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The Fortieth Anniversary History of Weather Radar Research in the U.S. Air Force

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"This technical report has been reviewed and is approved for publication"

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From its origin in 1948 the weather radar program of the U.S. Air Force has maintained a leading role in research and development. Detection of radar echoes from the optically clear atmosphere in the early 1950's led to vigorous debate within the weather radar community as to their origins. Members of this program later used the radars at Wallops Island, Va., to observe the clear atmosphere, detecting the tropopause by radar in 1966 and confirming that most of the clear air echoes were due to turbulence. Research through the 1950's and 1960's led to improved understanding of stratiform rain systems, hurricanes, and severe convective storms. The first "rain parameter diagram" was developed in 1957. Doppler radar was used in 1961 to produce the first wind profile from radar measurements and in 1968 to make the first radar observation of a mesocyclone. The research on severe storm dynamics, both at the Air Force radar site in Sudbury, Mass., and in collaboration with the National Severe Storms Laboratory in Oklahoma, laid much of the foundation for the Next Generation Weather Radar (NEXRAD) program. Field work at Wallops Island and at

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Kwajalein Atoll in the 1970's in support of Air Force reentry vehicle test programs included the first display of analysis products generated from radar data by a computer in real time. In recent years much effort has been devoted to the development of data analysis algorithms for NEXRAD. Other current work includes measurement of wind profiles by UHF Doppler radar and the development of polarization diversity techniques for documenting hydrometeor microphysical parameters and processes. This program continues at the forefront of radar meteorological research and has contributed much to the Air Force, the meteorological community, and the nation.

Preface

The weather radar research program in the Air Force Geophysics Laboratory and its predecessor organizations is remarkable both for its duration as a research program and for the degree of continuity of its staffing. The compilation of its history began as a paper presented at the 1986 Spring Meeting of the American Geophysical Union in a special session entitled History of Meteorological Radar. That paper emphasized the 25 years during which the Ground Based Remote Sensing Branch (formerly the Weather Radar Branch) had been at its present site in Sudbury, Mass. A more complete history of the program was presented at the Battan Memorial and 40th Anniversary Conference on Radar Meteorology, sponsored by the American Meteorological Society and convened in Boston, Mass., in November 1987. That conference celebrated the fortieth anniversary of the First Weather Radar Conference and honored the memory of Prof. Louis J. Battan, a pioneer of radar meteorology, who died in 1986. An abridged version of the present account appears in *Radar in Meteorology*, which is the proceedings of the conference. As the earliest members of the weather radar program retire, we realize that the personal recollections which make any history more vivid will gradually be lost. We extend our special thanks to David Atlas, Albert Chmela, Ralph Donaldson, and Wilbur Paulsen, all of whom have retired from Federal civil service, for recalling their experiences for us. Ralph Donaldson also provided original or nearly original source material for Figures 10, 11, and 17.

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1. INTRODUCTION

The weather radar research program of the U. S. Air Force has a distinguished history of scientific productivity and resulting contributions to the Air Force, the meteorological community, and the nation. Many well-known scientists have been associated with this program as laboratory staff members, as visiting scientists, or as collaborators in joint research efforts. In addition to these direct connections with the broader scientific community, there have been indirect and subtle connections and influences as a result of the scientific work and publications of the program. In this historical review we trace the evolution of the program from its origins shortly after World War II through successive stages of scientific and technological advancement. Our narrative is mainly chronological, with sections based on key events or distinct phases in the program. We highlight many of the unique contributions of the individuals who have constituted this professional and

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personal "family." The personal aspect of this history is summarized in the appendices, which document the civil service employees and military personnel who have participated in the weather radar program. It is noteworthy that six of the first nine employees of this program were on the staff of Air Force Geophysics Laboratory (AFGL) as late as 1980 and that three have worked in the weather radar program for thirty-four years or more.

This account is focused on the work and people of the weather radar program. We refer to the work of other organizations only as it has contributed to this program. Similarly, we note the prior or subsequent experience and affiliations of members of the weather radar program as these relate to the ongoing Air Force program. Over the years there have been changes in the larger organizational structure within which the weather radar program has been conducted, reflecting changes of emphasis and orientation in Air Force research and development. These changes result in varying references to organizational elements throughout the narrative. Details of the laboratory organizational structure and evolution, which were compiled by Liebowitz (1985), are generally beyond the scope of the present paper.

2. ORIGINS -- 1948-1954

SIGNIFICANT EVENTS AND ACCOMPLISHMENTS

Backscattering and propagation studies
Observation of upper snow bands and melting layer
Observation of "angel" echoes in sea breeze, Round Hill, 1953

Weather radar research activity was underway in several places by 1947, largely as an outgrowth of radar development during World War II. The U.S. Army Signal Corps had established a Weather Radar Section in its Evans Signal Laboratory in Belmar, N.J., with primary emphasis on radar storm detection, and in early 1946 had begun to support the Weather Radar Research Project at Massachusetts Institute of Technology (MIT). The Army Air Forces (AAF) had initiated a weather radar program (Project AWMET-8) in the All Weather Flying Division (AWFD) at Wright Field, Ohio, in December 1945 "to investigate the use of airborne radar in meteorology with particular emphasis on the avoidance of hazardous weather conditions (Atlas, 1947)." The program was led by three first lieutenants: David Atlas, who had attended radar school at MIT and Harvard University as a weather officer and had been attached to AWFD in 1945, Robert W. Miller, and W. C. Kellogg. (The latter two are not to be confused with meteorologists R. C. Miller and W. W. Kellogg.) The operational phase of the program continued through July 1946, encompassing both winter and summer weather regimes (Miller, 1947). The second phase of the Thunderstorm Project, coordinated by The University of Chicago and conducted in Ohio in the summer of 1947 in collaboration with AWFD, further served both to demonstrate the value of radar for storm measurement and to establish directions for future research and equipment development. Weather radar research was also underway at Harvard University, the University of Florida, McGill University in Montréal, the University of Texas at Austin, and the Naval Research Laboratory.

An atmospheric laboratory was established by the Air Materiel Command of AAF in its Watson Laboratories in Red Bank, N.J., in March 1947. This laboratory, renamed the Geophysical Research Division (GRD) in February 1948, hired David Atlas in May 1948 to lead a new weather radar research program. He moved from Red Bank to the Boston area in October, when GRD was transferred from Watson Laboratories to the Air Force Cambridge Field Station. This program was initially part of the Electromagnetic Propagation Laboratory, directed by Nathaniel C. Gerson, and was located at Watertown Arsenal with other elements of the Division. Early members of the program included Harold Banks, who came from Red Bank with David Atlas; Ludwig Katz; and Wilbur Paulsen. Wilbur Paulsen had worked in the Radiation Laboratory during World War II and subsequently at the Naval Research Laboratory until the end of 1949. Harold Banks and Ludwig Katz were in the weather radar program only briefly. Banks left in 1950 or 1951 to serve as a weather officer during the Korean War. Katz transferred to the space physics research program in GRD by late 1951 and remained with that program until retiring from civil service in 1976. Vernon Plank joined the weather radar program in the spring of 1951, having previously been involved with radio signal propagation research at the Naval Electronics Laboratory in San Diego, Calif.

Later that year, the program was transferred to the Atmospheric Physics Laboratory, directed by Peter H. Wyckoff, where the weather radar group became the Field Studies Unit within the Cloud Physics Section under Charles Anderson. (It became the Weather Radar Unit in April 1954.) In December 1951 the weather radar group moved to a new building at L. G. Hanscom Field, Bedford. The new building was a small brick structure, which still stands as Building 1115, on Katahdin Hill near the present-day buildings of AFGL. Albert Chmela joined the group in April 1952, having been a member of the Atmospheric Physics Laboratory since early 1951. Airman 2nd Class Kenneth Glover was assigned to the Unit in November 1952 as an electronics technician; he separated from the Air Force (as Staff Sergeant) in September 1955. Vernon Plank reluctantly left the Unit in 1953 to join the new airborne cloud physics research group led by Robert Cunningham, who had recently joined the Section after finishing his doctorate at MIT. Plank was selected for this transfer because of his prior experience in airborne meteorological measurements. Ralph Donaldson, who had been a member of the Electromagnetic Propagation Laboratory since 1949 but not in the weather radar program, then transferred into the Field Studies Unit. Graham Armstrong joined the Unit as a radar technician in February 1953; he was reclassified as an engineer in 1961. Leonard Shodin, who is remembered as a skillful technician, joined the Unit in March 1953. He transferred to the Antenna Laboratory of AFCRC in May 1954 to avoid a lengthy commute to the Great Blue Hill. He was replaced in June by Ruben Novack, who transferred from the transformer shop of the Research Services Branch. Wilbur Paulsen left the Unit in August 1954 to lead an effort in the development of operational remote sensing equipment in the Meteorological Development Laboratory.

A major research effort from the beginning involved the effects of the atmosphere on the scattering and propagation of radio-frequency signals. Part of this work was conducted in-house and part was conducted on contract at McGill University. This contract was a key element in the establishment of the Stormy Weather Group there under Prof. J. Stewart Marshall. (This Group was an outgrowth of Project Stormy Weather, established at McGill University by the Canadian Army Operational Research Group toward the end of World War II.) Among the students pursuing advanced degrees in this group were Kenneth Gunn and Walter Hitschfeld. From this contract came the landmark paper on the statistics of meteorological radar signals by Marshall and Hitschfeld (1953) and other reports on radar backscatter from rain, snow, and hail. Milton Kerker, a colloid chemist at Clarkson College of Technology in Potsdam, N.Y., attended a conference on scattering phenomena at McGill University, became interested in the problems of microwave scattering by hydrometeors, and spent some time at McGill. His early work on the subject inspired David Atlas to pursue the problem

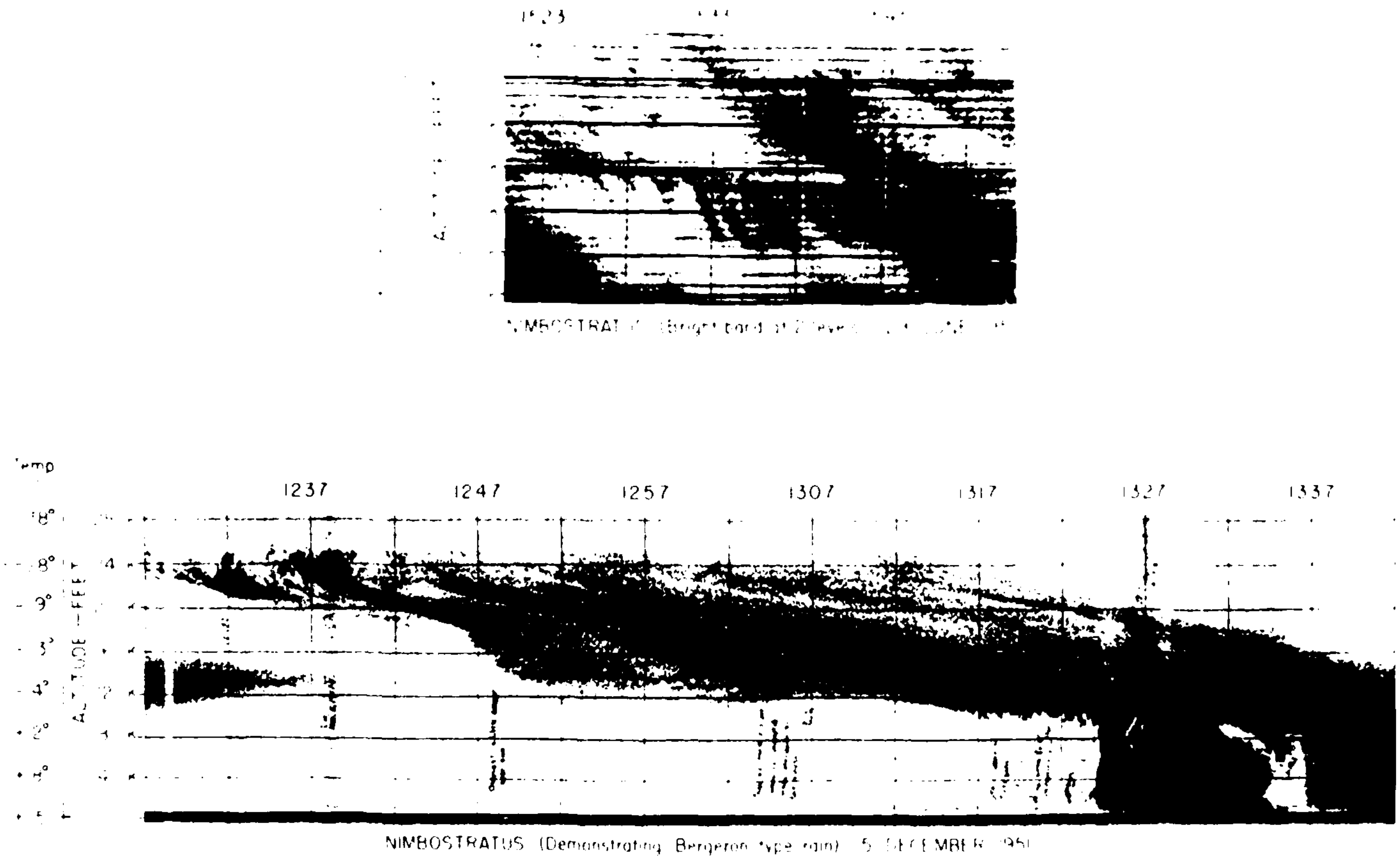

Figure 1. Precipitation Streamers Observed in 1951. Observation was made by vertically pointing 1.25-cm APS-34 radar (after Plank et al., 1955; copyright 1955 by the American Meteorological Society).

of polarization effects in backscatter from non-spherical particles as a master's degree thesis at MIT and in collaboration with McGill University (Atlas, 1951; Atlas et al., 1953a). The results of the entire effort were summarized by Atlas et al. (1952). David Atlas learned in 1987, while visiting Japan, that his work with Kerker and Hitschfeld had inspired Tomohiro Oguchi at the Radio Research Laboratories in Tokyo to pursue the study of electromagnetic scattering from non-spherical particles for which Oguchi is now well known. The scattering amplitude coefficients computed by Oguchi and his colleagues have been invaluable in studies of polarization dependent radar backscatter at AFGL and elsewhere.

