam squint and VSWR requirement. The length and/or position of the slot determine its relative excitation. For example, a uniformly illuminated array is obtained by an appropriate increase in the coupling of the slot to the traveling wave in the guide. The slots are usually equal in length; hence, the phase of the slot excitation voltage is principally dependent upon its spacing along the guide axis. The output end of the waveguide (Fig. IVC-3) is usually terminated in a matched load to prevent the existence of a standing wave in the waveguide. Interchanging the input and output ends of a slotted waveguide traveling-wave array results in a severe change in the relative amplitude of the excitation voltage of each slot; the phase is altered so as to squint the beam in the opposite direction. The latter is a manifestation of the fact that when the spacing between slots is greater than $\lambda/2$, the beam points off broadside in the direction away from the input terminal. For the foregoing reasons, a slotted waveguide array usually cannot be operated with its input and output ends interchanged. The array shown in Fig. IVC-3 is constructed of a rectangular waveguide with slots in its side wall. The tilt of the slot determines the amplitude of its excitation voltage. The direction of the tilt has the effect of introducing a 180° phase reversal and tends to reduce the cross-polarized field radiated in the direction of the main beam. The array is a reciprocal device and has the same radiation pattern, etc., when a plane wave is incident upon it.

The cylindrical lens can be illuminated in at least the two different ways shown in Fig. IVC-4. Assuming that the axis of the cylinder and the airplane are parallel, the first method shown (Fig. IVC-4a) will produce a beam scanned about the roll axis 15° and -15° from the vertical; the offset angle can be varied by changing the position of the feed along the circumference of the lens. These beams will point slightly away from the nadir direction because of the undesirable operation obtained when the beam radiates in the direction broadside to the waveguide array. It is not advisable to tilt the array to compensate for this because the array is then moved off the focus of the lens. Tilting the entire antenna (array and lens) may require an increase in the space occupied by the antenna. Arrays #2 and #4 radiate beams offset 15° in the forward and rear directions. The beams point slightly to the left and right of the nadir

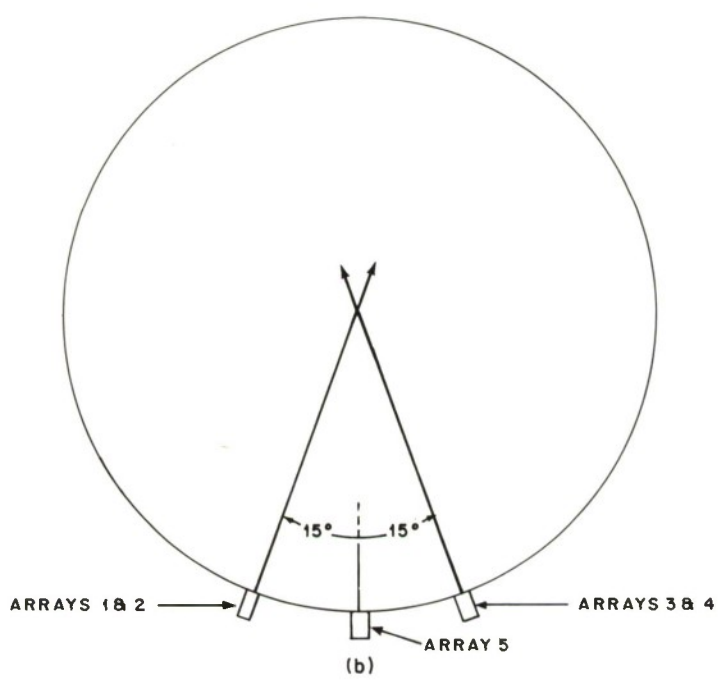
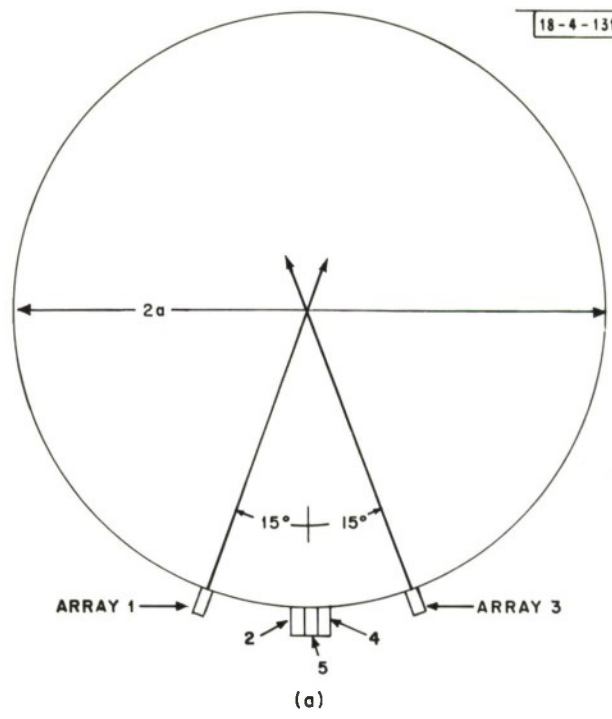


Fig. IV C-4. Cylindrical lens antenna.

direction because they cannot be located at the site of the downward-looking (array #5) nadir beam. It is for this reason that the narrow wall slot array was chosen; it minimizes the angular offset of beams #2 and #4 to the left and right of the nadir direction. For the 122-cm-diameter cylindrical lens, this offset angle equals 1.2° .

The alternate scheme shown in Fig. IVC-4b produces essentially the same beam arrangement rotated 45° azimuthally. Certainly, the same beam arrangement can be rotated through essentially any azimuth angle between 0° and 90° . However, once the arrays are designed and constructed, the beam positions are essentially fixed. Compensation for the pitch and yaw of the airplane could be made only by movement of the entire antenna system.

Having considered the cylindrical lens in some detail, it appears to be superior to the spherical Luneberg lens antenna only if a rectangular aperture is desired. This latter point will be discussed following the next section.

Planar Array

Consider the two-beam planar array shown in Fig. IVC-5. N slotted waveguide arrays form a plane (hence, Planar Array), and are excited through N ferrite "single pole double throw" switches and one of two "feed guides." The arrays are designed to radiate a "near-broadside" beam; the feed guides adjust the phase and amplitude distribution of the array parallel to the feed guide axis. Hence, the feed guide can cause the pencil beam radiated by the planar array to be scanned in the plane parallel to the feed guide axis (i. e., perpendicular to the plane of the array). The ferrite switches must be operated in synchronism with the switch system (Fig. IVC-2); however, this is a trivial complication.

A third or more beams may be obtained from the array by adding additional switches and feed guides — one feed guide and approximately N switches for each additional beam. Let us consider an array like that shown in Fig. IVC-5, and one very similar except with a third feed guide to produce a beam point $\approx 1/2$ HPBW from the direction broadside to the planar array. Rotating the first two-beam array 90° about an axis perpendicular to the plane of the array and placing it immediately under the three-beam array results in the configuration shown in Fig. IVC-6. The array on top (three-beam array) is unaffected by the two-beam array and the polarization of the latter is such that it can radiate "through" the three-beam array. Some development will be required but the scheme is plausible and in principle, the antennas are mutually independent. The input ports of the various beams are indicated; as before, the connection to the switch system (Fig. IVC-2) is not indicated. Approximate dimensions of the arrays are shown in the insert and the desired aperture dimensions are indicated.

This type planar array is usually more efficient than the Luneberg lens antenna, its aperture can be rectangular, near-in sidelobe levels more than 25 dB down can be obtained, and the structure is essentially two-dimensional (i. e., it is thin compared to either lens).

Summary

It is difficult to draw conclusions concerning the antenna systems described, but a comparative summary is helpful to bring the salient characteristics into focus. In the summary below, the 4-ft x 4-ft aperture is used as the basis for comparison and estimated costs. The results would be essentially the same for the 5-ft x 5-ft aperture. The rectangular aperture is discussed later.

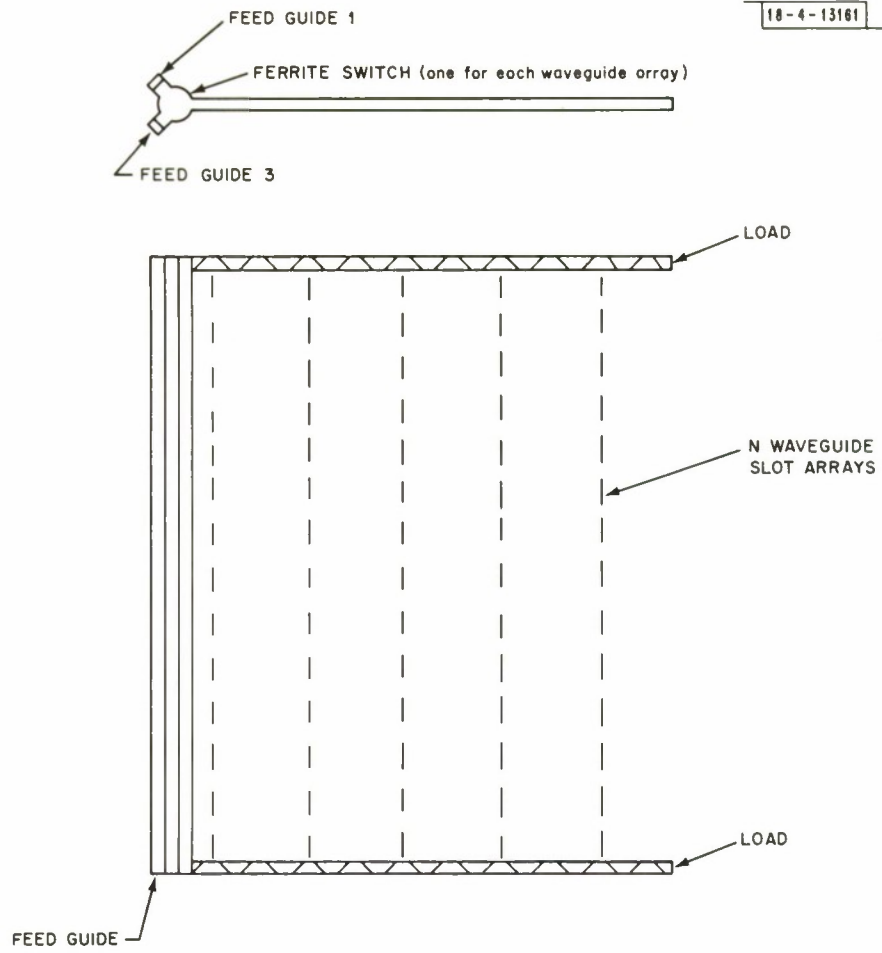


Fig. IV C-5. Two-beam planar array.