By 1951 the weather radar group had acquired and modified a war surplus APS-34 radar for quantitative meteorological studies. This 1.25-cm wavelength vertically pointing radar, which became known affectionately as the "clunker," was a mainstay of the observational work of the Unit for several years. The 21 December 1951 issue of the weekly *GRD Spectrum* described it as "a weird assortment of electronic equipment, all specially designed to measure the characteristics of the echoes received by radar, which unlike most radars looks only overhead." It was operated at Watertown Arsenal from June to December 1951 and thereafter at Katahdin Hill, Lexington (Plank, 1956). These observations led to improved understanding of the melting layer and of the precipitation streamers that were originally called "upper snow bands" (Figure 1). Efforts were also underway to develop improved quantitative measurement of precipitation by radar. This work contributed substantially to the development of statistical relationships between radar reflectivity and rainfall rate (Plank et al., 1955). In June 1952 the Unit acquired a TPQ-6 scanning 8.6-mm wavelength radar, designated a "Cloud Base and Cloud Top Indicator," which was put into routine observational use beginning in February 1954 (Figures 2 and 3).

In early 1951 work began on a "Cloud Contour Mapping System," which incorporated a 1.25-cm APS-1 radar. This system was intended to replace the "clunker." Because Dr. Gerson objected to the term "contour mapping," it was officially designated the "Hydrometeor Isopleth Determinator." Construction of the system was contracted to Polytechnic Research and Development Co. (PRD) of Brooklyn, New York. After several renegotiations and extensions of the contract, the system was delivered in November 1955. Several problems were identified, and work on improvements continued intermittently through 1956 and into 1957. By that time, however, because priorities had changed and new equipment was

Figure 2. Facilities of the Weather Radar Program at Hanscom Field about 1954. APS-34 radar antenna is on the trailer to the left of the building; TPQ-6 antenna is on the roof.

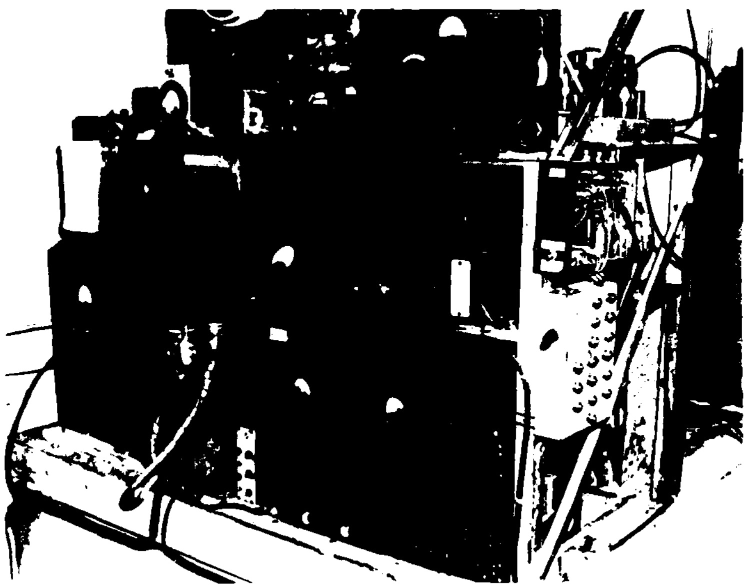

Figure 3. Controls and Display of the APS-34 radar. Equipment is located inside the trailer. Single oscilloscope display is just visible at the upper left, receiver gain control is on the right, and the signal integrator for a single range gate is at the left.

available, the system had limited use.

In May and June 1953 the Field Studies Unit, with other members of the Cloud Physics Section, went to the MIT Round Hill Field Station in South Dartmouth, Mass., with the APS-34 radar and other instrumentation to observe coastal fog. Observations included radar reflectivity at vertical and horizontal incidence by means of two fixed antennas, drop size distribution by means of a wind tunnel and impaction device, liquid water content by means of a ventilated screen collector, visibility by means of a transmissometer, and microwave refractivity. Prior to this time, the 1.25-cm radar had detected echoes in the absence of clouds and precipitation. This field measurement program yielded the first observations of such echoes in conjuction with refractivity observations (Figure 4), which strongly suggested that some of these "angel" echoes originated from regions of the atmosphere associated with strong refractive index inhomogeneities (Atlas et al., 1953b; Chmela and Armstrong, 1955; Atlas, 1960a). Vernon Plank developed an analysis of radar "angels" observed at Round Hill and elsewhere as a master's degree thesis at MIT (Plank, 1954) and later expanded it as a technical report (Plank, 1956). He favored the hypothesis that insects and birds were the cause of most "angel" echoes, but acknowledged that some might be due to refractive index inhomogeneities. Among his recommendations was that an investigation be conducted with radars of different wavelengths to determine the wavelength dependence, and hence the physical basis, of these echoes.

3. THE BLUE HILL YEARS -- 1955-1961

SIGNIFICANT EVENTS AND ACCOMPLISHMENTS

Quantitative precipitation measurements
First rain parameter diagram, 1957
Hurricane studies initiated, 1954
Severe convective storm studies (hail, lightning, winds)
    Observer network, 1955, 1956
Clear air backscatter observations, S. Truro, 1957
Hail backscatter theory and laboratory measurements
First wind profile by Doppler radar, 1961

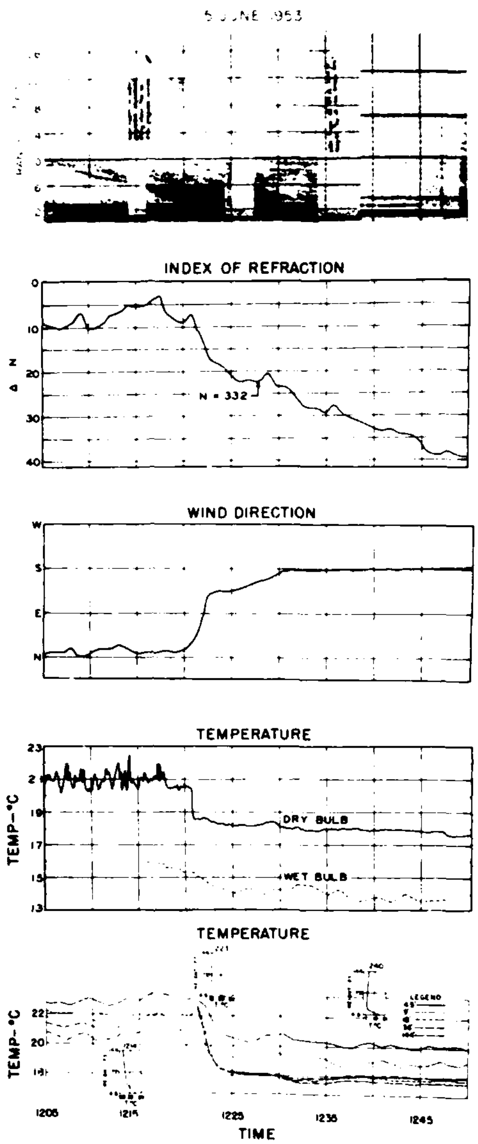

Figure 4. Radar Echoes Observed in the Sea Breeze at Round Hill, Mass., 15 June 1953. APS-34 radar antenna was pointed alternately horizontally toward the ocean (when ground echo is displayed to 3,000 ft range) and vertically. Range-time display shows the approach of echoes from as far as 10,000 ft horizontal range as the sea breeze front approached the coastline. Ancillary data indicate the associated changes of refrective index and meteorological parameters (after Atlas, 1959c, by permission of Pergamon Press).

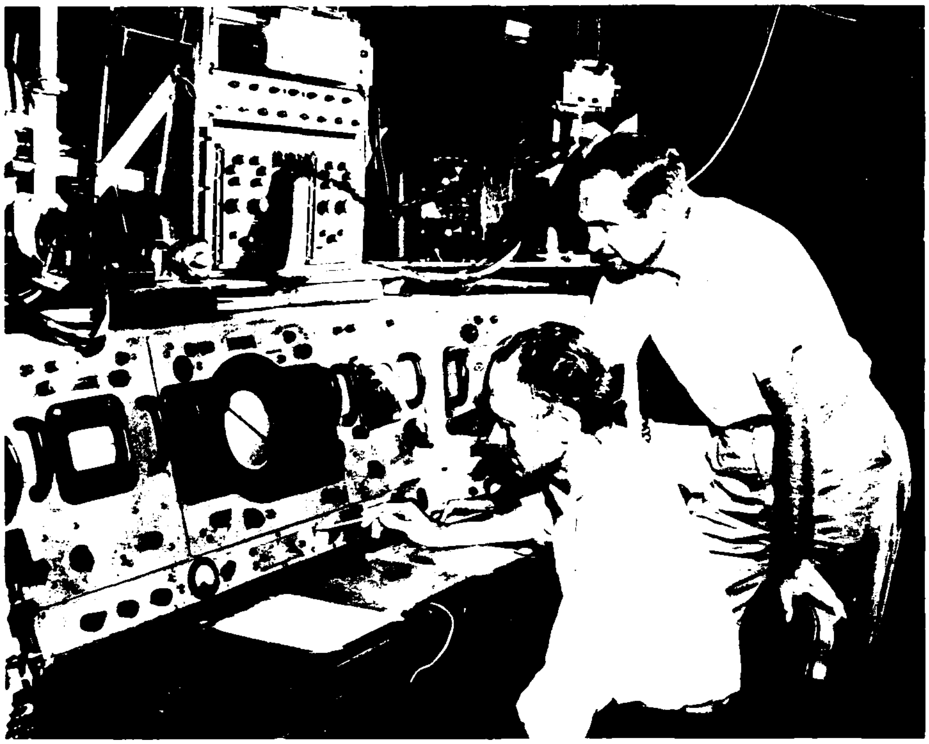

Figure 5. Console of the CPS-9 Radar on the Great Blue Hill, 1956. Roger Lhermitte (seated) and Ralph Donaldson are observing the display.

In 1954, as portions of the Air Force Cambridge Research Laboratories (AFCRL) were being moved to Hanscom Field from prior locations in Cambridge and Boston, plans were made to move the Weather Radar Unit from Katahdin Hill to more spacious quarters on the Great Blue Hill in Milton, Mass. The move was deemed necessary because of the construction of a large water tower on Katahdin Hill and because of anticipated interference from a high-power search radar being constructed by MIT Lincoln Laboratory nearby. In the same year the Unit acquired a new CPS-9 3.2-cm weather surveillance radar, one of about 45 which were being built by Raytheon Co. on contract from the Army Signal Corps for operational use by the Air Force and the Navy. This radar was installed on the Great Blue Hill in November 1954, and the move was complete by September 1955 (Figures 5 and 6). On the Great Blue Hill the Weather Radar Unit collaborated with the staff of the Blue Hill Meteorological Observatory, then operated by Harvard University and directed by Charles F. Brooks, founder of the American Meteorological Society (AMS). The observatory provided some office space, and the Air Force installed two canvas-covered Jamesway structures nearby to house the radar equipment and additional offices. The Unit had already contracted with the Observatory to conduct research related to radar observations of storms, and this contract was expanded to include the services provided to the Unit on the Great Blue Hill. Air Weather Service (AWS) established a unit there in July 1955 under Detachment 6, 4th Weather Group, at Hanscom Field and assigned 5 people to operate the CPS-9 and to relay observations to the Detachment at Hanscom Field and to the U. S. Weather Bureau office at Logan Airport, Boston. Among the AWS technicians assigned to the AWS unit from July 1955 to October 1956 was Edward Duquette, who joined the staff of the Branch in July 1961. Ronald Podsiadlo, who is now Program Area Coordinator for atmospheric sciences in AFGL, was officer in charge of the AWS unit on the Great Blue Hill as a first lieutenant from 1959 to early 1961.