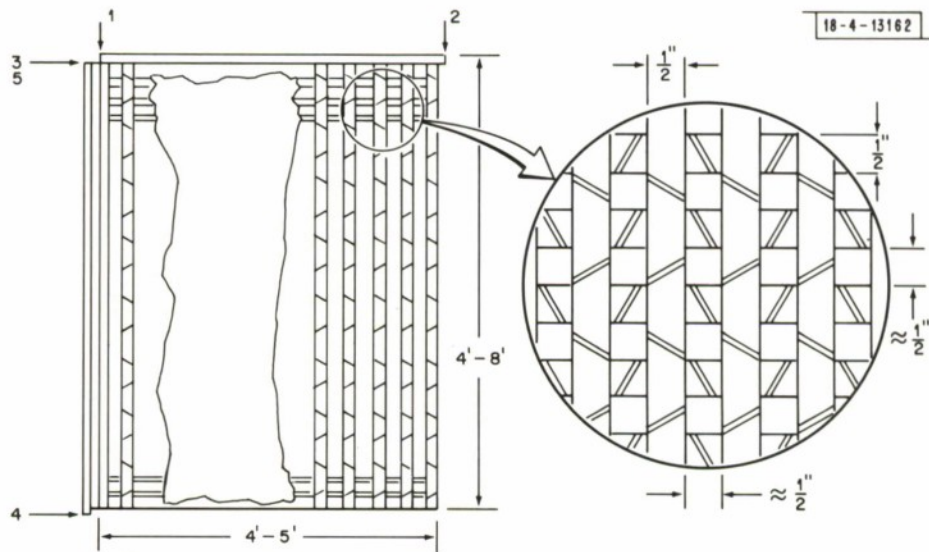


Fig. IV C-6. Four-beam planar array.

	<u>Spherical Lens</u>	<u>Cylindrical Lens</u>	<u>Planar Array</u>
HPBW	1.8°	1.8° x 1.7°	1.7°
Directivity	39 dB	39.5 dB	41.2 dB
Losses			
Lens	0.5 dB	0.5 dB	-
Waveguide Switch	-	-	1.0 dB
Switch System	0.4 dB	0.4 dB	0.4 dB
Gain	38.1 dB	38.8 dB	39.8 dB
Sidelobe Level	≈ -22 dB	≈ -22 dB*	-25 dB*
Estimated Cost	≈ \$25,000	≈ \$50,000	≈ \$50,000
Estimated Weight	50 lb	50 lb	50 lb
Power-Handling Capacity	Requires material development		500 kw peak, 5 kw ave.
Time to Develop	6 - 8 mo.	7 - 9 mo.	9 - 11 mo.
Compensate for A/C Motion	Only necessary to move feeds	Must move entire antenna	Must move entire antenna
Ability to Change Beam Arrangement	Need only move feeds over the surface of the lens	Beam offset along axes fixed. Beam offset about roll axis same as with spherical lens	Beams fixed by design
Beam Squint with Change in Frequency	Non-existent	Beam squint along axis of aircraft only	Beam squint in both planes (≈ 0.5°/‰ change in frequency)
Ability to Rotate Beam Cluster	Rotate feeds over surface of lens	Must rotate entire antenna	Must rotate entire antenna
Rectangular Aperture	Difficult	Easy	Easy

The spherical lens can be configured to have a rectangular aperture by arraying two of the devices described previously. The resulting aperture would have a 2:1 aspect ratio and the near inside lobes would be only 6 dB down in the plane of the larger dimension of the array. Additional transmission line and phasing would increase the losses in the required microwave circuitry; the net gain would be ≈ 2 dB. The HPBW would be halved and the stabilization system would be somewhat more complex.

Generally speaking, these antenna systems would cost approximately the same if they have the same size aperture. The larger 5-ft x 8-ft aperture would cost ≈ \$20,000 more to develop and would essentially double the cost to manufacture the production model.

The above summary cannot and should not be used as any more than a crude estimate of the particular parameters listed. It is even true that antenna designers, in general, might give a different value of the relative estimates that can be derived from the summary. The numbers quoted here are meant to portray the possible range. A detailed study could certainly produce a much more accurate assessment of the parameters listed. The major thrust of the summary lies in the comparison of the salient features of the three antenna systems as they apply to the radar design being considered here. Certainly, other systems might have been considered; these were chosen for their appropriateness.

* The sidelobes are distributed only in the principal planes as compared with the sidelobe "rings" of a circular aperture. The sidelobe level in the inter-cardinal planes will be ≈ 40 dB.

APPENDIX D

Radar Frequency Band Designations

Over the years there have been many different systems of band designations used to describe portions of the electromagnetic spectrum. The following table lists three such systems to aid the reader of this report in cross-referencing frequency bands. Frequently, there have been "in-house" letter designations employed – see parentheses for one example – which may depart at the band limits from those listed here, but band centers are reasonably consistent.

FREQUENCY BAND DESIGNATIONS

	<u>International</u>	<u>Microwave Radar Band</u>	
		Old Letter Designation (MHz)	New Letter Designation (MHz)
VLF	3 - 30 kHz	-	-
LF	30 - 300 kHz	-	-
MF	0.3 - 3 MHz	-	-
HF	3 - 30 MHz	-	A 0 - 250
VHF	30 - 300 MHz	-	B 250 - 500
UHF	300 - 3000 MHz	P 225 - 390	
		L 390 - 1550 (1000-2000)	C 500 - 1000
			D 1000 - 2000
		S 1550 - 5200 (2000-4000)	E 2000 - 3000
SHF	3 - 30 GHz	C 5000 - 6500 (4000-8000)	F 3000 - 4000
			G 4000 - 6000
		X 5200 - 10900 (8000-12000)	H 6000 - 8000
		K _u 12000 - 18000	I 8000 - 10000
		K 10900 - 36000 (18000-33000)	J 10000 - 20000
EHF	30 - 300 GHz	K _a 33000 - 36000	K 20000 - 40000
		Q 36 - 46 GHz	L 40 - 60 GHz
		V 46 - 56 GHz	
		W 56 - 100 GHz	M 60 - 100 GHz

kHz = 10³ Hertz KiloHertz
 MHz = 10⁶ Hertz MegaHertz
 GHz = 10⁹ Hertz GigaHertz

SECTION V

REPORT OF THE PLATFORM PANEL

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Airborne Severe Storm Surveillance Summer Study

August 1970

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I. SCOPE OF THE PLATFORM STUDY

The function of platforms is to place observation systems (equipment and/or personnel) in locations permitting the observation or modification of atmospheric disturbances. Although such other vehicles as satellites, ships, balloons, and buoys can be useful for these purposes, attention was limited to aircraft because they have been the most useful in hurricane work. The subject of the overall study, airborne reconnaissance, implied emphasis on aircraft and concentration on this area was considered to yield the best results in the available time. This does not suggest that other platforms are not useful, but rather that for the near future at least, the available technology makes aircraft of particular importance. An implicit factor in the choice was the importance of radar as an observation tool. Other classes of vehicles such as balloons, dropsondes, and rocketsondes launched from an aircraft are treated as subsystems.

The Platform Panel devoted time to consideration of the aircraft characteristics of special importance to severe storm observation, to a review of existing inventory aircraft, to the methods of selection of aircraft, and to certain aircraft subsystems which play a direct role in the meteorological observations.* Economic, operational, and logistic factors were considered. For example, the cost of developing a totally new aircraft compared to the cost of even a major modification of an existing airframe weighs heavily in favor of the latter choice.

In 1965 the National Center for Atmospheric Research published a catalog of aircraft used in meteorological research and their instrumentation.¹ The great diversity of aircraft used, ranging from small engine piston aircraft and helicopters to long-range, multi-engine jet aircraft, indicate some of the multiplicity of missions which can be accomplished and the characteristics needed.

II. AIRCRAFT SELECTION

A. Aircraft Characteristics

Aircraft characteristics of importance to severe storm work include:

1. Flight regime. Payload, range, maximum altitude, speed, and endurance are variables of importance to the mission which may be traded off against each other;
2. Structural integrity. Severe storm observation, particularly hurricane penetration, imposes requirements on the aircraft to survive loads and turbulence conditions beyond those met in normal aircraft operations.
3. Controllability. Flight characteristics must be suited to maintaining aircraft stability and control necessary to achieve the mission in the storm environment.
4. Adaptability to modifications required by weather equipment, which may include large radar antennas, etc.
5. Crew comfort. Weather observation may involve flights of unusual time length and turbulence conditions, which make

*Basic performance data and description of the present meteorological equipment is included in the report of the Contemporary Operations Panel.

1. "Aircraft and Instrumentation in Atmospheric Research," NCAR Technical Note TN-6, (1965), Facilities Division, National Center for Atmospheric Research, Boulder, Colorado.

crew comfort, fatigue, and other human factors of great importance.

The conflicting demands of different missions may mean that no one aircraft can ever satisfy all severe storm requirements. For example, the structure and payload characteristics required to meet both high-altitude over-flight and hurricane penetration may be mutually incompatible at any reasonable cost, or even mutually exclusive in terms of feasibility. However, there is a sufficient variety of existing airframes so that the required characteristics of each separate mission may be met, if the missions are divided into those of (1) hurricane penetration, (2) high-altitude overflight (60,000 ft), and (3) long-term observation without penetration of the hurricane eye.

It should be noted that hurricane penetration may be a requirement indefinitely into the future, first for observations alone and for seeding experiments, then to continue seeding operationally if one assumes that the experiments have been successful and that improvements in observation methods have permitted discontinuance of penetrations for observation purposes.

B. Present Inventory and Selection Methods

Aircraft now in use by the DoD and DoC for weather observation are the following:

Air Force: WC-130, WC-135, RB-57F

Navy: WV-121

RFF: DC-4, DC-6, A/B, B-57A

In addition to these currently-operational aircraft, RFF has been assigned to a C-130 to replace its DC-4, and the Navy has chosen the P-3 to replace the WV-121. The Air Force is conducting a study of modifications of its weather aircraft. Other aircraft in the Air Force inventory with characteristics useful for severe storm surveillance are the C-141, B-52, U-2, and SR-71. NASA has mounted a wide variety of equipment, including some for meteorological use, in a Convair 990; however, the limited number of these aircraft and the long time since production has ceased to make them logistically attractive.

Availability of airframes has depended upon budget considerations within the DoC and priority considerations within the Department of Defense. Every aircraft currently used for weather purposes by either the NOAA RFF, the Air Force, or the Navy, was originally designed for another purpose and was adopted for weather use because it fitted the budget or the priority of the user, could withstand most of the environmental conditions, and could carry some of the instrumentation desired. Examples from the past are the B-47 and B-50, assigned to the AWS when no longer needed elsewhere.

Reconnaissance aircraft designed for other purposes, but with particularly useful characteristics for weather observation are the Air Force WC-135 and RB-57F and the Navy WV-121. These were assigned to weather use after the higher-priority missions had been satisfied. The WC-130 is the only aircraft in the DoD fleet whose primary mission is weather work.

One cannot expect DoD to place highest priorities on weather observation. It is fortunate that the sampling missions of the WC-135 and RB-57F and the electronic reconnaissance mission of the WV-121 suited these aircraft for the weather observation so well. It is unfortunate that the budget of the RFF has left it equipped with the ancient DC-4 and vintage DC-6 and B-57A, with a higher-quality hand-me-down in the form of a C-130, arriving only recently as a result of a higher priority given to hurricane work.

C. Major Modification - Specific Design

No major airframe has ever been designed specifically for weather work, nor has there ever been a major modification of an existing aircraft exclusively for weather purposes. By major modification is meant a significant change in engines, wing, or fuselage, of the sort, for example, which changed the B-57 into the RB-57F, or the C-121 into the EC-121 or WV-121.

D. The Present Reconnaissance Fleet

The present weather fleet, especially the aging Navy WV-121 and the NOAA DC-6 aircraft, cannot be expected to last indefinitely, and long-range planning for replacements should not be done on the low-priority basis of the past. However, RFF should be funded promptly to replace the DC-6's with WC-130's even as an interim measure.

E. Priority

Severe storm observation should be given a high enough priority so that major modifications of aircraft may be considered for weather purposes alone. Cost considerations suggest that design of a totally new airframe be avoided, and engineering considerations suggest that major modifications can provide acceptable characteristics.

III. AIR FORCE SELECTION OF WEATHER RECONNAISSANCE AIRCRAFT

Air Force acceptance of the WC-130 and -135 for its weather reconnaissance mission was based on a thorough study of available airframes. Flight characteristics, performance, and limitations, as well as cost effectiveness were reviewed. The following conclusions were reached.

A. Conclusions

1. The C-141 and B-52 were not acceptable due to their limited availability and questionable capability to perform storm reconnaissance.
2. The C-135 was suitable for synoptic reconnaissance or storm overflight, but not for storm penetrations; however, its quick reaction, short turn-around time, long range, and multiple-altitude capabilities made it a very desirable platform for another customer. A weather instrumentation modification was added to the sampling modification to provide meteorological data on a piggy-back basis. The sampling mission complemented the weather mission in that most sampling routes were over areas of sparse synoptic data.
3. The WC-130 and P-3 were both suitable for storm reconnaissance, and their operational cost figures were almost identical. The primary consideration for selection became the maintenance support capability. The C-130 was picked since the Air Force had these in the inventory. This eliminated procurement, supply, and training problems that would have arisen if a new type aircraft were to be introduced.
4. U-2's were not available for weather reconnaissance and the SR-71 was not even in the inventory. Neither are readily available today.
5. The RB-57F was specifically designed to meet the sampling customer's requirements. It has proven itself to be an extremely versatile platform for numerous high-altitude missions and should be considered for exploitation in the storm reconnaissance area. It could perform over-the-top reconnaissance in the same manner as a U-2/SR-71. The speed of the SR-71 would make precise Doppler measurements difficult, and this may be a problem even in the relatively slow RB-57F (411 knots True Air Speed at 60,000 feet; 130 knots Indicated Air Speed, which is 27KIAS above stall).

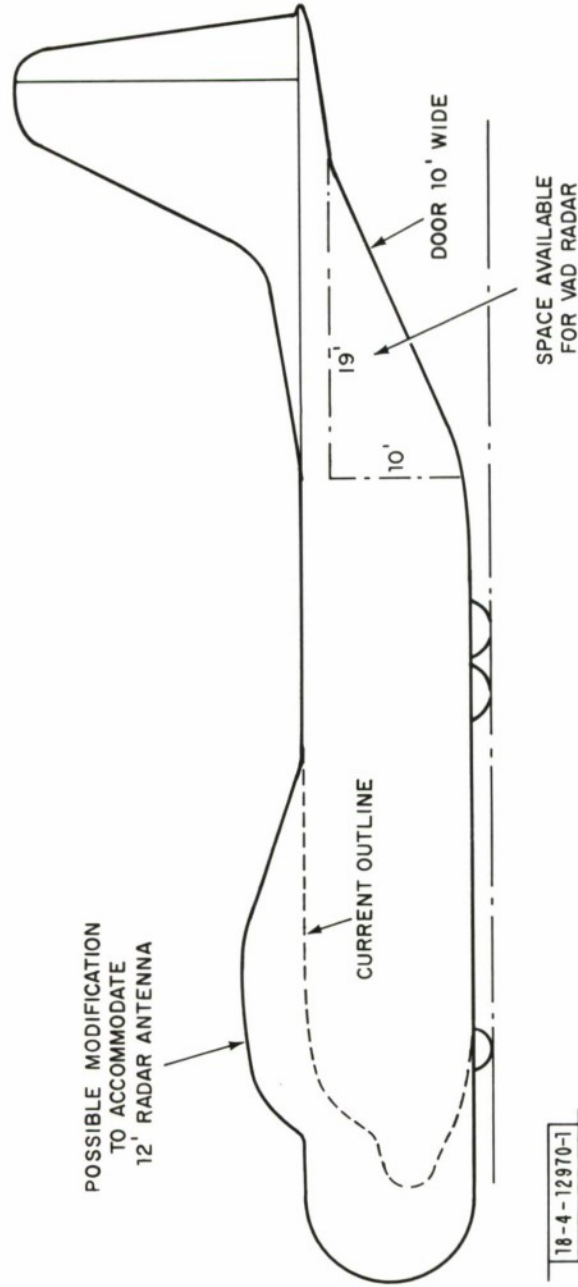


Fig. V-1. Possible "guppy-like" modification of the WC-130 to permit installation of a large forward-looking antenna. Horizontal scan $\pm 90^\circ$; vertical scan nadir to zenith.

IV. NAVY SELECTION OF AIRCRAFT

Navy weather reconnaissance has endured the same low priority as the AWS, when it comes to obtaining platforms. The antiquated WV-121 now in use outdates the WB-50 (the Air Force predecessor to the WC-130). The Navy has plans to replace its WC-121's with P-3's. It is believed that the Navy's prime decision factor in the P-3 was, like the Air Force, based on in-house maintenance capability (as Navy tests on suitable aircraft also showed a close comparison between the P-3 and C-130).

Meteorological improvements are scheduled for both the Air Force and RFF WC-130's. Other sensor improvements are recommended in this report for existing, available, and experimental-type aircraft. Improvement of capability and accuracy of required data should be a continuing program. Strong emphasis should be applied to require commonality and standardization of airframes, sensors, recorders, transmitters, procedures, and techniques.

Since the Navy is already considering the replacement of the WV-121 by the P-3C, an interim fleet of current airframes (WC-130, WC-135, RB-57F, WV-121, P-3C, B-57A) could be used until platforms designed on a new basis permitting major modifications are available. (This assumes prompt replacement of RFF DC-6's by WC-130's.)

This suggests single management and centralized control of the operational weather reconnaissance mission, leaving research and development with the RFF. The Air Force, with its diversified fleet of aircraft dedicated to the weather mission and its commonality with at least one RFF aircraft is the logical choice for the single manager.

V. LARGE ANTENNAS FOR CURRENT AIRCRAFT TYPES

The importance of large radar antennas in hurricane observation dictates special consideration of this subject.

A. WC-130 Aircraft

For a hurricane-penetrating aircraft such as the WC-130, a forward-looking radar is desired which is capable of a $\pm 90^\circ$ horizontal scan and $\pm 30^\circ$ vertical scan, having a dish dimension of about 12 feet. In order to accomplish this, it would be necessary to modify the aircraft, as shown in Fig. 1. The cockpit would have to be raised about five feet and a radome 12-1/2 to 13 feet in diameter installed. The radome may be required to extend 7 to 10 feet ahead of the present nose. For a velocity azimuth display radar (VAD), sufficient space is available above the rear door, as shown in Fig. 1, to house as may be desired an 8-foot-diameter downward VAD or a 4-foot by 8-foot oval dish for backward and downward VAD, or a flat phased-array radar up to dimensions of about 12 by eight feet. A side-looking phased-array radar can probably be located on the vertical tail surface, but with attendant problems of stabilization.

B. B-57F Aircraft

This airplane has a bomb bay compartment which with some modifications can provide space having approximate dimensions of 19 feet by 5 feet by 4-1/2 feet, adequate to house a 4- by 8-foot oval downward VAD. The nose of the aircraft is currently equipped with a 2-1/2 foot dish, which although not optimum, would be usable for the mission. It does not appear feasible to measure the size of the forward radar appreciably without major aircraft modification, due to ground clearance problems. The tail section of the fuselage has space approximately 20 feet long and 5 feet in diameter available for housing dropsondes and other instruments.

C. WC-135 Aircraft

This aircraft has a side area about 6 feet high and 12 feet wide in the cargo door area to

accommodate a side-looking radar. In addition, two areas along the bottom of the fuselage and aft of the wheel well, one about 8 feet x 10 feet and another 10 feet x 10 feet, can probably be used to house a downward-looking VAD radar. At this writing, information on the actual usable space between the floor and the fuselage skin is not available. If a nose dish of 10-foot diameter or greater is desired, the cockpit would have to be raised, as in the case of the WC-130.

VI. AIRCRAFT SUBSYSTEMS

A. Autopilot Modification for Flight in Strong Turbulence

It is standard procedure to disengage the autopilot from elevator control when turbulence is encountered. For hurricane reconnaissance, this implies that the pilot must fly the aircraft manually whenever it is very close to the hurricane eye. For normal penetrations, the duration may be only fifteen minutes or so, and fatigue is not a critical problem, although automatic flight control would permit greater concentration on other matters.

Navy WC-121 crews find that winter storm surveillance fatigue from manual flying is excessive. Flying for an hour or more in these storms has been described as the most severe test of endurance a pilot can experience. Clearly, automatic flight control is much needed.

Autopilots are decoupled in turbulence because the tight pitch control loop produces strong elevator angle commands in response to rapid changes in altitude. This strains the components of the servo system. Reducing the gain in the autopilot loop might avoid this saturation problem. At present, there are aircraft with dual-mode autopilot operation. A review of contemporary gust alleviation techniques along with a study of the behavior of the aircraft with the autopilot engaged in the altitude-hold mode using realistic hurricane or winter storm turbulence models should be made to determine the appropriate modifications to the autopilot. This should be done for both Air Force and Navy aircraft and should lead to a manually switchable mode to permit automatic flight in turbulence.

B. Gust Level Monitor

In penetrating hurricanes, reconnaissance aircraft can experience severe gust loads, which should be monitored to help assess structural fatigue. A VGH-type recorder can provide such information, which can be used in the structural design of future aircraft. For more detailed analysis of the gust structure in hurricanes, special gust probes mounted ahead of the aircraft may be used for measuring three components of gust velocity.

Installation of a VGH recorder on each of the aircraft used for hurricane penetration is recommended to provide a continuous measure of gust loads. An inertial navigation system can replace the VGH unit if suitable recording is provided.

C. Static Pressure at Flight Level

One of the more important measurements to be made by an aircraft in storm reconnaissance is the ambient static pressure. The accuracy of such a measurement depends primarily on the static-pressure source and the altimeter or pressure sensor. The static-pressure source can consist of a static vent on the sides of the fuselage or a pitot-static tube located either ahead of the wing tip, the fuselage nose, or on the side of the fuselage. From an operational standpoint, fuselage static vents are the most desirable if they can be located in regions of minimum pressure error and are free of interference effects of the fuselage structure such as protruding cover plates, doors, etc. If the vents cannot be located in the region of desired minimum pressure error because of structural interference, static-pressure tubes as an alternative can be mounted in nearby regions free of structural interference and aerodynamically

compensated to take care of the larger pressure error. Static vents should have orifice configurations which are not susceptible to water ingestion, and fuselage static tubes, if used, should be heated sufficiently to evaporate water and prevent water ingestion. In order to provide a valid basis for comparison of pressure measurements made with various aircraft in a reconnaissance fleet, each aircraft should have a periodic calibration of the static-pressure source, since accuracy may be affected by manufacturing differences, operational damage, etc. A number of suitable flight calibration techniques are available to provide a calibration over the operational range of air speeds and angle of attack.