As a remotely located organization, the Unit generated many requests to the Laboratory for supporting equipment and supplies. One of the challenges of the Blue Hill site was access in winter. A request in December 1955 for a St. Bernard dog with brandy was declined, allegedly because of the lack of fire hydrants along the road. Following two particularly heavy snowfalls in March 1956, when the road was impassible by car for nearly four weeks, members of the Unit were issued snowshoes to aid the 400-ft ascent from the parking lot at the base. The Unit eventually had the use of an Army four-wheel drive weapons carrier to negotiate

Figure 6. Summit of Great Blue Hill in Winter, 1960. Blue Hill Meteorological Observatory is in the "castle" at right. Air Force radar facility, including the CPS-9 radar, is in fenced area at left.

the snow-covered road to the hilltop. Near the top was a place where water seeped out from the rocks and froze on the road surface, forming a treacherous ice slope known as the "glacier." On one occasion while descending the hill, Graham Armstrong lost control at this point and, with Pio Petrocchi and Ruben Novack as passengers, had to guide the vehicle down a ski slope.

Research continued to focus on precipitation microphysics and the structure of precipitation systems. Primary goals of this work were the measurement of precipitation by radar and the use of radar to deduce precipitation growth mechanisms. Theoretical and experimental studies of precipitation development in stratiform clouds provided the basis for David Atlas' doctoral dissertation at MIT (Atlas, 1955). The microphysical and synoptic influences on the reflectivity-rainfall relationship were studied in considerable detail, and the first rain parameter diagrams relating reflectivity, rainfall rate, and drop size distribution parameters were developed (Atlas and Chmela, 1957). On 11 September 1954 Hurricane Edna was observed with the FPS-3 (23 cm), FPS-4 (3 cm), and FPS-6 (10.7 cm) radars operated by MIT Lincoln Laboratory at South Truro, Mass. On this occasion the FPS-6 provided the first vertical cross-section of radar reflectivity through the eye of a hurricane (Figure 7). Edwin Kessler, who had joined the Unit the previous month, led the comprehensive analysis of this hurricane (Kessler and Atlas, 1956; Kessler, 1958) and in subsequent years made comparative studies including other hurricanes observed from the Great Blue Hill and from South Truro (Kessler, 1957a). These and other observations of hurricanes by radar were reviewed by Donaldson and Atlas (1964). The intense snowstorm of 16 March 1956 provided the subject for Kessler's doctoral dissertation at MIT (Kessler, 1957b), which was a comprehensive analysis of the radar observations and synoptic data associated with this storm. The problem of hail detection by radar received considerable attention as quantitative methods improved. Theoretical work (Atlas and Donaldson, 1955) was based on earlier studies of scattering and propagation effects and included the first suggestion of identifying hail by means of the parameter now known as differential reflectivity. Atlas and Donaldson focused on the possibility of identifying large, oriented hailstones by means of a differential reflectivity greater than unity (positive decibel values), which is contrary to modern understanding. Their report was classified for four years and remained obscure thereafter. In 1955 and 1956 a network of over 200 cooperative observers was organized to support research on the identification of severe storm hazards by radar. The 28 June 1956 issue of *GRD Spectrum* encouraged GRD employees and

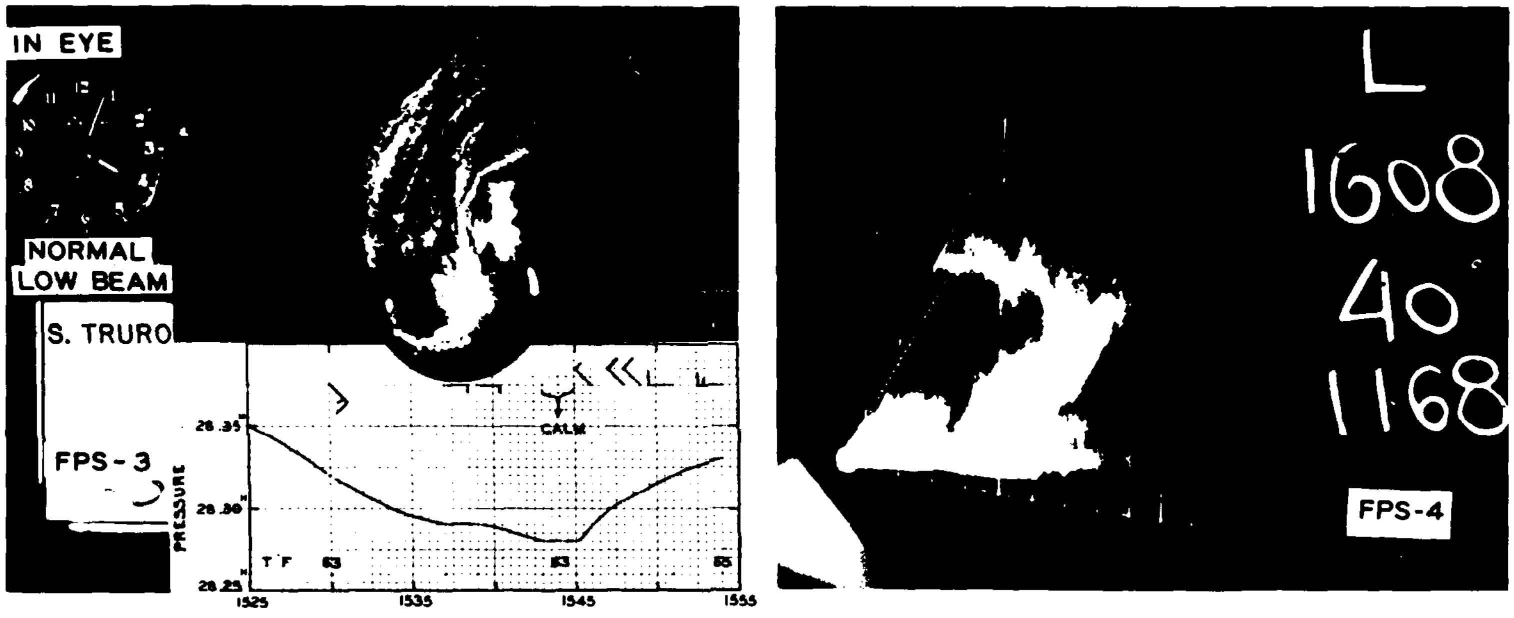

Figure 7. Radar Reflectivity of Hurricane Edna, 11 September 1954. Hurricane was observed in plan position (left) by the 23-cm FPS-3 radar and in vertical section through the eye (right) by the 3-cm FPS-4 radar at South Truro, Mass. Range markers are at 10 nautical mile intervals on left and at 5 nautical mile intervals on right. Eye of hurricane was located 15 nautical miles northeast of the radar and appears as a "V" in the low-level echo in the vertical section (after Kessler and Atlas, 1956, and Kessler, 1958; copyright 1958 by the American Meteorological Society).

their families to participate in this network. Various characteristsics of storms as measured by radar were related to the occurrence of hail, lightning, and severe winds (Chmela, 1960; Donaldson, 1958, 1959, 1961). A significant part of the research on the relationship of lightning to storm parameters observable by radar was performed by Charles Shackford (1960), working under contract first at Blue Hill Meteorological Observatory and subsequently at Allied Research Associates, Inc., in Concord, Mass.

The Unit continued to use the FPS-6 radar at South Truro, primarily for observations of thunderstorms. In July 1957 this radar revealed echoes due to lightning, extending upward from the precipitation echo of a severe convective storm (Atlas, 1959a). In June and July of 1957 Lincoln Laboratory was conducting propagation studies, using a refractometer mounted on an aircraft. By means of refractive index soundings it was possible to associate observations of layer echoes in the clear atmosphere with the existence of refractive index gradients (Atlas, 1959b). A review of these and earlier measurements of radar backscatter from the clear atmosphere was presented by Atlas (1959c) in the Proceedings of the Fourth Meeting of the Joint Commission on Radio-Meteorology, which was held at New York University in August 1957. Considerable disagreement developed within the radar meteorological community, and within the Unit, concerning the relative significance of "point targets" (birds or insects) and refractive index inhomogeneities in the occurrence of these "angel" echoes. It would be the mid-1960's before this issue was finally resolved.

At the Sixth Weather Radar Conference, held at MIT in March of 1957, David Atlas was the surprised recipient of the Meisinger Award of the AMS. This award, given annually with preference to individuals of age 35 and under (Atlas was 32), recognizes "research achievement that is, at least in part, aerological in character." In honor of his pioneering work in radar meteorology since the inception of the weather radar program, David Atlas also received the Guenter Loeser Award from Air Force Cambridge Research Center (AFCRC) in 1957. This annual award recognizes the career contributions to science by the recipient. His lecture on the occasion of receiving this award summarized the progress and prospects of radar meteorology (Atlas, 1960b).

The personal character of the group evolved gradually. In December 1955 William Lamkin was hired as a technician to replace Kenneth Glover, who had separated from the Air Force in September. Edwin Kessler was a member of the

Unit until 1960. In 1956 Roger Lhermitte, from the Research Department of the French Meteorological Office, collaborated with the Weather Radar Unit while visiting the Blue Hill Meteorological Observatory for a few months under Air Force sponsorship; he joined the Branch as a staff member in January 1961. Roland Boucher, who joined the Branch in 1967, was a member of the Observatory staff from 1952 to 1957 and was substantially involved in the contract studies of storm structure as revealed by radar measurements. Throughout this period David Atlas urged Peter Wyckoff, Chief of the Atmospheric Physics Laboratory, and Milton Greenberg, Director of the Geophysics Research Directorate (GRD), to establish the weather radar program as a separate section with responsibility for all Air Force research and development related to weather radar. In February 1958 this change was accomplished, coincident with a reorganization of GRD. At the same time Wilbur Paulsen returned to the group with Pio Petrocchi, whom he had hired in 1955. They had worked on the development of the TPQ-11 cloud detection radar and lightning detection equipment, and the 1958 reorganization brought these activities into the Weather Radar Section, which in April 1958 was redesignated the Weather Radar Branch. New members of the engineering staff included Frank Gibson, who was hired in April 1960, and Hugh Sweeney and Paul Daly, who transferred into the Branch from the Electronics Research Directorate of AFCRC in May 1960.

From June 1959 to August 1960 David Atlas was at Imperial College, London, on a National Science Foundation post-doctoral fellowship. There he first met Keith Browning and collaborated with Frank Ludlam and William C. Macklin of Imperial College and W. G. Harper of the British Meteorological Office in studies of severe storm structure and radar backscatter from hail (Atlas et al., 1960). The Wokingham storm of 9 July 1959 yielded the first radar observation of the region of weak or undetectable radar echo which Browning and Ludlam (1962) associated with the main updraft in the storm. (Keith Browning, who had studied architecture, named it the "echo-free vault;" Ralph Donaldson preferred the term "chimney" to describe this feature, because of its association with the updraft; now it is known as a "bounded weak echo region.") The studies of hail backscatter led to subsequent studies of backscatter from dielectric spheres at the AFCRC radar measurement facility in Ipswich, Mass. (Atlas and Wexler, 1963; Atlas and Glover, 1963), and at Eglin Air Force Base, Fla., where artificial hailstones were dropped from a balloon for observation by radar (Willis et al., 1963). Some of these backscatter measurements were presented at the Interdisciplinary Conference on

Electromagnetic Scattering convened at Clarkson College of Technology in August 1962 under the leadership of Milton Kerker and under the partial sponsorship of AFCRL.

In addition to the Cloud Contour Mapping System described above, another 1.25-cm radar, capable of rapid elevation scanning, was under development in 1955 and 1956. The APS-1 eventually supplanted the APS-34, but neither it nor the zenith-scanning radar saw extensive use in the research of the Branch. A contract for the development of a prototype of the TPQ-11 was let by the Air Force in 1958, and one of the early units was delivered to the Great Blue Hill in August 1959. Wilbur Paulsen and Pio Petrocchi were primarily responsible for its evaluation, an effort that continued into the 1960's (Petrocchi and Paulsen, 1966; Paulsen et al., 1970). In 1960 the development of a Storm Radar Data Processor (STRADAP) was initiated, with the goals of analyzing radar reflectivity data in real time and displaying digital representations of the received power and the echo top height. This processor, originally conceived by David Atlas, was developed and constructed by the Budd Electronics Co. Its initial use, in 1962, is described in the following section.

In the summer of 1961 David Atlas, Roger Lhermitte, Graham Armstrong, and William Lamkin went to Flagstaff, Ariz., to collaborate with the Cloud Physics Branch and other research agencies in Project High Cue, a study of precipitation initiation in the convective clouds that occur regularly in summer over the San Francisco Peaks nearby. They took two recently acquired APQ-70 dual-wavelength (0.86 and 1.82 cm) radars and sferics detection equipment. Among the participants in the project was Kenneth Hardy from the University of Michigan. Although useful results emerged from the cloud physics measurements (Hardy, 1963), attempts to deduce rainfall rates from the radar measurements yielded inconclusive results (Rogers and Wexler, 1963). Participation of the weather radar group in this project is memorable primarily for the attempt by Atlas, Lhermitte, Armstrong, and others to rescue a pilot and graduate student following the crash of their helicopter near a mountaintop, where they were attempting to place a meteorological instrument package. They found the pilot dead at the site, and the student, who was severely injured, was evacuated to a local hospital, where he died three months later.

4. GETTING ESTABLISHED IN SUDBURY -- 1962-1971

SIGNIFICANT EVENTS AND ACCOMPLISHMENTS

Doppler radar observations and techniques
- Airborne Doppler radar development, 1962
- Plan Shear Indicator, 1966
- First mesocyclone observation, 1968

Multi-wavelength observations of rain, 1970-1971

Clear air backscatter observations, Wallops Island, 1964-1971
- First detection of tropopause by radar, 1966

Dr. Brooks retired from Harvard University in 1957 and died suddenly in January 1958. Subsequent changes at the Observatory and the reluctance of the Metropolitan District Commission, which owns the Blue Hills as a public reservation, to allow the Air Force to expand its facilities forced the Branch to seek a new location. Ralph Donaldson, Wilbur Paulsen, and Pio Petrocchi investigated several prospective sites, including Prospect Hill in Waltham, where the Air Force already had a microwave facility; Air Force property on Fourth Cliff in Scituate; Moose Hill in Sharon; Monks Hill in Kingston; Nobscot Hill in Framingham; Summer Hill in Maynard; and a hill in the Army Quartermaster Corps property in Sudbury. The latter site was selected, and the first building was occupied in September 1961. This building was a prefabricated metal building from Hamburg, Germany, which was known, therefore, as the Hamburg Building. A concrete block building for offices, instrumentation, and data analysis was ready for occupancy in February 1962, when the move from the Great Blue Hill was completed (Figure 8). The hill was known in the local community as Hapgood Hill because members of the Hapgood family had resided there for more than 100 years before the Army acquired the land in the 1930's. It was known to the Army as Pig Hill, because it was alleged that the carcass of a pig that had been used in conjunction with early atomic bomb tests in the Pacific was buried there. The official name of the installation was the Weather Radar Field Station.

Several new staff members were hired in the early 1960's. Roger Lhermitte was in the Branch from January 1961 until May 1963. Keith Browning joined the Branch in September 1962, following completion of his doctorate at Imperial College. He remained with the Branch until late 1966, when he returned to

Figure 8. Weather Radar Field Station on Pig Hill, Sudbury, about 1969. Hamburg Building is to the right and behind main building. CPS-9 radar is on tower immediately behind main building. FPS-6 radar antenna is on the more distant tower. Trailer in left foreground contains Porcupine radar. Truck in center foreground contains the dual-beam radar.

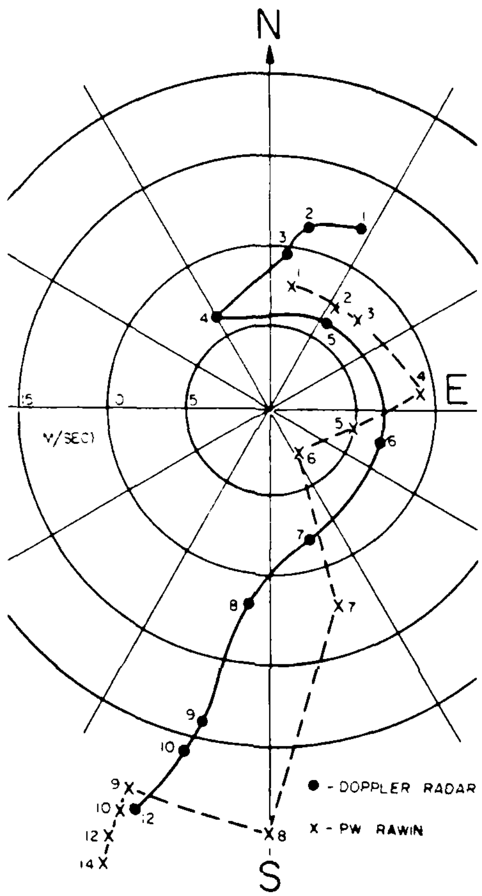

Figure 9. First Wind Profile Derived from Doppler Radar Data, 27 May 1961. Wind profile was derived by the Velocity-Azimuth Display (VAD) technique from measurements by the Porcupine Doppler radar. Solid line denotes the radar measurements and broken line denotes the National Weather Service rawinsonde observation from Portland, Maine. Hodographs are labeled with height in thousands of feet above mean sea level (after Lhermitte and Atlas, 1961).

England to pursue a distinguished career in the British Meteorological Office. (He is now Deputy Director for Physical Research and is a Fellow of the Royal Society.) Kenneth Glover rejoined the Branch as a civilian in 1962, and Kenneth Hardy came to the Branch in 1963 after completing his doctorate at the University of Michigan.

Wilbur Paulsen, Paul Daly, Frank Gibson, and Pio Petrocchi transferred into the Meteorological Development Laboratory in 1961, when once again the function of operational instrumentation development was separated from the function of weather radar research. In 1961 and 1962 they conducted tests at Pig Hill with the FPS-68 radar, and they continued with the development of its successor, the FPS-77, which became the operational weather radar of the Air Force (Paulsen and Petrocchi, 1966; Paulsen, 1968).

When the research contract with the Observatory ended, several of the Observatory staff, including Roland Boucher, Charles Shackford, and Raymond Wexler, joined Allied Research Associates, Inc., to continue their collaboration with the Branch under a new contract. In 1965 a contract was initiated with Northeastern University in Boston to modify the APQ-70 radars and to provide additional technical support for radar operations. Alexander Bishop, who had worked previously for Lincoln Laboratory as a radar engineer at *Millstone Hill*, and technician William Smith worked at Pig Hill under this contract, and both joined the Branch in 1967. (This contract was one of several technical support contracts of AFCRL that were terminated about this time when it was decided that these functions should be performed by an expanded civil service staff.) On Pig Hill the Branch required a secretary, having relied previously on the secretarial services in the Cloud Physics Section or the Blue Hill Meteorological Observatory. Gloria Bedard served as secretary for a short time in 1962. She was succeeded by Geraldine Reynolds, whose husband Charles was a branch chief in the Aerospace Instrumentation Laboratory, and Beverly Goldberg, whose late husband Paul had been administrative assistant to the director of the Meteorology Laboratory. Alice Wood came to the Branch in 1964 and worked for about four years before moving to Connecticut; she has stayed in touch with the Branch through Christmas cards and occasional notes. June Queijo, a resident of Sudbury, became secretary in 1967 and remained until 1972.

Before moving to Sudbury, the Branch had obtained the use of a 5-cm wavelength Doppler radar known as "Porcupine" which had been built by MIT

Lincoln Laboratory. It was first used by the Branch in 1957, when an audio recording of the Doppler velocity in a single range gate was made during an azimuth scan. This radar, with a RAYSPAN frequency analyzer, yielded the first radar-derived wind profile, using the Velocity Azimuth Display (VAD), on 27 May 1961 (Figure 9). The VAD technique, described first by Lhermitte and Atlas (1961) and later in more detail by Browning and Wexler (1968), derives a horizontal wind speed and direction and other wind field parameters from the predominantly sinusoidal variation of Doppler velocity with azimuth at each given range. In late 1961 the Branch acquired the Porcupine radar from Lincoln Laboratory and in 1962, as part of a major overhaul of the radar, acquired an analog signal processor known as a Coherent Memory Filter (CMF) for derivation of Doppler spectral parameters at multiple ranges (Donaldson et al., 1969). The CMF provided the basis for the Plan Shear Indicator (PSI), conceived by Graham Armstrong and developed by Armstrong and Donaldson (1969), whereby Doppler velocity could be displayed in azimuth and range on a conventional radar Plan Position Indicator (PPI). The PSI was a display of concentric arcs, the radii of which were proportional to the ranges at which the received signal was gated. The width of each arc was proportional to the reflectivity and the Doppler spectrum variance, and the radial displacement of each arc from its nominal radius was proportional to the mean Doppler velocity. The variations of the concentric arcs on this display provided a semi-quantitative indication of radial and azimuthal shear of the Doppler velocity. Ralph Donaldson determined the PSI pattern indicative of a cyclonic vortex and on this basis on 9 August 1968 first identified in real time the rotating wind field aloft (now known as a mesocyclone) which precedes and accompanies a tornado (Figure 10). Donaldson (1970a) described in more detail the technique for identifying a mesocyclone from observations by a single Doppler radar. By demonstrating the value of a single Doppler radar for real-time evaluation of severe storm dynamics, Donaldson laid the cornerstone for the development that led to the Next Generation Weather Radar.

The Porcupine radar was used for a variety of measurements of turbulence and air motion in storms. Sweeney (1968) used the recently developed Cooley-Tukey fast Fourier transform algorithm to analyze observations of turbulence in the lowest few hundred meters of the atmosphere. Jan Børresen, from the Norwegian Defence Research Establishment, visited the Branch in 1968-1969 on a North Atlantic Treaty Organization (NATO) Science Fellowship. He conducted measurements with the Porcupine radar and deduced characteristics of turbulence

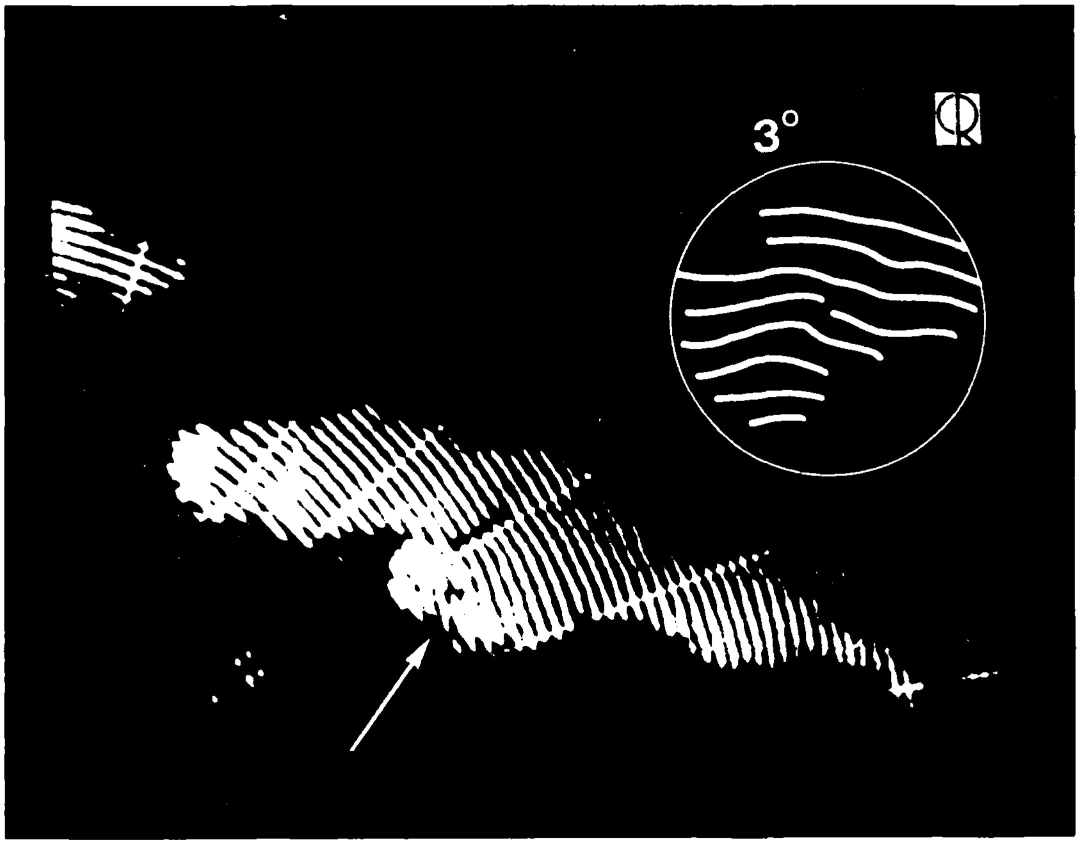

Figure 10. First Radar Observation of a Mesocyclone, 9 August 1968. Plan Shear Indicator (PSI) display shows the Marblehead, Mass., storm in northeast quadrant (radar location at lower left). Mesocyclone pattern, marked by arrow, is near 50° azimuth and 30 km range, corresponding to a height of 1.6 km at 3° elevation angle. Inset depicts mesocyclone structure in detail (after Donaldson et al., 1969).