Recommendation

Each aircraft of a weather reconnaissance fleet should have the static-pressure source calibrated over the operational range of air speed and angle of attack. The calibration should be repeated whenever the airplane experiences structural deformation or damages in the area of the static-pressure source. With such calibration information available, accurate corrections can be made for the operating altitude, air speed, and aircraft weight, or through an air data computer.

D. Temperature at Flight Level

The ambient temperature can be determined from measurements made with thermometers ranging from the vortex type to the total-temperature type. The recovery factors for such thermometers range from about zero to or near 1.0. The low-recovery-factor thermometers are subject to errors due to local flow conditions (local flow temperatures) and, hence, are sensitive to location on the aircraft. To measure ambient temperature accurately, a zero-recovery-factor thermometer must be located in a region where the local static-pressure source is equal to free-stream static, which is a problem shared by static-pressure source location. A high-recovery-factor (≈ 1.0) thermometer, on the other hand, is insensitive to location on the aircraft. For accurate determination of the free-stream temperature, a high-recovery-factor thermometer is therefore desirable. The recovery factor of an installation can be determined by a simple flight calibration consisting of recording temperature over a range of speeds at a constant pressure altitude and repeating this at low or more widely separated altitudes.

Recommendations

Recommended is the use of a high-recovery-factor (≈ 1.0) thermometer to determine free-stream temperature. It is also recommended that the recovery factor of the installation be checked by air in-flight calibration.

E. Dropsonde - AN/AMT-13 Data-Handling Procedures

The AN/AMT-13 dropsonde is used by the AWS at the rate of approximately 1200 per month. This sonde does not meet current Air Force specifications for pressure, temperature, or relative humidity.

In the WC-135, an IBM CP-821 computer uses the AMQ-25 operational program to reduce the dropsonde data. The program covers all of the data-handling requirements, including interpolation of missing data, extrapolation of data to sea surface level, and coding of the processed data for transmission. The function of the weather officer in this aircraft is to provide visual observations, to insert flight altitude data, and to plot the processed data as a verification of the computer operation. It appears that no significant problems are associated with the processing equipment.

In the WC-130, the dropsonde data is processed manually to derive temperature, pressure, and relative humidity as functions of geopotential height. Although extensive use of correction and reference tables helps to simplify the task, it takes at least forty minutes for an experienced meteorological operator to process a drop from the 700-mb level and twice that for a drop from 300 mb. The computation includes ten corrections for flight-level data, applying drift corrections to the sonde data, and downward integration of the pressure profile, terminating in plots of temperature, pressure, and relative humidity, so that significant levels can be identified for transmission. The lengthy manual computation must be made while in an extremely turbulent environment. This encourages fatigue and errors, and introduces significant delay in detecting faulty sonde data. Thus, the turn-around time for the normal process may adversely influence the flight plan by calling for a second drop considerably later than would be called using the automatic processor. Although a programmable desk calculator is to be installed next year, the computation time is not expected to diminish below twenty-five minutes.

Recommendation

Development and installation of automatic dropsonde data-processing equipment in the WC-130 aircraft is recommended.

F. Navigation

Navigation has the function of specifying aircraft location/aircraft velocity with respect to the earth, so that observations made with respect to the aircraft can be transformed into earth coordinates. Any observations, in situ or remote, not directly referenced to the earth, require this transformation. Winds are obtained as the difference between a ground-speed vector and an air-speed vector.

A particular navigation system may also serve other functions in hurricane observation, depending on its characteristics. Examples: aircraft acceleration, air turbulence, and aircraft orientation measurements for an inertial system, observation of precipitation, and particle velocities for a radar system, etc.

1. Doppler Navigation

Doppler navigation of aircraft is based on use of the Doppler effect to determine velocity of the aircraft with respect to the surface inspected, normally assumed to be the earth's surface and at rest. Observations of systematic errors have led to sea-flow corrections for use in over-water flight. During a hurricane, the water surface is highly perturbed and returns from water in motion at the surface and from spray blown free from the surface, produce a corresponding frequency spread. In such conditions, many current systems cease functioning in the normal Doppler mode.

If the system is pure Doppler, in the "memory" mode which then follows, there is no means of current measurement of aircraft ground speed, and thus, no current measurement of wind. In a Doppler-inertial system, the inertial system continues to measure ground speed (velocity vector), and thus, the air speed and drift-angle measurement continue to provide current wind velocity.

In principle, it is possible to separate the Doppler return from the sea surface and to determine a ground-speed vector, but existing Doppler navigators do not do this. Thus, even if they are not in "memory" mode, the information they provide is of questionable accuracy and reliability. There is no justification for development of a new navigation system specifically for severe storm reconnaissance when alternatives are available in the inventory. It is disappointing to find hurricane reconnaissance aircraft all equipped with Doppler navigation when

the EC-121 aircraft has a Doppler-inertial system which could function in hurricane conditions.

Recommendation

It is recommended that pure Doppler navigation not be used for hurricane reconnaissance aircraft.

2. Inertial Navigation

Inertial navigation, like Doppler, is a dead-reckoning system which depends on initial conditions for position and integration of velocity. In all such systems, error generally grows with time. There are numerous operational military inertial navigation systems and two operational commercial systems in commercial aviation, Litton's LTN-51 and GMC Delco Electronics' Carousel IV. Preliminary data on commercial experience with the LTN-51 shows rms error propagation of the order of 0.5-1.5 knot; further data are expected from the manufacturers and users. Cost of the systems is approximately \$100,000 each; dual installation is generally used in DC-8 and -707 aircraft, and triple installation is standard in the 747. Mean time before failure for the Carousel IV 747 installations in May 1970 was about 600 hours; based on 43,000 operation hours and 30,000 flight hours in the preceding three months, MTBF is rising steadily. In-flight MTBF was considerably higher — 2750 hours in April 1970 (six failures in 16,500 flight hours; in each case, the failed system could continue to serve as an attitude reference).

Many of the military systems are classified, but the performance of the HIPERNAS IIB system in the USAF RC-135A is unclassified. In a series of flight tests of this navigation system by USAF, rms error propagated for 8- to 10-hour periods at the rate of 0.17 knot; thus, the rms position error after 6 hours was 1 nautical mile. However, this system was procured in limited quantity, has poor reliability, and is not recommended for hurricane observation use.

Current inertial navigators use digital computers with major cycle times of the order of 600 milliseconds. Position and velocity data are available in digital form at these rates for recording or transmission.

An important property of the inertial systems is that velocity is derived by integration of acceleration signals and requires no smoothing. The velocity uncertainty due to quantization and computer cycle time is the only high-frequency error and is negligible for navigation purposes.

An inertial navigator also measures aircraft acceleration, and thus, turbulence, if the appropriate signals within the computer are recorded or transmitted. This feature may be useful in research flights. No hardware modifications of the system are required, merely use of data in existence in the computer.

An inertial navigator also supplies aircraft orientation automatically — pitch, roll, and heading. It can be used as a reference for other devices requiring attitude information or control.

The commercial inertial systems also provide automatic navigation of the aircraft, which can reduce pilot duties and crew fatigue.

A basic problem of the inertial systems is the increase of position error with time. For long flights, the position error may increase to unacceptable values of the order of 5 miles. These errors may be bounded if position information from another source is available; and the commercial systems have provisions for the use of such "updates" as VOR-DME, LORAN, or OMEGA fixes.

Note: An inertial or Doppler navigation system can provide a wind vector without measuring air speed if a sufficient averaging time is permitted. This may be changing aircraft heading and measuring ground speed and heading angle twice, while maintaining the same air speed. Although possible, this procedure is not necessarily recommended.

3. Radio Navigation

Radio navigation systems determine position directly. Hurricane reconnaissance requires long-range systems, which limits the choice of operational systems to TRANSIT, LORAN C/D, and OMEGA. LORAN C/D is not available in the areas to be covered, and extending the coverage is expensive. TRANSIT has high accuracy, but is more expensive than OMEGA, whose performance is adequate to bound errors of a dead-reckoning system. The interval between position fixes with TRANSIT prevents it from being used to derive velocity information, and the improvement in accuracy over OMEGA (0.1-0.6 n. mi versus 0.5-2 n. mi) is not required for hurricane reconnaissance. Hence, OMEGA appears to be the most suitable radio system for hurricane reconnaissance. The NOAA RFF indicates it has met no problems in performance of OMEGA in hurricane flights.

While velocity information can be derived from OMEGA, there are problems during thunderstorms in the presence of sferics. This may interfere with deriving velocity information just at the time it is most needed. Thus, it seems unwise to attempt to use OMEGA alone as the source of velocity unless a careful test program indicates it can be so used with satisfactory results in a hurricane.

Recommendation

It is recommended that OMEGA radio navigation be used in hurricane reconnaissance aircraft as an adjunct to inertial navigation,

4. Doppler-Inertial Navigation

Doppler-inertial systems have no substantial advantage over pure inertial systems for hurricane reconnaissance in either cost or performance. Doppler-inertial systems are more complex than pure inertial and therefore, tend to have lower reliability. During flight through the hurricane, a Doppler-inertial system should always be in pure inertial mode of operation because of uncertainties in water surface motion.

Recommendation

It is recommended that Doppler-inertial systems not be used for navigation of hurricane reconnaissance aircraft unless a particular system of demonstrated high reliability happens to be available in the inventory. Note: This recommendation does not preclude the use of Doppler radar as a means of observing the motion of water particles with respect to the aircraft. On the contrary, such observations are highly recommended.

The P-3C navigation system is a Doppler-inertial system. Provided its accuracy and reliability are adequate, it is satisfactory for this mission. In the hurricane area, it should always be operated in the pure inertial mode. An OMEGA system should be added to bound its total error.

5. Stellar Navigation

Stellar navigation has little to recommend it for hurricane reconnaissance, and many drawbacks. No further consideration need be given to its use here.

6. Summary

A combination of inertial navigation and OMEGA can fill all navigation requirements for hurricane reconnaissance with adequate accuracy and reliability. While inertial navigators are expensive, their elimination should only be considered when it has been proven that adequate velocity information can be obtained from other sources. There appears to be no need for development of new navigation systems for this mission.

APPENDIX A

OUTLINE DRAWINGS OF SELECTED AIRCRAFT

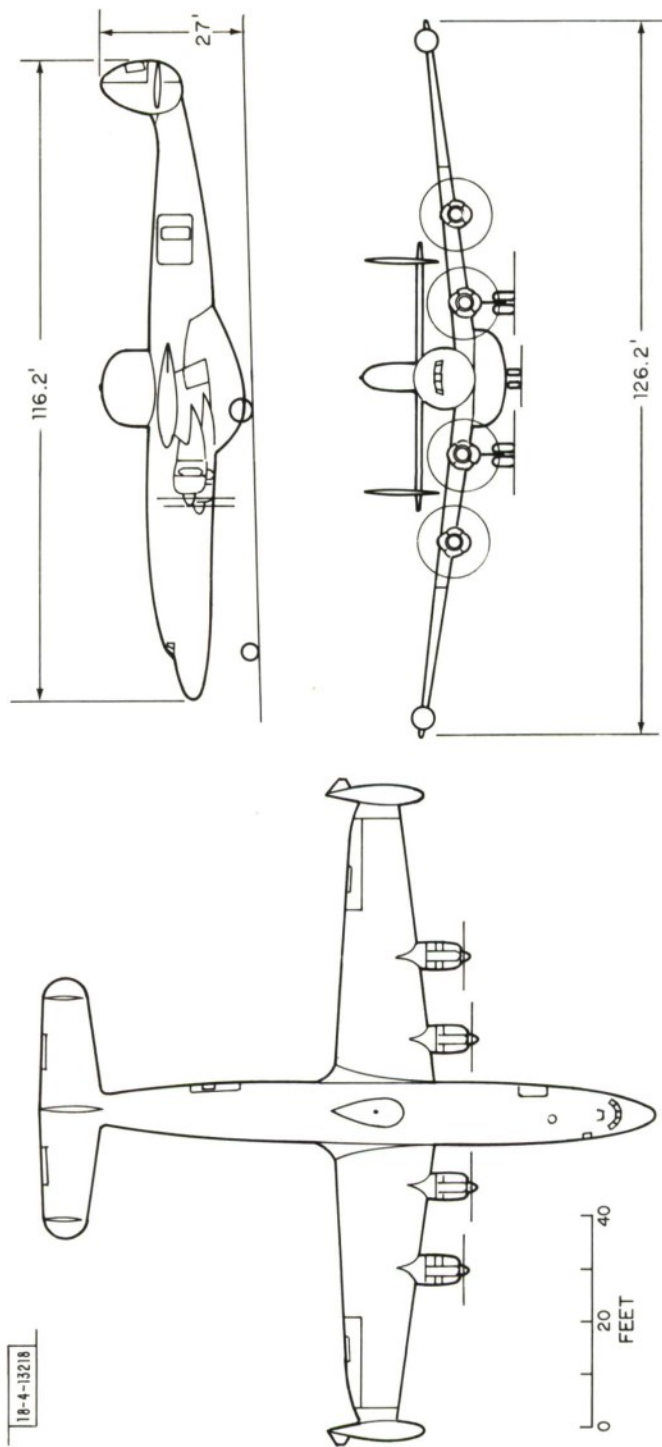


Fig. V A-1. WV-2 Constellation.

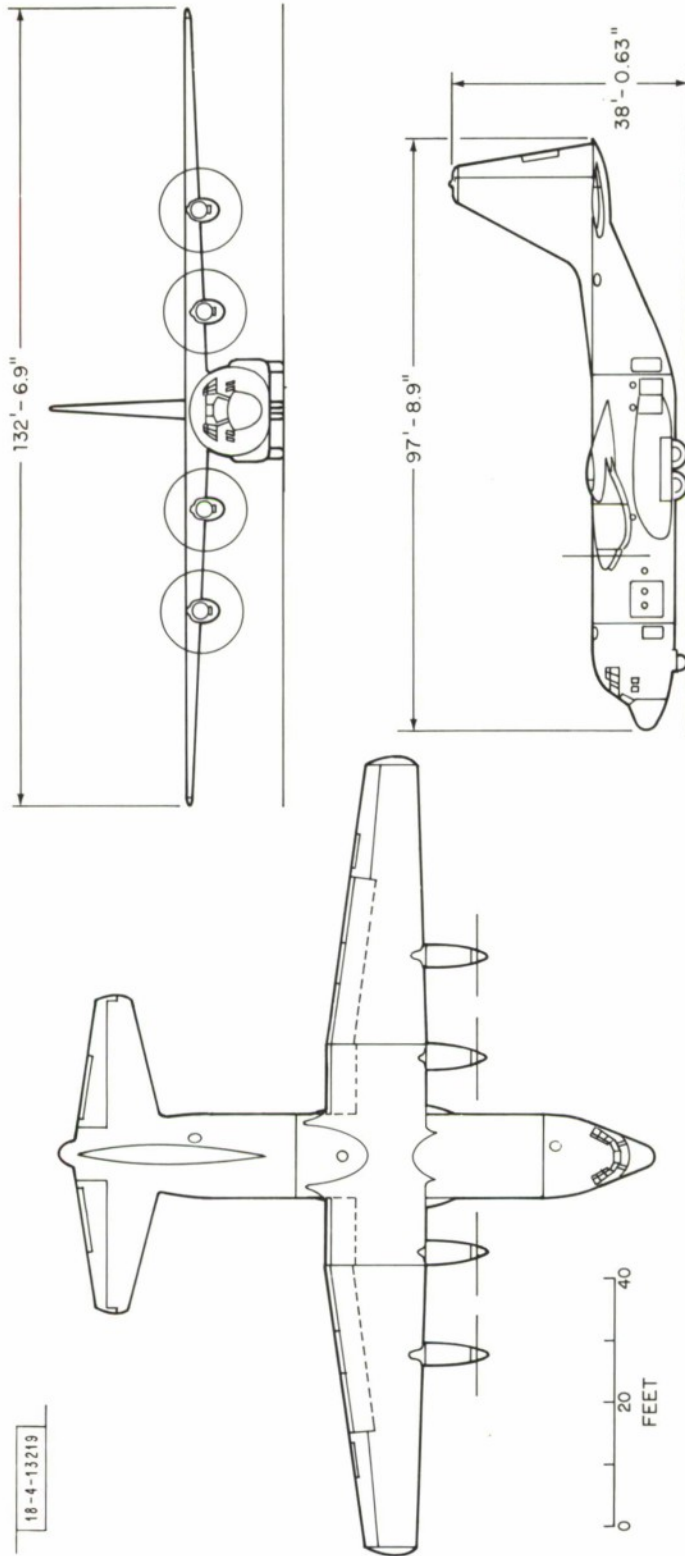


Fig. V A-2. C-130 Hercules.

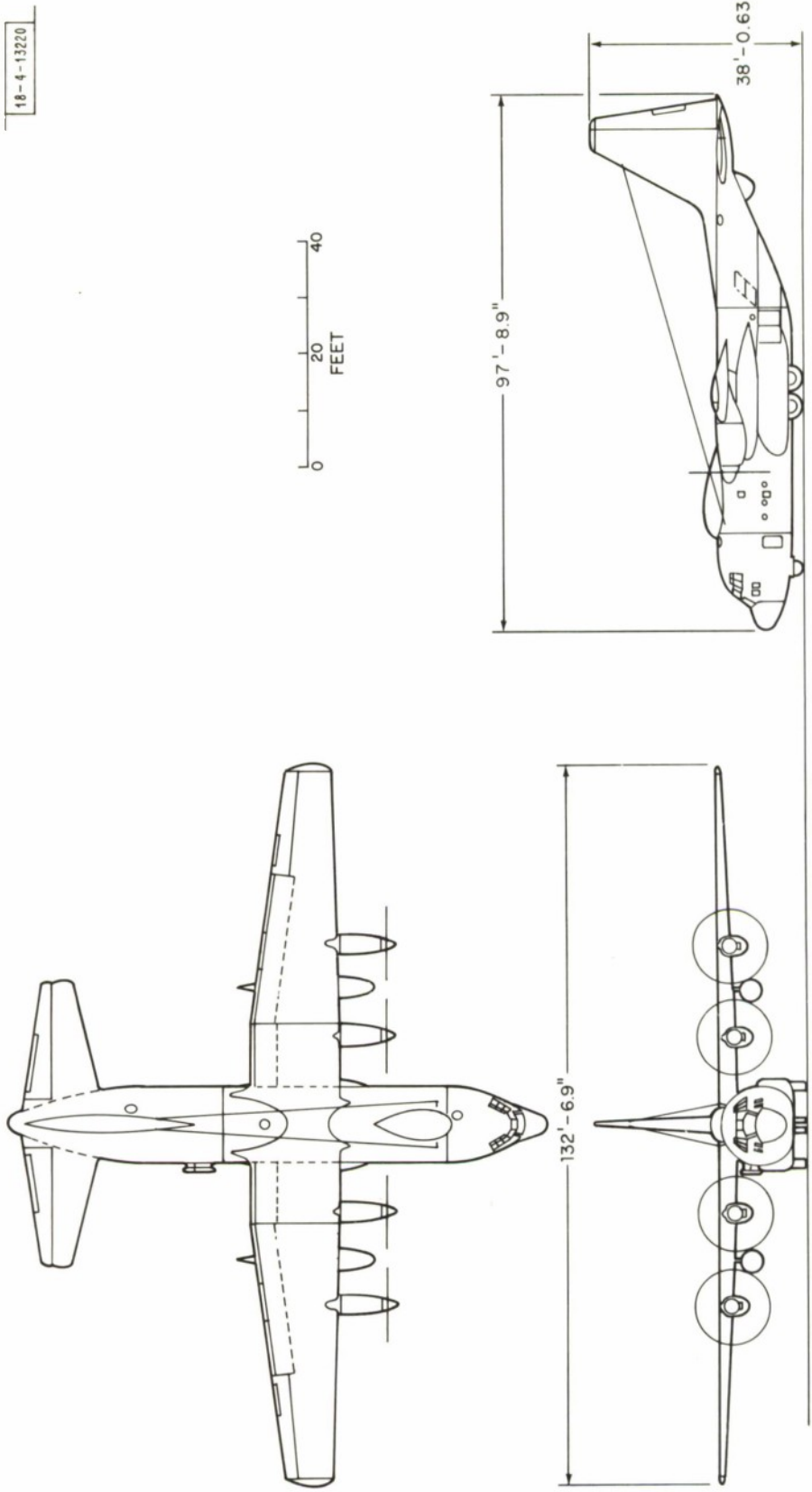


Fig. V A-3. WC-130 with suggested radome modification.

18-4-13221

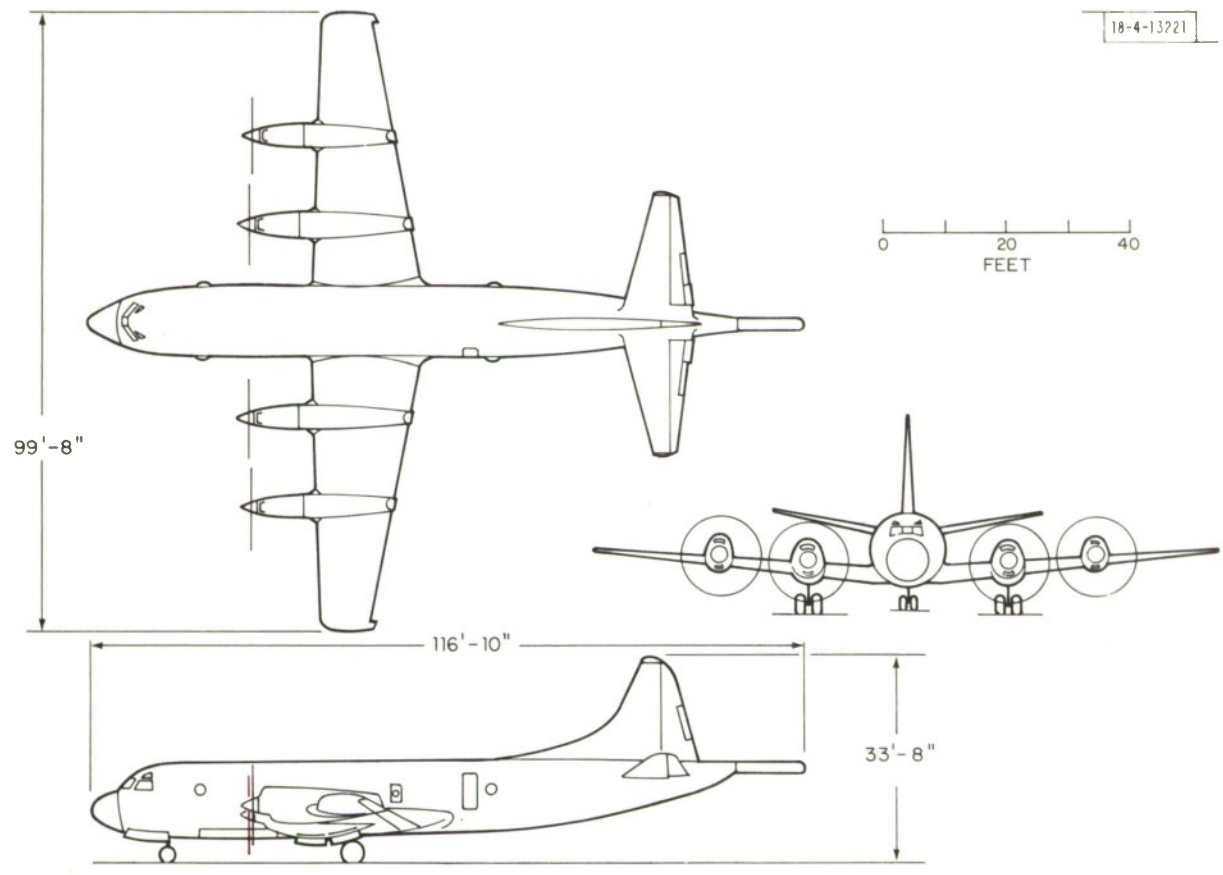


Fig. V A-4. Lockheed P-3 Orion.