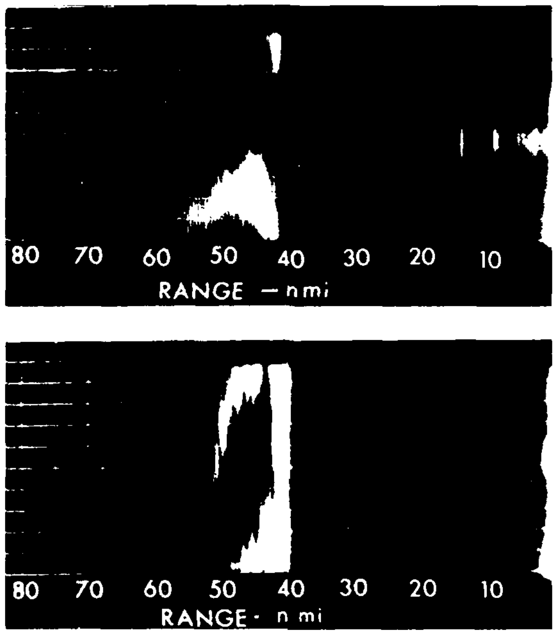

Figure 11. Examples of Doppler Radar Data Recorded on Microfilm. Output from Coherent Memory Filter (CMF) is displayed on a Range Velocity Indicator (RVI), where the intensity represents power spectral density across the 25 m sec^{-1} unambiguous velocity interval. Mean velocity is estimated visually from this display, typically at 1 km range increments. The apparent spectral width on the display is related to both Doppler spectrum variance and signal intensity. Upper panel: Ground echoes are displayed with velocity near zero within about 15 miles range. Precipitation echoes at ranges of 40-60 miles are moving away from the radar; near 42 miles the velocity is partly aliased. Lower panel: Precipitation echoes at ranges of 40-50 miles exhibit severe velocity aliasing. Spectrum spanning the entire unambiguous velocity interval represents extreme shear or severe turbulence, and possibly a tornado vortex signature (after Donaldson et al., 1969).

and wind shear from small-scale azimuthal variations of the Doppler mean velocity, as an extension of the VAD technique (Børresen, 1971). Donaldson and Wexler (1969) examined the significance of the Doppler spectrum variance as an indicator of hazardous turbulence in storms, and Donaldson (1970b) applied the VAD technique to observations of thunderstorms.

The Storm Radar Data Processor (STRADAP) was delivered to the Branch in October 1962 and put to immediate use with the CPS-9 radar for the observation of convective storms and stratiform precipitation. The display of "7's" (the highest digital value) in conjunction with a tornado in Charlton, Mass., on 12 October 1962 was a cause for great delight on the part of the originator of STRADAP (Atlas et al., 1963a, 1963b). In 1963 STRADAP was taken to Norman, Okla., and adapted to the 10-cm wavelength WSR-57 radar there.

From the earliest years of the weather radar program there was substantial collaboration with the National Severe Storms Project and its successor, the National Severe Storms Laboratory (NSSL), headed by Edwin Kessler from 1964 to 1986. Major collaborative efforts in Norman, Okla., occurred from 1961 onward and involved many members of the Branch. The storm which produced the Geary, Okla., tornado in 1961 also produced the first radar observation of a "vault" in association with a tornado (Browning and Donaldson, 1963). On 26 May 1963, Ralph Donaldson and William Lamkin were at an Air Force radar site just east of Tinker Field, near Oklahoma City, and had the opportunity to observe visually a developing tornado passing overhead prior to touching down a few miles to the east (Donaldson and Lamkin, 1964). This storm was one of several on that day which were analyzed in detail by Keith Browning and others. The resulting case study encompassed synoptic and sub-synoptic atmospheric structure, storm initiation and organization, and precipitation development (Browning and Fujita, 1965). Portions of it were also published separately (Browning, 1964, 1965a, 1965b, 1966; Browning and Atlas, 1965). A summary of the early observations, with specific applications to severe thunderstorm forecasting, was presented by Donaldson (1965). Michael Kraus joined the Branch in 1968, after completing his master's degree at MIT and having worked with Ralph Donaldson during the two preceding summers. During the following eleven years Kraus and Donaldson were the leaders of the severe storm research in the Branch. This research increasingly emphasized the dynamics of severe storms as revealed by Doppler radar, which was the subject of Kraus' doctoral dissertation at McGill University (Kraus, 1974). Measurement of Doppler mean velocity and spectrum variance in the early 1970's was a tedious process, requiring visual examination of analog spectral data recorded on microfilm (Figure 11).

As the value of meteorological Doppler radar became evident, it was recognized that an airborne Doppler radar would greatly expand the measurement capability. Beginning in 1962, the Branch contracted with Motorola, Inc., to develop a Velocity Intensity Storm Analysis Radar (VISTAR), based on a radar built by Motorola under a previous Air Force contract (Bretzel and Kinzer, 1965). Data processing proved to be an insurmountable obstacle, as the multiple filters required for on-board Doppler processing were unreliable. The idea of an airborne meteorological Doppler radar would remain unrealized until the early 1980's.

Two of the APQ-70 radars were used as the basis of a dual-beam radar that was constructed by members of the Branch and by contractors. The goal of this development was to derive the cross-beam component of wind from the beat frequency in the incoherent video signal that resulted from the oppositely directed radial components of wind in the two beams. The theory was developed by Atlas and Wexler (1965), and measurements were reported by Lob and Bishop (1968) and Glover and Bishop (1968). While the wind speeds derived by this technique in some cases were similar to those measured by a Doppler radar, significant errors resulted from curvature of the wind field. The effect of curvature precluded the intended application of the technique, which was to measure wind speeds in hurricanes from an aircraft.

In June 1964 David Atlas received the Marcus D. O'Day Memorial Award from AFCRL. This annual award is given to the author or authors of the best AFCRL paper published in a scientific journal during the preceding calendar year. The award to David Atlas was for his review of radar methods of severe storm analysis (Atlas, 1963).

Investigations of radar backscatter from the clear atmosphere, which began in 1953 at Round Hill and included the observations from South Truro, were continued in 1964 with radar measurements in conjunction with aircraft operations at National Aeronautics and Space Administration (NASA) Wallops Station, Va., in collaboration with the Applied Physics Laboratory (APL) of The Johns Hopkins University (Hardy et al., 1966). The designation of the Wallops Island radars as the Joint Air Force NASA (JAFNA) facility was due substantially to the efforts of David Atlas to secure the radars for research after Lincoln Laboratory ceased operating them in 1964. These investigations yielded the first

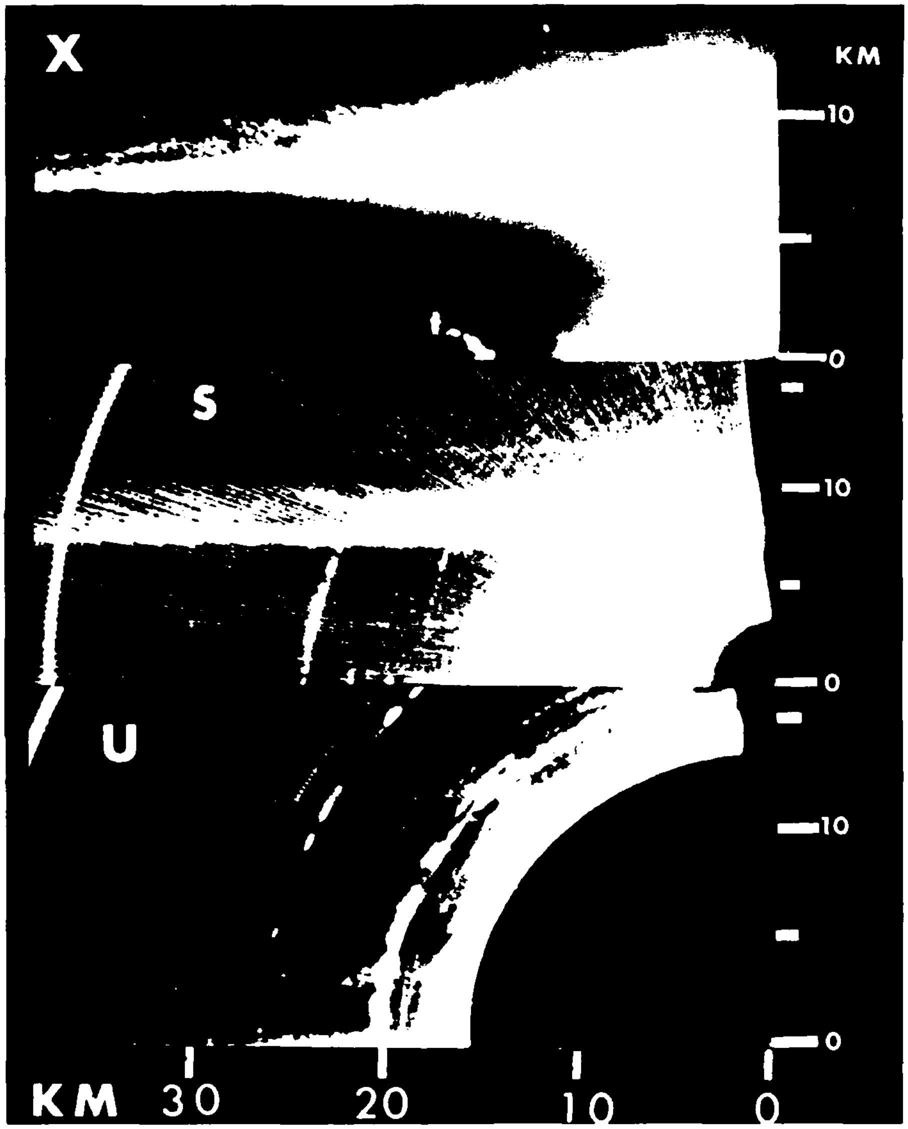

Figure 12. First Observation of the Tropopause by Radar, 18 February 1966. Observations (top to bottom) were made at Wallops Island, Va., with radars of 3 cm (X-band), 11 cm (S-band), and 72 cm (UHF) wavelengths. Tropopause is near 11 km height, above a cloud layer, which is strongly reflective at the shorter wavelengths but undetectable at 72 cm (after Atlas et al., 1966b; copyright 1966 by the American Association for the Advancement of Science).