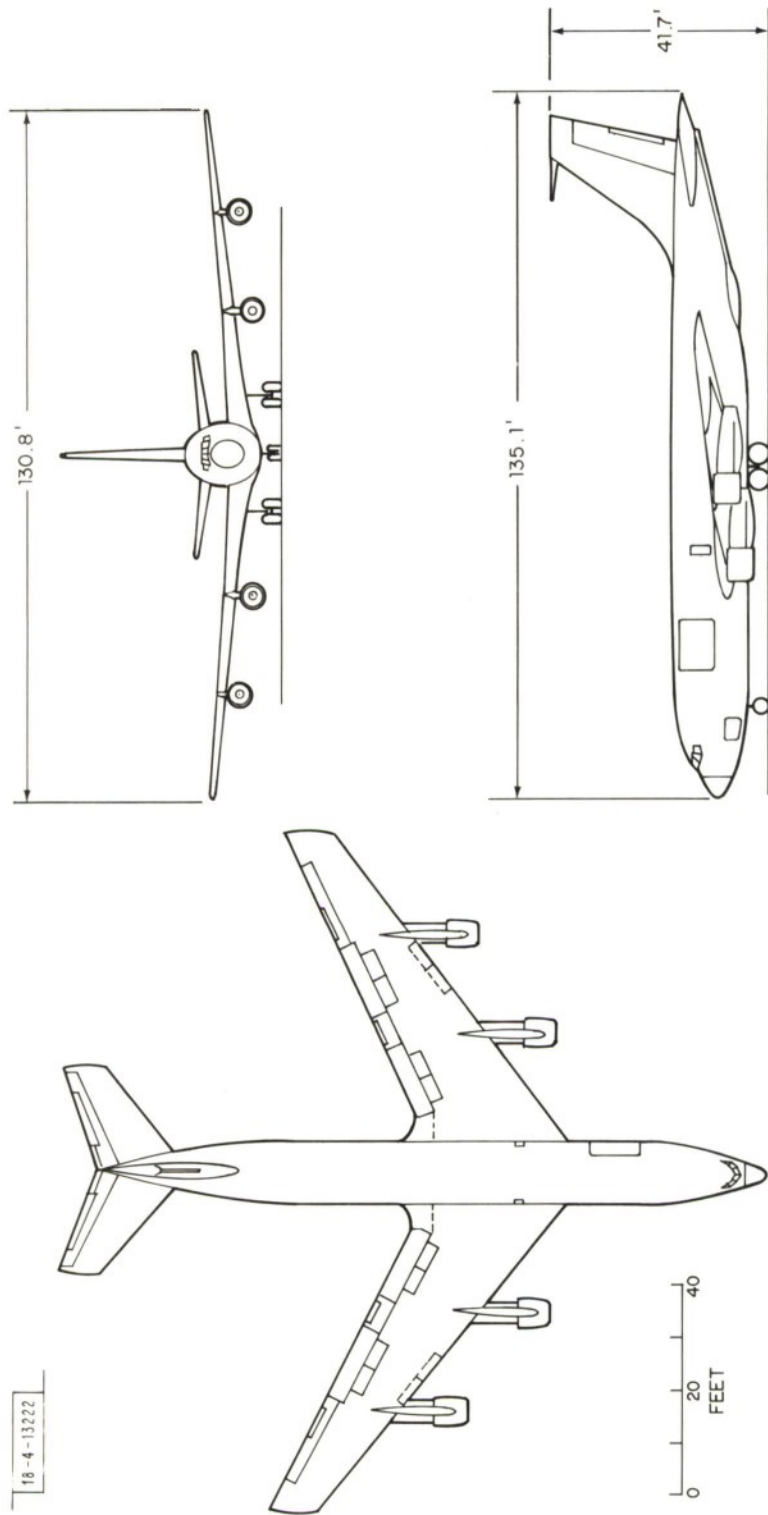


Fig. V A-5. WC-135.

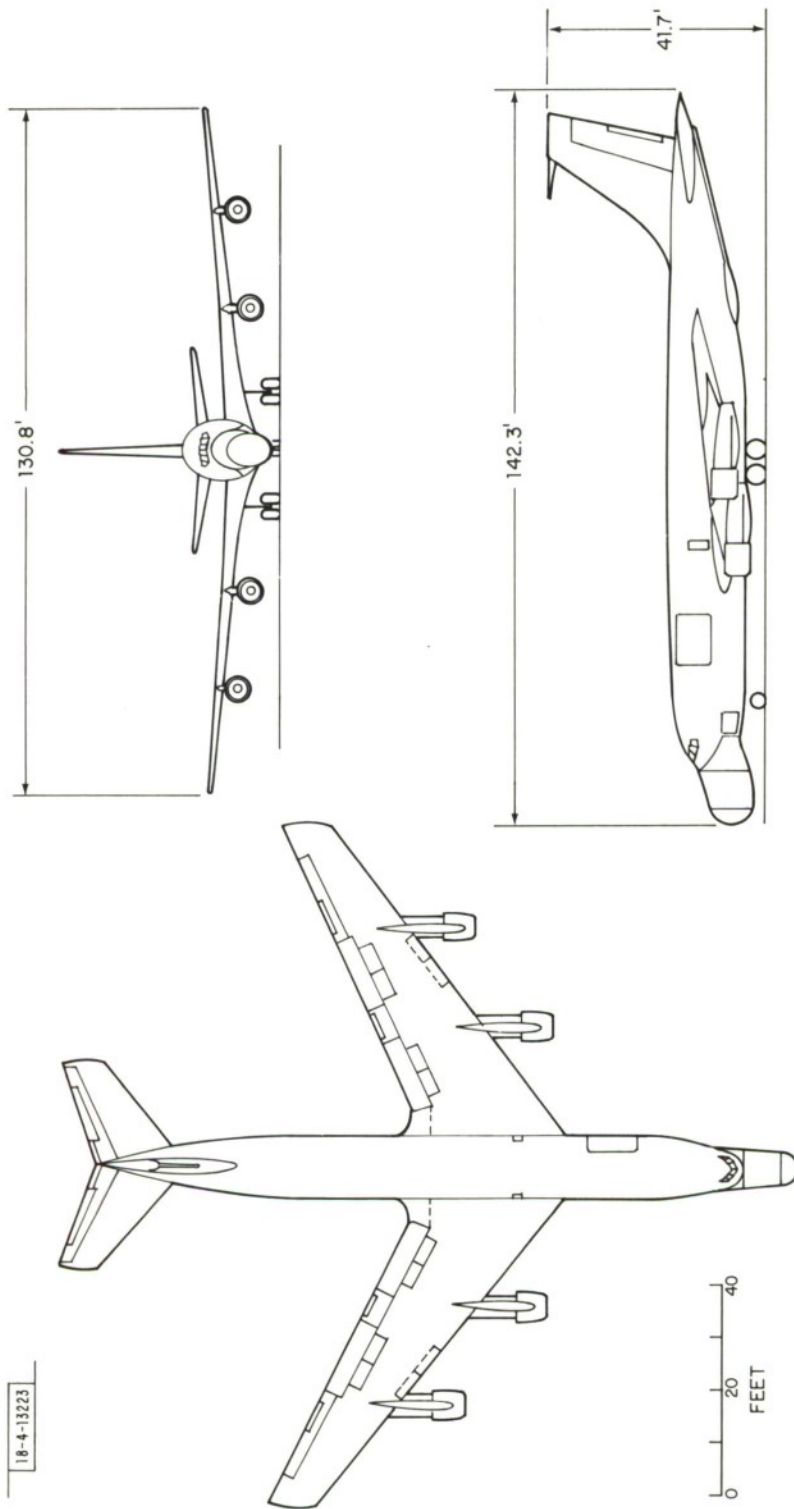


Fig. V A-6. EC-135N Apollo Range Instrumentation Aircraft (ARIA).

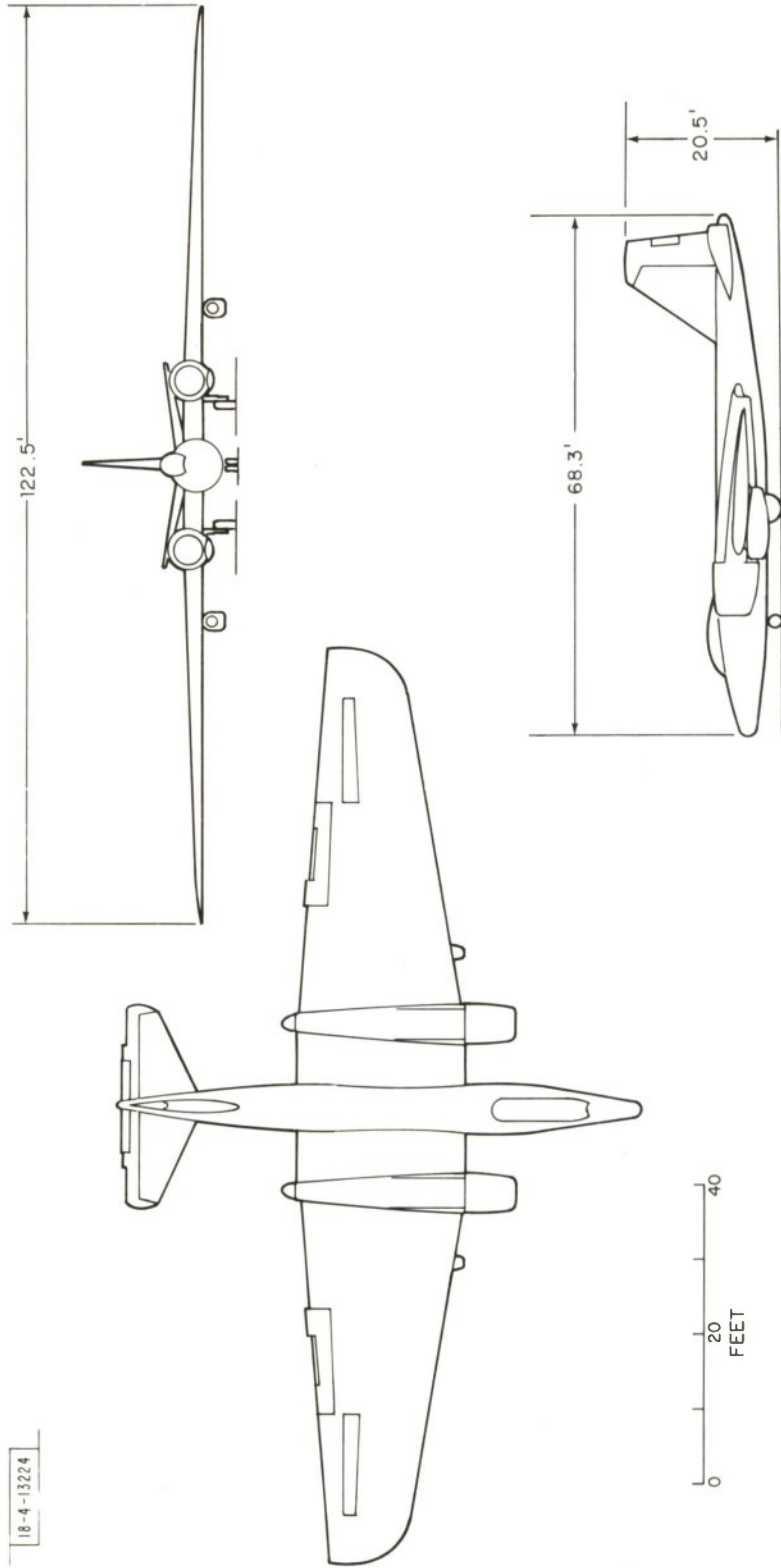
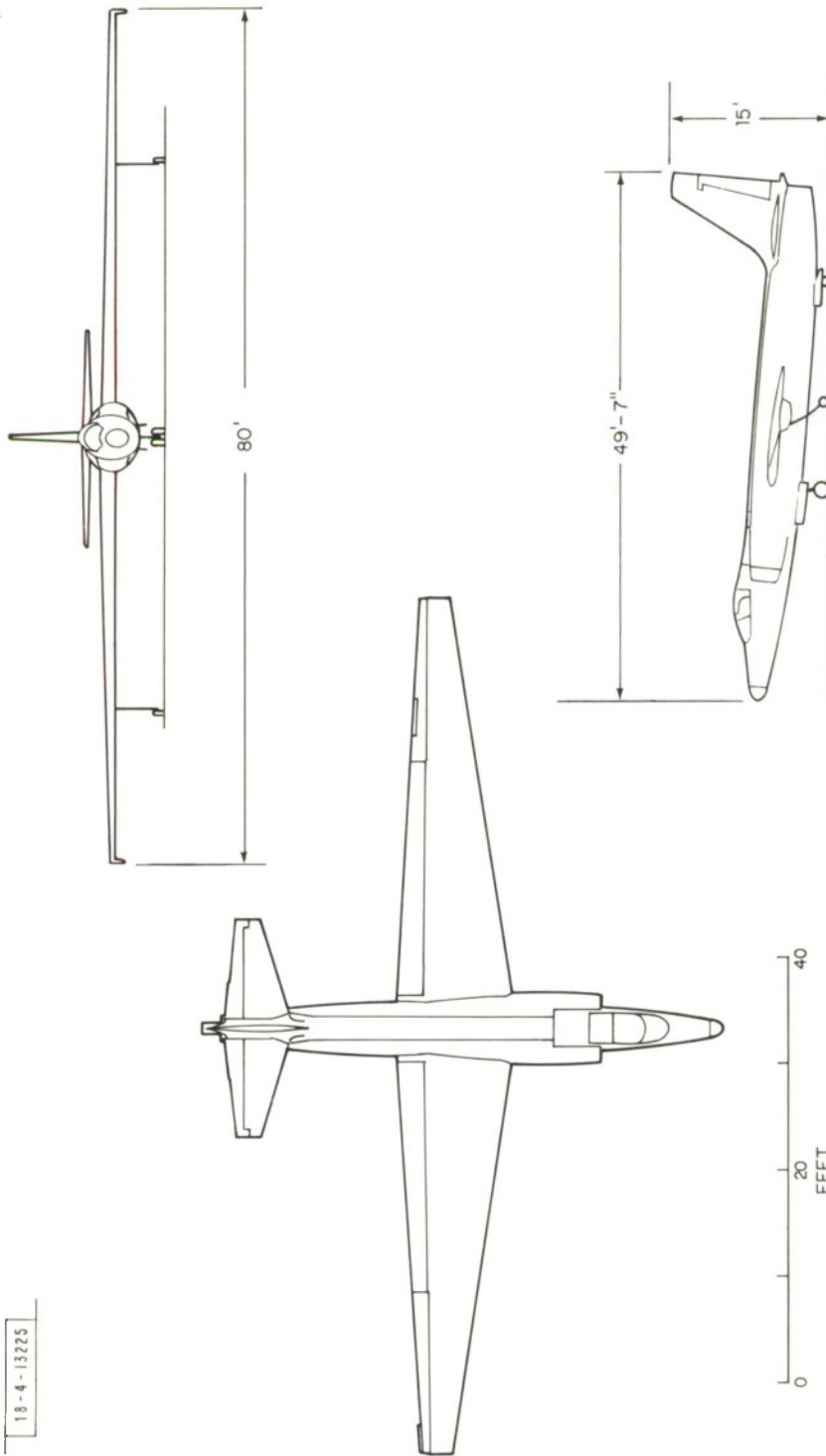


Fig. VA-7. RB-57F High-Altitude Special Reconnaissance Aircraft.



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Fig. V A-8. Lockheed U-2.

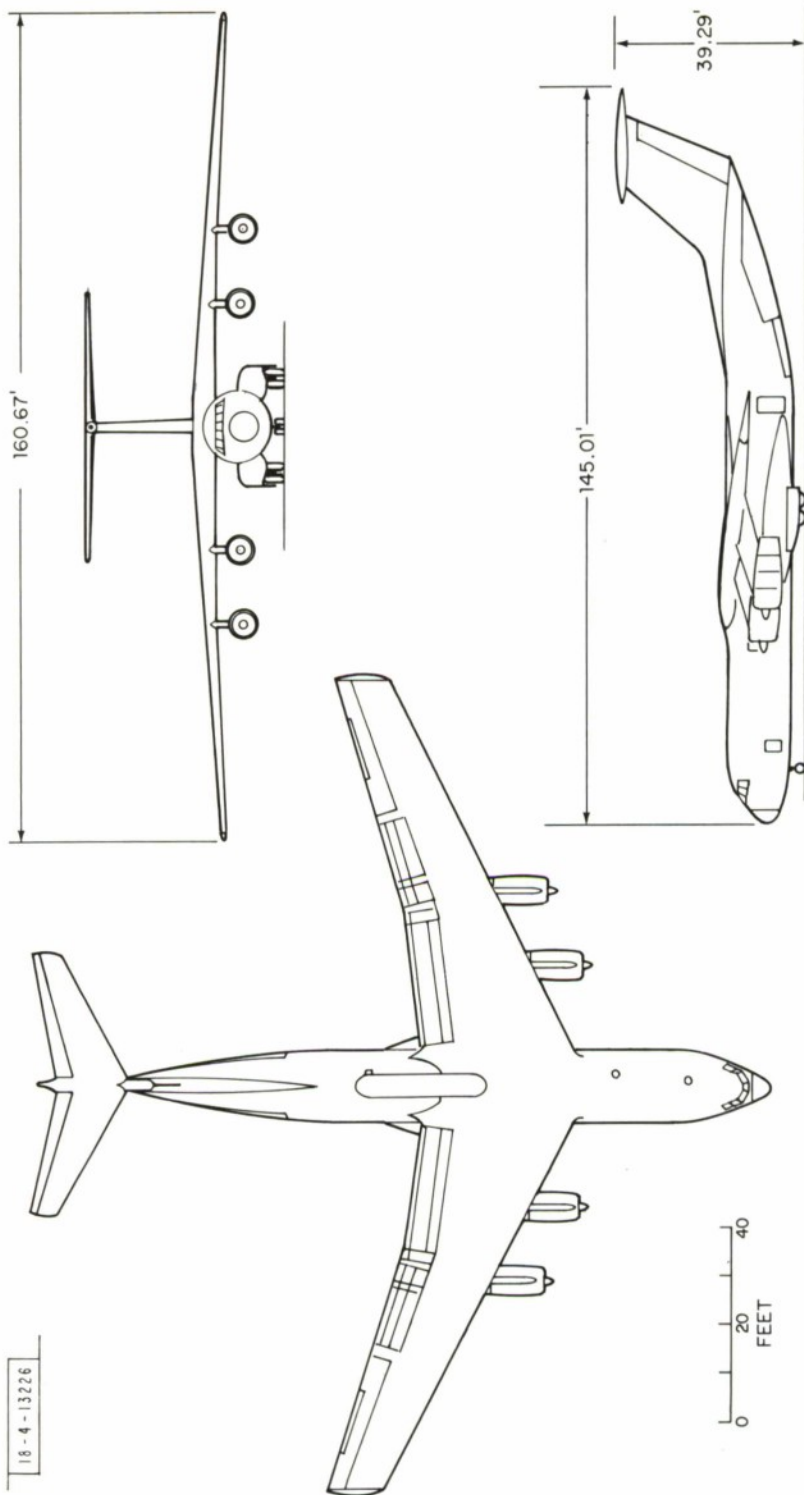


Fig. VA-9. C-141.

APPENDIX B

CHARACTERISTICS OF RESEARCH FLIGHT FACILITY AIRCRAFT

TABLE VB-1
RFF AIRCRAFT OPERATIONAL CAPABILITIES

	<u>DC-6 A/B</u>	<u>C-54 (DC-4)</u>	<u>B-57A</u>
Registration number(s)	N6539C N6540C	N91282	N1005
Number of aircraft	2	1	1
Take-off runway length required (max. gross weight)	6000 ft	4300 ft	6500 ft
Landing distance required (over a 50-ft obstacle at landing wt)	3200 ft	2800 ft	6500 ft
Long-range endurance (at optimum altitude, w/reserve)	12 hrs	17 hrs	4 hrs, 50 min
Practical service ceiling	18,000 ft	18,000 ft (oxygen required above 10,000 ft)	43,000 ft
Max. mission radius (no time on station)	1300 n. mi	1350 n. mi	950 n. mi
Max. range (w/reserve)	2600 n. mi	2700 n. mi	1900 n. mi
Rate of climb	600 ft/min	600 ft/min	1500 ft/min
Climb time (from sea level)	45 min (to 18,000 ft)	45 min (to 18,000 ft)	30 min (to 40,000 ft)
Max. cruise speed	248 kt (TAS)	217 kt (IAS)	350 kt (IAS)
Max. fuel capacity	5512 gal.	3540 gal.	3440 gal.