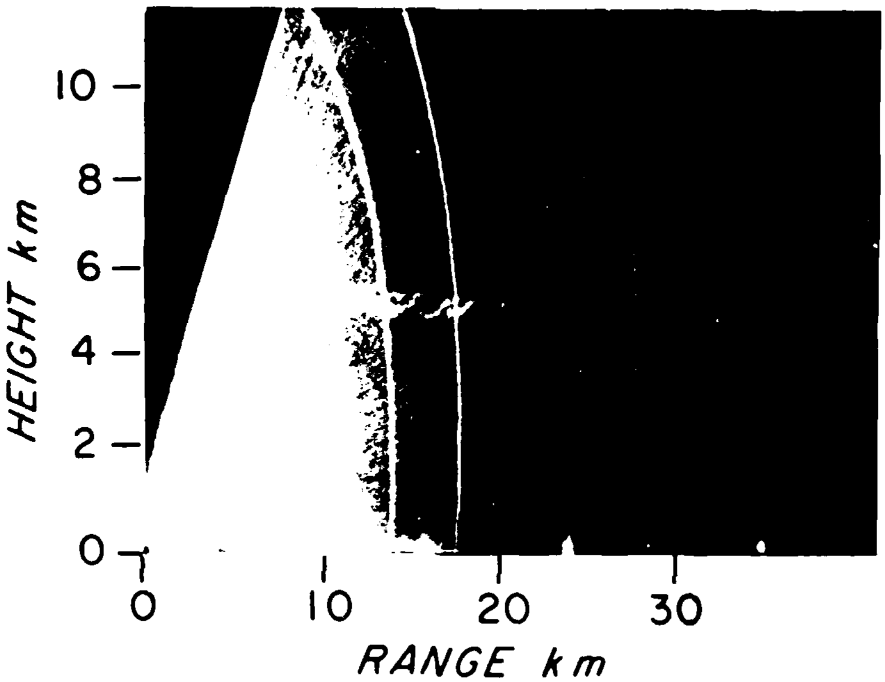

Figure 13. Classical "Braided" Structure of Clear Air Turbulence. Observation was made at Wallops Island, Va., with 10-cm wavelength radar in 1969. Structure near 5 km height is ascribed to the presence of breaking waves in a layer of strong refractive index gradient (after Boucher, 1970; copyright 1970 by the American Meteorological Society).

observation of the tropopause by radar (Figure 12; Atlas et al., 1966b). This paper provided inspiration to Richard Doviak, now at NSSL, and Julius Goldhirsh, now at APL, both of whom were then involved in electromagnetics and ionospheric propagation research at the University of Pennsylvania, to become involved with tropo-scatter and other meteorological applications of radar. Clear air turbulence observations at Wallops Island each winter through 1971 yielded greatly increased understanding of the origin, structure, and evolution of clear air turbulence (Figure 13; Glover et al., 1969; Boucher, 1970, 1974). In January and February 1970 the radars were used in coordination with an instrumented aircraft and a network of radiosondes in Project Haven Hop (Hardy et al., 1973). Jiro Aoyagi, an electronics engineer from the Meteorological Research Institute in Tokyo, was with the Branch for a year in 1964 and 1965 and was involved in the development of instrumentation for the early observations at Wallops Island. Keikichi Naito, also on leave from the Meteorological Research Institute in Tokyo for a year in 1965 and 1966, worked at Northeastern University, Boston, under the AFCRL contract and collaborated in the studies of clear air turbulence (Atlas et al., 1966a). Hans Ottersten, from the Research Institute of National Defence in Sweden, was a member of the Branch from December 1966 to June 1970 and was deeply involved in these investigations and related theoretical studies (Ottersten, 1969). Kenneth Hardy was also a key participant in the turbulence program. He spent the academic year 1970-1971 at the University of Washington, where he collaborated with Richard Reed in studies of clear air turbulence (Reed and Hardy, 1972). Hardy (1972) provided a comprehensive review of radar studies of the clear atmosphere. He succeeded David Atlas as chief in 1966, when Atlas left the Branch to become a professor of meteorology at The University of Chicago.

The other major thrust of research in the Branch was toward understanding of precipitation microphysics and the effect of precipitation on microwave signals at different wavelengths. The work on hail backscatter begun in the late 1950's was updated as new measurements of backscatter from spheres of mixed ice and water became available (Atlas et al., 1964). Landry and Hardy (1970) used the radars at Wallops Island, Va., to measure the fall speeds of plastic spheres simulating ice spheres and studied the effects of size and roughness on drag coefficient and fall speed. Rosemary Dyer, who joined the Branch in 1967 following graduate study at McGill University, used the Porcupine radar to deduce microphysical information from Doppler spectra, including a bi-modal spectrum observed within a melting layer (Dyer, 1970). Jurg Joss, from the Swiss Meteorological Institute, visited the

Branch in 1970-1971 under sponsorship of the National Research Council and conducted measurements of radar reflectivity and attenuation at wavelengths of 5 cm, 3 cm, and 8.6 mm. Robert Crane, then at Lincoln Laboratory, and Rosemary Dyer collaborated with him in correlating these measurements with measurements of raindrop size distributions at the surface (Joss and Crane, 1972; Joss and Dyer, 1972).

In the late 1960's Ralph Donaldson and Rosemary Dyer became involved in the evaluation of a radar system for ground-controlled approach that was being developed by the Electronic Systems Division (ESD) of Air Force Systems Command. This system, designated the TPN-19, incorporated an airport surveillance radar operating at 10.3-11.1 cm wavelength (2.7-2.9 GHz) and a precision approach radar operating at 3.26-3.33 cm wavelength (9.0-9.2 GHz). Donaldson, Dyer, and others, under the leadership of Alan C. Schell of the Microwave Physics Laboratory, evaluated the effects of rain on target detection, including both the masking effect of rain in the vicinity of the target and the attenuating effect of rain in the propagation path. Their results (Schell et al., 1972) cast some doubt on the ability of the precision approach radar to meet its specifications, particularly in heavy tropical rain. Partly as a result of this analysis, ESD reduced the number of units from 28 to 9 in the production contract.

Longtime members of the Branch remember the years 1968-1971 with particular fondness. Col. Dale Flinders, a former weather officer, was commander of AFCRL at that time and took particular interest in the work of the Branch. He would occasionally make an unannounced visit to the field site, 18 miles from Hanscom Field, "to see if [his] driver could find the way." In July 1970 the Office of Aerospace Research, which had been the headquarters agency for AFCRL, was abolished and all the Air Force laboratories were assigned to Air Force Systems Command. A result of this organizational change was an increased emphasis on laboratory support of Air Force systems development.

5. NEW TECHNOLOGY AND NEW APPLICATIONS -- 1972-1979

SIGNIFICANT EVENTS AND ACCOMPLISHMENTS

Missile and reentry vehicle test programs, 1971-1979
First on-line computer-generated displays, 1975
Pulse pair computation of Doppler mean velocity and spectrum variance, 1974
First downburst observed by radar, 1975
Hurricane Belle observed by Doppler radar, 1976
Joint Doppler Operational Project, 1977, 1978, 1979
Algorithm development for NEXRAD initiated, 1979

In 1969 the Branch funded Raytheon Co. to investigate the application of the "pulse pair" signal processing technique, which had been described a year earlier by Rummler (1968) at Bell Telephone Laboratories. This technique, which was to revolutionize radar meteorology, uses the signal autocovariance function computed at one-pulse lag time, i.e., from pairs of consecutive pulses, to derive estimates of Doppler mean velocity (from the phase) and spectrum variance (from the magnitude relative to that at zero lag time). The result of the Raytheon work (Benham et al., 1972) led to the design and construction of the first pulse pair processor for the real-time computation of Doppler mean velocity and spectrum variance. This processor was delivered in July 1974 (Novick and Glover, 1975). (Real time computation of Doppler mean velocity by the pulse pair technique had been achieved by Lhermitte [1972] at the University of Miami in July 1972.) Coincident with and subsequent to this development the Branch acquired two precision digital video integrators (Glover, 1972) for use in Sudbury and elsewhere, color video monitors in 1974 (Jagodnik et al., 1975) for display of reflectivity and Doppler parameters, and a Perkin-Elmer 732 computer in 1975 for the first real-time analysis of weather radar data. The initial application of this system was the derivation of water content profiles from reflectivity measurements (Figures 14 and 15).

These equipment acquisitions were facilitated by the involvement of the Branch in a series of missile test programs between 1971 and 1979, initially at NASA Wallops Flight Facility, Va., and subsequently at Kwajalein Missile Range in the Marshall Islands. The role of weather radar in these programs was for the

Figure 14. Vertical Section of Reflectivity in Stratiform Precipitation. Observation was made at Wallops Island, Va., in April 1975. Incremental markers are at 16 km distance and 4 km height. Equivalent reflectivity factor (mm^6 m^{-3}) is shown in decibel notation (dBZ). "Bright band" due to melting snow is near 2 km height.

Figure 15. Profile of Liquid and Ice Water Content. Display was derived in real time from the data of Figure 14. Computation incorporates different relationships of reflectivity and water content according to the hydrometeor type.

forecasting and documentation of weather conditions through which missiles and reentry vehicles passed (Plank, 1974; Barnes et al., 1974). These programs yielded improved techniques of displaying and analyzing weather radar data and also much experience in relating radar measurements to microphysical measurements at the surface and by aircraft. Nearly all members of the Branch were involved in the extensive field measurements required by these programs. One participant was 1st Lt. James Metcalf, who, following graduate study under David Atlas at The University of Chicago, was assigned to the Branch as a research physicist from July 1972 until he separated from active duty (as Captain) in September 1975.

While the pulse pair processor was under construction, members of the Branch took the Coherent Memory Filter to NSSL in 1973 and detected a mesocyclone in conjunction with the severe tornado which hit Union City, Okla., on 24 May 1973 (Donaldson, 1978). Observations by Doppler and other radars, by three mobile photographic teams, and by surface weather instrumentation in addition to subsequent damage surveys made this the best documented tornado to that date. By 1973 the Air Weather Service (AWS) was planning an operational weather radar to replace the FPS-77 at Air Force Base Weather Stations. While the value of Doppler radar in research was well established, its operational value was uncertain, because data processing was cumbersome and because operational techniques were not well defined. A planning document prepared in 1973 by a joint working group of AWS and AFCRL under the leadership of Morton Barad, Director of the Meteorology Laboratory, emphasized automated processing and display of reflectivity and made only passing reference to the need to evaluate Doppler techniques. Within two years, however, due to advances in Doppler radar analysis techniques and to the availability of the pulse pair processor, scientists in the Weather Radar Branch and at NSSL were urging AWS and the National Weather Service (NWS) to develop an operational Doppler radar (Donaldson et al., 1975; Lemon et al., 1977). Both agencies accepted this recommendation and ultimately, in collaboration with the Federal Aviation Administration (FAA), launched the Next Generation Weather Radar (NEXRAD) Program. The key to the establishment of the NEXRAD Program was the Joint Doppler Operational Project (JDOP), conducted at NSSL during the spring severe storm seasons in 1977, 1978, and 1979 by AFGL, AWS, FAA, NSSL, and NWS (Glover et al., 1979; JDOP Staff, 1979; Donaldson and Glover, 1980; Donaldson and Bjerkaas, 1980). Contributions by the Branch included the pulse pair processor and related color displays in all three seasons, automated real-time analysis of weather radar data,

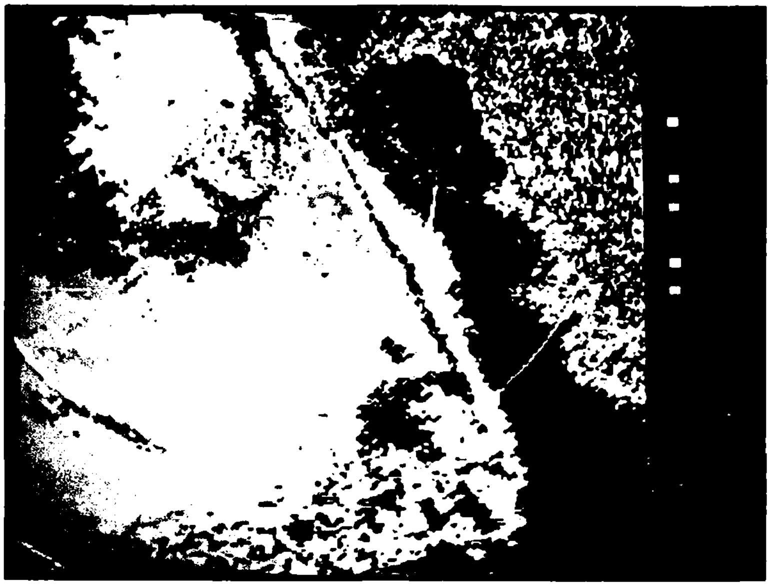

Figure 16. Thunderstorm Gust Front in Oklahoma. Range markers are at 32 km increments. Gust front is oriented north-northwest to south-southeast and is about 15 km past the radar site. The radial component of the flow is inward ahead of the gust front and outward behind it (after Donaldson and Bjerkaas, 1980).

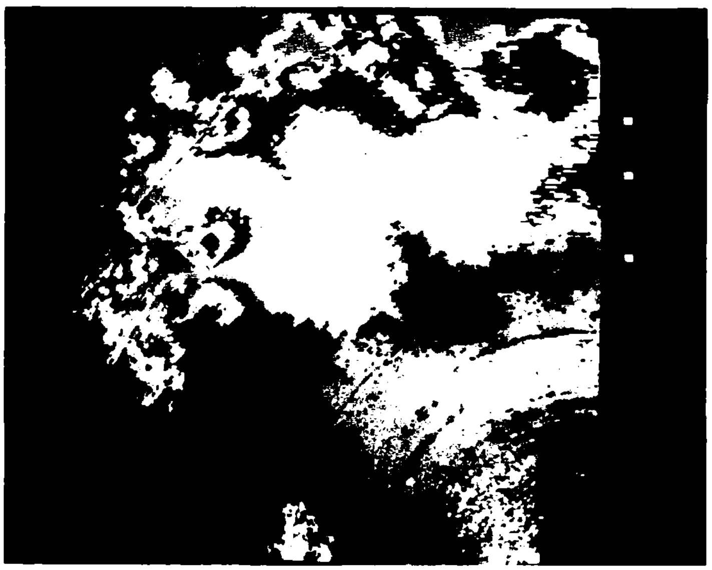

Figure 17. Mesocyclone in Oklahoma, 30 April 1978. Range markers are at 32 km increments and elevation angle is 3.0°. Distinctive couplet of high-speed approaching and receding winds is near 55 km range west-northwest of the radar at 1742 CST. This mesocyclone persisted for more than 1 hr and produced the severe Piedmont tornado, which began at 1820 CST.

and the Porcupine Doppler radar in 1979. AFGL research staff participating in JDOP included Capt. Carlton Bjerkaas, Ralph Donaldson, Kenneth Glover, and Michael Kraus. Graham Armstrong, Ruben Novack, and William Smith aided in the installation and operation of the equipment. Capt. Bjerkaas was assigned to the Branch in 1976 following a master's degree program at MIT and remained until 1982. JDOP proved the capabilities of Doppler radars for early detection and warning of tornadoes and other storm hazards (Figures 16 and 17). It also provided an extensive data base for use in development and testing of computer algorithms for storm tracking and storm hazard assessment.

In 1977 the Branch had contracted with Raytheon Co. to develop an automated Echo Track and Significance Estimator (ETSE) to run on the Perkin-Elmer 732 computer (Boak et al., 1977). The main analysis program of ETSE scanned each azimuthal sector of reflectivity and derived the reflectivity-weighted centroids and areas of as many as 20 storms. The resulting display included a depiction of the present locations and sizes of the twelve most significant storms and the present and past locations of their centroids. Capt Douglas Forsyth developed a centroid correlation and forecasting algorithm and other refinements of ETSE (Forsyth, 1979), which were used during the second season of JDOP. Forsyth, who was attached to the Branch in 1977 as an AWS liaison officer, worked with Capt. Carlton Bjerkaas to expand the tracking algorithm for the 1979 season of JDOP. Using expanded computer memory, the program accepted data from azimuthal scans at six elevation angles as part of the significance estimation. The modified program computed not only the centroid location in three dimensions but also the echo base and top heights, the maximum reflectivity and maximum Doppler spectrum variance and their heights, the maximum velocity at the lowest elevation angle, the echo volume, and the reflectivity-weighted volume. Following the 1979 season of JDOP the analysis program was streamlined and a new display format was developed (Bjerkaas and Forsyth, 1980). This program was the first element of the automated data processing and analysis effort in support of NEXRAD that continues to be a major part of the work of the Branch.

During these years observational work continued at the Sudbury field site. The primary emphasis was on the dynamics and structure of severe convective storms, and there was close collaboration with the NWS Forecast Office in Boston whenever severe weather threatened the Boston area. On 9 August 1972 Michael Kraus observed a mesocyclone associated with a confirmed tornado that struck Brookline, Mass. Kraus (1973) showed that within the mesocyclone was a small

Figure 18. Probable Microburst in Auburndale, Mass., 12 August 1975. Range markers are at 8 km increments. Maximum receding velocity near 12 km range east-southeast of the radar indicates the storm outflow. The feature was not evident on azimuthal scans 20 min earlier and 15 min later (after Dyer et al., 1976).

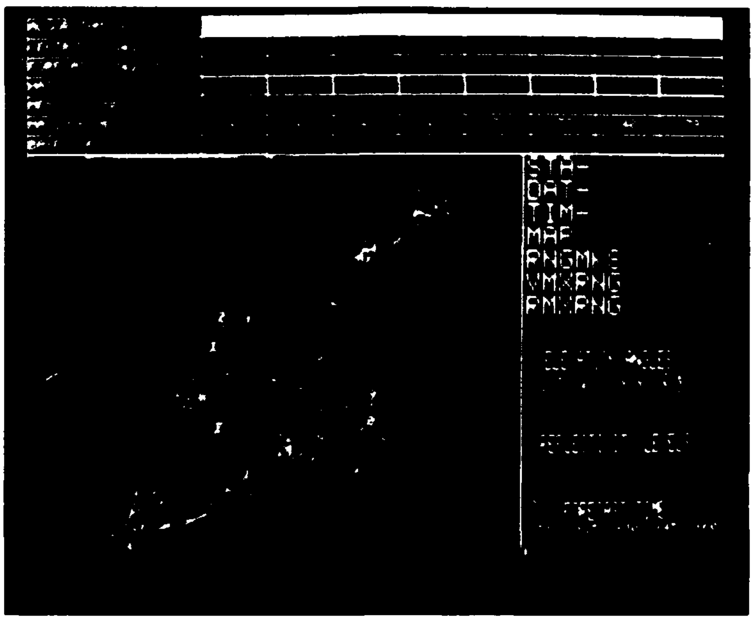

Figure 19. Storm Tracks Generated in Real Time during the Boston Area NEXRAD Demonstration. Geographical features are shown, and range markers are at 50 nautical mile increments. Upper portion of display contains summary data on cells being tracked. Cell tracking algorithm yields predicted positions of cells.

region in which the mean velocity could not be determined because the Doppler spectrum was spread across the entire unambiguous velocity interval. This was the first unequivocal observation of a tornado by pulse Doppler radar. Also of significance was a storm which produced very localized damage in the Auburndale section of Newton, Mass., on 12 August 1975 (Dyer et al., 1976). The Doppler velocity display (Figure 18) yielded what may be the first radar observation of the severe outflow wind phenomenon now known as a "microburst." The first Doppler radar observations of the outer rain bands of a hurricane were made with the Porcupine radar on 10 August 1976 as Hurricane Belle crossed western Connecticut and western Massachusetts (Donaldson et al., 1978). During several winters the Porcupine and CPS-9 radars were used by Roland Boucher for observations of snowfall, with the goals of improved measurement of snowfall rate, improved prediction of snow depth, and improved understanding of visibility in snow (Boucher et al., 1976; Boucher, 1978, 1981; Boucher and Wieler, 1985). These operations also provided valuable experience in the display and interpretation of Doppler velocity measurements in stratiform precipitation (Kraus and Donaldson, 1976).

Several personnel transfers took place in the early 1970's. William Lamkin transferred to the Mesoscale Forecasting Branch in 1972 to work with the FPS-77 radar at Hanscom AFB in a mesoscale forecasting project. Arnold Barnes transferred from the Upper Atmosphere Branch in the spring of 1972. He had headed a program to derive atmospheric density and wind information at 80-100 km altitudes from very high frequency (VHF) radar backscatter from meteor trails (Barnes, 1969, 1972). A by-product of this work was the development at Stanford University of a combined radar and acoustic sounding system for measuring the temperature profile in the lowest 2 km of the atmosphere (Marshall et al., 1972). Arnold Barnes expected to work on the development of wind profiling techniques, but instead he became involved in the missile test programs and led the first weather documentation mission at Kwajalein in August 1973. In October 1974 Barnes left the Branch to become chief of the Cloud Physics Branch, succeeding Robert Cunningham. In the spring of 1973 Wilbur Paulsen and Pio Petrocchi rejoined the Branch, but within a few months Paulsen was transferred to the Cloud Physics Branch, from which he retired in 1980. Hugh Sweeney was transferred to the Cloud Physics Branch in 1974. George Ritscher, an electrical engineer, was transferred from the Cloud Physics Branch in 1974 and took a key role in designing the new radar operations building. In August 1974 Kenneth

Hardy left AFCRL and Kenneth Glover became chief. Suzanne Vallerand transferred from ESD to become secretary in the Branch in 1972. She became known as "Hurricane Suzanne" after Roland Boucher inadvertently used her name when referring to a hurricane during one of his morning weather broadcasts on WKOX in Framingham. When she left in 1974 June Queijo returned and stayed for seven years. Her outstanding abilities were repeatedly demonstrated in dealing with the documentation and the movement personnel and equipment required by two major field operations (the missile test programs and JDOP) that sometimes were running concurrently. Although no longer a resident of Sudbury, she has stayed in touch with the Branch.

In a major reorganization in January 1976, AFCRL became the Air Force Geophysics Laboratory (AFGL), and the organizational units formerly known as laboratories became divisions. The mid-1970's were, in some ways, difficult years for the Laboratory. A series of staff reductions effectively precluded the hiring of new civilian personnel for several years. This situation had eased by 1980, when Michael Kraus left the Branch to manage the advanced development of meteorological sensors and techniques in the Meteorology Division and Alan Bohne, a recent doctoral graduate of The University of Chicago, was hired to replace him.

6. THE RECENT PAST -- 1980-1988

SIGNIFICANT EVENTS AND ACCOMPLISHMENTS

NEXRAD algorithm development continued
Joint Agency Turbulence Experiment, NASA Wallops Flight Facility, 1981, 1982, 1983
Short-term precipitation forecasting study initiated, 1984
Hurricane Gloria observed by Doppler radar, 1985
Polarization diversity measurements begun, 1986
Doppler radar measurements at 3.2 mm wavelength, 1987

Facilities of the Branch received a major upgrading in 1980 with the completion of the new radar operations building* and a new sensitive 10-cm Doppler radar (Bishop and Armstrong, 1982) and the acquisition of expanded data processing capabilities. These improvements have greatly enhanced the current work of the Branch, much of which has roots in the major developments described in the foregoing sections. In early 1981 the Branch was renamed the Ground Based Remote Sensing Branch and tasked to broaden its activities in atmospheric remote sensing. Concurrently the installation in Sudbury was redesignated the Ground Based Remote Sensing Facility.

As the NEXRAD System Program Office initiated the procurement process in 1981, the Branch continued the development of algorithms for automated detection and warning of weather hazards. These are incorporated in the Modular Radar Analysis Software System (MRASS), which was described by Forsyth et al. (1981) and which runs on a Perkin-Elmer 3242 computer. One of the algorithms develops a time-height profile of the horizontal wind, based on the VAD technique. Other algorithms enable the tracking of precipitation cells and the detection of hail, mesocyclones, tornado vortex and wind shear. The algorithm development was initially the responsibility of Capt. Carlton Bjerkaas and Capt. Douglas Forsyth. Capt. Forsyth worked with the Branch as an AWS liaison officer from 1977 until 1982, when he was reassigned to the NEXRAD Interim Operational Test Facility in Norman, Okla. In that position and in his current position as head of the Scientific Support Division at NSSL he continues to interact with the Branch in the development and testing of NEXRAD algorithms. Much of the NEXRAD algorithm development from 1981 onward has been performed under contract by personnel of Systems and Applied Sciences Corp. (SASC) and its successor, ST Systems Corp., working at the Remote Sensing Facility. From November 1983 through June 1984 the Branch hosted the Boston Area NEXRAD Demonstration (Forsyth et al., 1985). This demonstration used the AFGL 10-cm Doppler radar to test techniques being developed for NEXRAD. Automated analysis products were provided in real time to local AWS, FAA, and NWS offices and to Air Force Global Weather Central and the National Severe Storms Forecast Center (Figures 19, 20, and 21). The composite hazards product and the derived wind profiles were found to be very useful, and operational forecasters responded favorably to both

* During the excavation for the foundation of the new building a skeleton, thought to be that of a pig, was uncovered and reinterred; no radioactivity tests were made.

the format and the content of the displays. The experience revealed the need for improvement of some algorithms, including the mesocyclone detection algorithm. Recent results of the algorithm development program include the concept of excess rotational kinetic energy (ERKE) for estimation of the intensity of tornadoes (Desrochers et al., 1986) and an improved algorithm for the detection of mesocyclones (Desrochers and Forsyth, 1988).

In collaboration with NASA Langley Research Center and NASA Wallops Flight Facility the Joint Agency Turbulence Experiment was conducted at NASA Wallops Flight Facility, with field operations in 1981, 1982, and 1983 (Bohne, 1985). The objective of the Branch in this experiment was to develop techniques of evaluating turbulence intensity from radar measurements in precipitation, using either the Doppler spectrum variance or the width of the power fluctuation spectrum derived from a non-coherent radar on an aircraft, following the theoretical work of Bohne (1982). The experiment also yielded new information on the relationships of radar reflectivity structure and the occurrence of lightning (Bohne and Chmela, 1985, 1986).