TABLE VB-2
RFF INSTRUMENTATION SYSTEMS

<u>PARAMETER</u>	<u>INSTRUMENT/MFGR</u>	<u>RANGE</u>	<u>ERROR</u>	<u>39C</u>	<u>40C</u>	<u>282</u>	<u>05</u>	<u>TC</u>
Latitude	a) Doppler APN-153 GPL Div., General Precision, Inc.	90° N/S		x	x	x	x	
	b) Doppler APN-82 GPL Div., General Precision, Inc.	90° N/S		x	x	x		
Longitude	a) Doppler APN-153	180° E/W		x	x	x	x	
	b) Doppler APN-82	180° E/W		x	x	x		
Absolute Position	OMEGA Navigation System, Tracer Corp.	90° N/S		x				
Ground Speed	a) Doppler APN-153	60-1000 kt	(0.2%±0.35)	x	x	x	x	
	b) Doppler APN-82	70-700 kt	+2.1 kt or ±0.3% GS	x	x	x		300 Hz/sec ~14 kt/sec
Drift Angle	a) Doppler APN-153	+40°	+0.17°	x	x	x	x	
	b) Doppler APN-82	+45°	+0.15°	x	x	x		
Wind Direction (DDD)	a) Doppler APN-153	360°		x	x	x		Response 2.6°/ sec, TC ~ 35 sec
	b) Doppler APN-82	360°	+ [0.4+(150/FFF)]°	x				
Wind Speed	a) Doppler APN-153		+3 kt for FFF < 150 kt					
	b) Doppler APN-82	0-240 kt	+0.02 FFF for FFF ≥ 150 kt					
Distance Travel Count (DTC)	Doppler APN-82	0-999,999 n. mi	~ 1% (ΔDTC)	x	x			
Pitch/Roll Angle	Doppler APN-81 Antenna, C-1160 Gyro	+30° (pitch) +45° (roll)	+0.1° +0.1°	x	x	x		36°/sec 36°/sec
Magnetic Heading	N-1 Flux Gate Compass; C-2 Xmtr Mil-type	360°	+0.2°	x	x	x	x	36°/sec
Magnetic Var.	Manual Setting	180° E/W		x	x	x	x	
Ambient Press.	Press. Transducer Giannini 555T1	1050-50 mb	+0.5 mb	x	x	*	x	10 mb/sec

* RFF C-54 (DC-4) employs co-pilots' pitot-static system source for this information.

TABLE VB-2 (continued)

PARAMETER	INSTRUMENT/MFGR	RANGE	ERROR	39C	40C	282	05	IC
Differential Pressure	Press Transducer Giannini 555T2	0-200 mb	±0.5 mb	x	x	*	x	10 mb/sec
Indicated Air Speed	a) Press Transd. Giannini 555T2	50-400 kt	±5 kt	x	x	*	x	
	b) IAS Meter, Kollsman	50-400 kt	±5 kt	x	x	x	x	
True Air Speed	TAS Transducer Kollsman A-2	50-700 kt	±5 kt	x	x	x	x	80 kt/sec
Pressure	a) Kollsman Altitude	0-50,000 ft		x	x	x	x	
	b) Giannini 555T1	0-50,000 ft	±15 ft	x	x	*	x	
Radar Altitude	APN-159 Stewart-Warner	Classified	±8 ft or 1%	x	x	x	x	500 ft/sec
Ambient Temp.	a) ML-471/AMQ-8 Vortex, Bendix	-80 to +50C	±1C	x	x	x	x	10 sec
	b) RFF mod. AMQ-8	0 to 400K	±1C	x	x	x	x	<5 sec
Sea-Surface Temp.	a) Barnes PRT5 IR	-40 to +40C	±0.5C	x	x	x	x	50 msec
	b) Te Radiometer	-20 to +45C	±0.5C	x	x	x	x	2 sec
Total Temperature	Rosemount System	-60 to +40C	±1C	x	x		x	~20 msec
Liquid Water Content	a) Levine Hot-Wire	0-10 gm/m ³	30-50%	x	x			4 sec
	b) Johnson-Williams	0-6 gm/m ³	within 30%	x	x			< 5 sec
Abs. Humidity	RFF IRH System	0-20 gm/m ³	5%	x	x	x	x	0-10 sec(90% chg)
Dew (Frost) Point Temp.	Hygrometer, Cambridge System	-50 to +50C	within ±2C of IRH	x	x			10 sec
Ice Detector	Press Diff. Cyclic			x	x		x	
Aitken Nuc C+	APCL			x	x			
Vertical Acceleration	Statham AJ-43	0 to ±3g	1.0%	x	x	x		
Refractive Index	Microwave Ref., WPL			x				

* RFF C-54 (DC-4) employs co-pilots' pitot-static system source for this information.

TABLE VB-2 (continued)

<u>PARAMETER</u>	<u>INSTRUMENT/MFGR</u>	<u>RANGE</u>	<u>ERROR</u>	<u>39C</u>	<u>40C</u>	<u>282</u>	<u>05</u>	<u>TC</u>
Vertical Velocity	See Table VB-3			x				
WVF	See Table VB-3			x				
Solar Radiation	Eppley Prec. Spectral Pyranometer	λ : 285-2800 m μ		x	x	x	x	1 sec; sensitivity 5 mv/cm ² /min
Radar Systems	APS-20E	10.4 cm PPI		x	x			
	WP-101	5.6 cm PPI	200 n. mi	x	x			
	RDR-1D	3.2 cm X	150 n. mi	x	x			
	RDR-1D	3.2 cm PPI	20 n. mi	x	x			
	APS-42A	3.2 cm PPI	150 n. mi				x	
Radiation Detection	F1-2A, w/B200	0-200,000		x	x	x	x	
	90 GM Foil Assembly							
Atmospheric Turbulence	See Table VB-3			x				

TABLE VB-3
RFF AIRBORNE TURBULENCE MEASURING SYSTEM

Vane Force	Vane	Probe-Boom	Lockheed	FT 3809	155	±12 lb, ±2 lb	0.004 lb
Probe Normal Accel.	Accel.	Probe-Boom	Statham	AJ43-2-350		±2g, ±1 g	0.0036 g
Airspeed	Δ Press.	Probe-Boom	Statham	PL 283TC	3600	0-1 psid, 0-200 kt	0.2 kt
Temperature	Thermistor	Probe-Boom	Fenwall	K1C 26			
Pressure Altitude	Press. Trans.	Boom	Rosemount	830A		0-16 psi	0.1% full scale
Vertical Acceleration	Stable Platform	A/C CG	Litton	LN 3A		1 ±8g, 1 ±0.5 g	
Roll Angle	Stable Platform	A/C CG	Litton	LN 3A			
Pitch Angle	Stable Pla	A/C CG	Litton	LN 3A			
Roll Rate	Gyro	Nose	R. C. Allen	F2880-045	15	±10°/sec, ±10°/sec	0.02°/sec
Pitch Rate	Gyro	Nose	R. C. Allen	F2880-045	15	±10°/sec, ±10°/sec	0.02°/sec
Elevator Position	Potentiometer	Tail				±2.5°, ±2.5°	

TABLE VB-4
RFF AIRBORNE RECORDING SYSTEMS

<u>Recorder/Display</u>	<u>Mfgr./Model</u>	<u>Speed</u>	<u>Channels</u>	<u>39 C</u>	<u>Aircraft</u> <u>40C</u>	<u>282</u>	<u>05</u>	<u>Remarks</u>
Digital (magnetic tape) recorder	ESS GEE, Inc. modified by RFF	*	7-BCD	x	x		x	See (1) below
Digital (magnetic tape) recorder	Radiation, Inc.	**	7-BCD 20 FM Analog			x		See (2) below
FM (IRIG) analog recorder	Sangamo, Series 3560	Var.	14	x				See (3) below
Strip chart recorder (6&8 in)	Honeywell Visicorder	Var.	14 28	x	x	x		See (4) below
Strip chart recorder	Hewlett-Packard		2	x	x	x		See (5) below
Cloud camera, side-mounted, 35 mm	Automax G-2	1 fr/5 sec	1	x	x			Mounted left/right
Cloud camera, f'wd-looking, 16 mm	Milliken DBM-5C	1 fr/2 sec	1	x	x		x	
Photo-panel camera 35 mm	Automax G-1	1 fr/5 sec	1	x	x	x		
Radar camera 35 mm	Fairchild 0-15	Var.	1	x	x	x	x	All aircraft radars

- (1) Records are each 150 BCD characters in length. * Tape moves at 76 cm/sec. Recording capacity 4500 BCD characters per sec with bit density of 200 bits per in. Original system modified by RFF.
- (2) Records are each 150 BCD characters in length. ** Capability of recording 50 complete samples per sec. System can also be used to record 20 channels of analog (FM) data.
- (3) Used to record individual components of the water vapor flux system.
- (4) Light beam galvanometer type. Used to record, continuously, output of special instruments.
- (5) Electrostatic recorder used for IR and solar radiation measurement recording.

TABLE VB-5
RFF SUPPORT OF BOMEX

<u>Phase</u>	<u>Aircraft</u>	<u>Missions</u>	<u>Block Time</u>
Pre-BOMEX	Research 6A	16	55 hrs, 40 min
	Research 6B	9	49 hrs, 55 min
	Research 4	10	56 hrs, 00 min
I	Research 6A	10	74 hrs, 05 min
	Research 6B	6	54 hrs, 00 min
	Research 4	5	48 hrs, 25 min
II	Research 6A	12	85 hrs, 45 min
	Research 6B	10	92 hrs, 40 min
	Research 4	9	96 hrs, 50 min
III	Research 6A	10	84 hrs, 55 min
	Research 6B	7	71 hrs, 50 min
	Research 4	9	81 hrs, 40 min
IV	Research 6A	10	97 hrs, 25 min
	Research 6B	10	86 hrs, 15 min
	Research 4	13	102 hrs, 30 min
TOTALS:	Research 6A	58	397 hrs, 50 min
	Research 6B	42	354 hrs, 40 min
	Research 4	46	385 hrs, 25 min
		146	1,137 hrs, 55 min

TABLE VB-6
RFF WC-130B OPERATIONAL INFORMATION

Critical field length at gross wt and 90°F (135,000 lb max. gross wt; max landing gross wt - 118,000 lb)	4000 ft (6000 ft)
Time to climb to 21,000 ft (cruise ceiling)	30 min (45 min to 18K)
Distance to climb to 21,000 ft	100 n. mi
Fuel to climb to cruise ceiling	2650 lb
Total fuel available after T/O	44,000 lb
Cruise speed	290 kt (TAS) (248)
Long-range endurance at 20,000 ft (4 eng.) at 25,000 ft (4 eng.)	7.6 hrs 7.7 hrs (12 hrs)
Service ceiling at 130,000 lb at 100,000 lb	21,000 ft 28,000 ft (18-20,000)
Max. mission radius at sea level, standard day, 20°C with reserve	740 n. mi
Max. mission radius at 15,000 ft, standard day, 20°C with reserve	850 n. mi (1300)
Max. mission radius at 20,000 ft, standard day at 20°C with reserve	1115 n. mi
Max. range at gross wt, standard day, 20°C with reserve	2350 n. mi (2600)

RFF is scheduled to receive a WC-130B aircraft from the U. S. Air Force in Sept. 1970
DC-6 A/B values are in parentheses.

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