In the fall of 1984 the 10-cm Doppler radar was used in collaboration with the Illinois Natural History Survey, which had an Air Force contract to observe nocturnal bird migrations and to assess the feasibility of using NEXRAD for this purpose. While these observations were in progress, the azimuth bearing in the antenna pedestal failed. The process of disassembling the pedestal, evaluating alternative designs, reconfiguring the bearing, and reassembling the pedestal took nearly eleven months. The riggers completed the reassembly and removed their staging on 25 September 1985, as Hurricane Gloria was moving up the Atlantic coast. The engineers and technicians of the Branch worked around the clock for two days to reassemble the microwave hardware and control cables and test the system in time to observe the hurricane. The passage of Hurricane Gloria through New York and New England on 27 September 1985 provided an unusual opportunity to observe the structure and kinematics of a hurricane. The northern rain bands were observed as the eye approached Long Island, and observations continued until after the center of the decaying storm had moved across central Massachusetts and into New Hampshire. The high quality of the data is due primarily to the sensitivity of the radar and the negligible attenuation of the 10 cm signal at long range. The first results of analysis of these data were presented at the 23rd Conference on Radar Meteorology (Glover and Forsyth, 1986; Donaldson and Ruggiero, 1986; Bohne et al., 1986). The techniques of analyzing Doppler

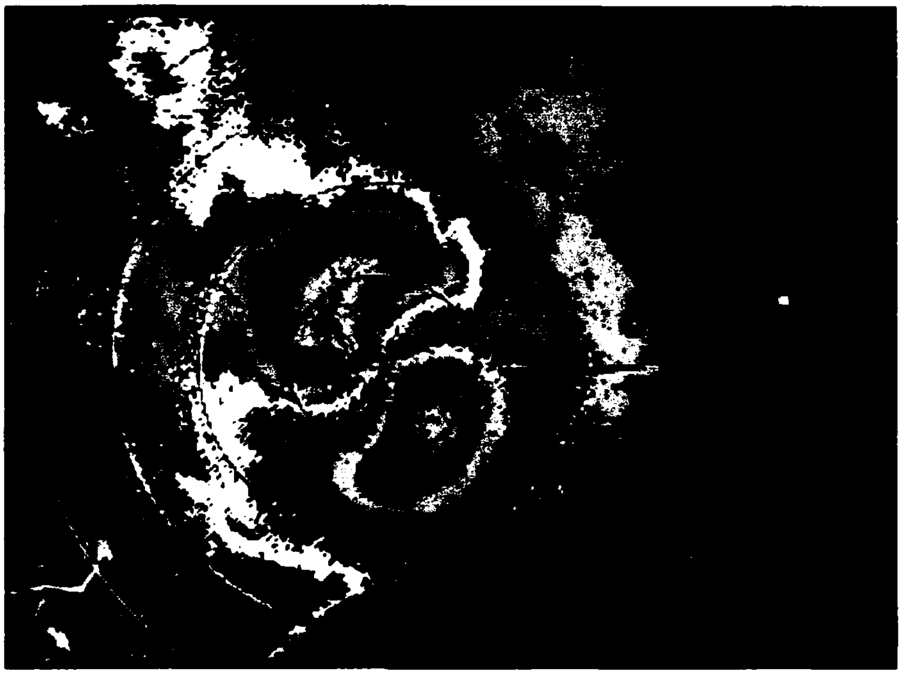

Figure 20. Doppler Velocity on a Plan Position Indicator (PPI). Data were recorded during the Boston Area NEXRAD Demonstration. Radar antenna is at 4° elevation angle and range markers are at 32 km increments. Wind is from west-northwest near the surface and veers to north-northwest at 3.5 km height (50 km range), with maximum speed about 33 m sec^{-1} near 2 km height (30 km range). Above 3.5 km, wind backs to west-southwest at 6.7 km height (96 km range) (after Forsyth et al., 1985).

Figure 21. Time-Height Display of Horizontal Wind. Display was derived in real time from data preceding and following those of Figure 20. Display uses conventional representation of wind speed and direction in addition to color coding of speed (after Forsyth et al., 1985).

radar observations of curved flows were presented in more detail by Donaldson and Harris (1988).

During the past few years the Branch has modified the 10 cm Doppler radar to permit the measurement of polarization dependent quantities. The basic goal of this effort, the roots of which may be traced to the earliest studies of polarization dependent backscatter by members of this group, is to characterize remotely the sizes, shapes, orientations, and thermodynamic phases of hydrometeors and thus to understand cloud physical processes more fully. In the late 1970's and early 1980's research conducted on contract at Georgia Institute of Technology yielded concepts for interpreting measurements by coherent polarization diversity radars (Metcalf and Echard, 1978) and, ultimately, a design for modifying the 10 cm radar (Ussailis et al., 1982). When the modifications are completed, the radar will be capable of transmitting horizontal, vertical, or right or left circular polarization and receiving polarizations identical and orthogonal to that of the transmitted signal. From these signals we shall be able to derive power ratios such as differential reflectivity and depolarization ratio, cross-correlations, spectral functions (Metcalf, 1984), and the polarization differential Doppler velocity parameters (Metcalf, 1986). Metcalf et al. (1987) described the status of the system in early 1987 and our first measurements of the polarization differential reflectivity of precipitation. A subsequent stage of development and the first measurements of the differential reflectivity of lightning were described by Metcalf (1988). In the next few years we expect to use the full polarization capability to investigate the electrical structure of clouds, as revealed by the shapes and orientations of hydrometeors.

The increasing speed, capacity, and flexibility of data processing equipment facilitated a new program begun in 1984 aimed at combining radar and satellite imagery for short-term forecasting of precipitation development. Such forecasts can be used by the Air Force to anticipate precipitation effects on microwave communication links. This application will also rely on the results of another recent program that involved the joint measurement of radar backscatter at wavelengths of 10 cm and 8.6 mm. These measurements, made in coordination with surface measurements of rainfall rate and raindrop size distribution, will permit more precise specification of attenuation effects in relation to small-scale precipitation structure, particularly near the melting level. A research contract with the University of Miami enabled Roger Lhermitte to bring his 3.2-mm wavelength Doppler radar to Sudbury in the spring and fall of 1987. Simultaneous measurements of Doppler spectra and reflectivity profiles by Lhermitte's radar and reflectivity profiles at 8.6 mm wavelength by the AFGL TPQ-11 radar have produced new understanding of the dynamics of clouds and the details of the melting layer (Lhermitte, 1988). In support of the forecasting program, the Branch acquired a VAX 11/750 computer and an Adage image processor. Acquisition of this equipment and development of the associated data acquisition and processing capabilities were the responsibility of Capt. Paul Allan Sadoski, who was assigned to the Branch from 1984 to March 1988 (Bohne et al., 1988; Sadoski et al., 1988).

A major restructuring of the Atmospheric Sciences Division of AFGL occurred in October 1987. This included the transfer of the short-term precipitation forecasting program to the Atmospheric Prediction Branch, located in the main laboratory building at Hanscom AFB. Alan Bohne and Capt. Gerald Freeman transferred with the program. A new program was established in clear-air wind profiling, for which the Branch plans to install an ultra high frequency (UHF) Doppler radar in 1989. James Morrissey transferred from the Cloud Physics Branch to lead this program.

The personal character of the Branch has continued to evolve. Donna Velardi transferred to the Branch from ESD after June Queijo left in 1981. She has taken a key role not only in the Branch but also in the Atmospheric Sciences Division in the implementation of automated word processing for a variety of administrative functions. Ralph Donaldson retired from Federal service in December 1981, ending 29 years in the weather radar program; he has continued to work on a part-time basis for SASC and ST Systems Corp. In 1983 he was elected to be a Fellow of the American Meteorological Society. James Metcalf rejoined the Branch as a civilian in November 1981. Ian Harris, who had also studied under David Atlas at The University of Chicago, joined SASC in July 1981 and is now the supervisor of the other employees of ST Systems Corp. at the Remote Sensing Facility. Albert Chmela retired in June 1986, ending 34 years in the weather radar program. Roland Boucher retired in December 1986, and at the same time Frank Ruggiero, who had been employed by ST Systems Corp. since 1984, joined the staff of the Branch. Ruben Novack plans to retire in February 1989 after 34½ years in the weather radar program. Other long-time members of the Branch are also eligible for retirement. It will be difficult to replace their knowledge of the organization, the program, and the unique research equipment. Thus we shall face major challenges as we strive to maintain the scientific creativity and productivity that have characterized the weather radar program.

7. SUMMARY

From its origin more than 40 years ago the weather radar research group at AFGL has made significant pioneering contributions to the study of the atmosphere by radar. Early work in precipitation measurement and studies of storm structure demonstrated the importance of radar reflectivity in operational forecasting of precipitation and severe storm phenomena. Some of the earliest observations of radar backscatter from the clear atmosphere were made by members of this group; subsequent observations and analysis elucidated the mechanisms of clear air turbulence and clear air radar backscatter. These results were fundamental to the development of Doppler radar wind profilers elsewhere. Key developments in Doppler radar equipment and techniques for the observation of severe storms were made by this group and in collaboration with other research organizations. These developments provided much of the foundation for the Next Generation Weather Radar (NEXRAD) Program. We are expanding the analytical capability of the NEXRAD system by our development of algorithms for the identification, measurement, and prediction of a variety of meteorological phenomena.

The future will offer many opportunities to develop new meteorological radar techniques and apply them to the solution of problems for the Air Force. We can identifty three interrelated categories of future research.

(1) *Improvement and expansion of NEXRAD*

As deployment of the NEXRAD system progresses there will be requirements and opportunities for new data processing algorithms, both in the context of the planned radar capability and in the context of major modifications to the hardware. Future decisions concerning hardware modifications, such as the addition of polarization diversity, will require the evaluation of new technology, the development of techniques for interpreting and using the expanded measurements, and the operational evaluation of those techniques.

(2) *Support of specialized Air Force operations*

Even at present, there are many requirements that lie beyond the capability of NEXRAD for remote atmospheric measurements to support the development, test, and operation of Air Force systems. Examples may be found in spacecraft launch and recovery operations, aircraft operations in electrically charged clouds, and millimeter and submillimeter wavelength communication systems. We have begun to work in these areas by applying polarization diversity radar techniques to the study of electrical phenomena in clouds and by initiating a program in wind profiling by UHF Doppler radar.

(3) *The frontier of radar meteorology*

Radar meteorology is substantially, but not entirely, dependent on the technology of radar systems and data systems, and this technology is not static. New understanding of the atmosphere and new and improved applications of radar measurements have emerged as technological advances have expanded the domains and accuracy of measurements. The technological frontier now includes, for example, the use of shorter wavelengths, flexibility of polarization and transmitted waveforms, rapid scanning techniques, and the ever-expanding capability of data systems. The meteorological frontier includes, for example, the interpretation of polarization diversity and multiple wavelength measurements in terms of cloud microphysical proceses, the development of analytical techniques to use the extensive data bases generated by modern weather surveillance radars and by wind profilers, and the integration of meteorological radar observations with other meteorological measurements. In recent years AFGL has advanced the frontiers particularly in the areas of wind field analysis in large storms, polarization diversity radar techniques, and 3.2-mm wavelength radar observations of precipitation. Through the further development and use of these and other techniques, we look forward to continued service to the Air Force and the nation.

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Abbreviations

AAF	Army Air Forces
AFB	Air Force Base
AFCRC	Air Force Cambridge Research Center (1951-1960)
AFCRL	Air Force Cambridge Research Laboratories (1949-1951, 1960-1976)
AFGL	Air Force Geophysics Laboratory (1976-present)
AMS	American Meteorological Society
APL	Applied Physics Laboratory (The Johns Hopkins University)
AWFD	All Weather Flying Division (Wright Field, Ohio)
AWS	Air Weather Service
CMF	Coherent Memory Filter
ERKE	Excess Rotational Kinetic Energy
ESD	Electronic Systems Division
ETSE	Echo Track and Significance Estimator
FAA	Federal Aviation Administration
GRD	Geophysical Research Division (1948), Geophysics Research Division (1951-1952), Geophysics Research Directorate (1952-1963)
JAFNA	Joint Air Force NASA (radar facility at Wallops Island, Va.)
JDOP	Joint Doppler Operational Project
MIT	Massachusetts Institute of Technology
MRASS	Modular Radar Analysis Software System
NASA	National Aeronautics and Space Administration

NATO	North Atlantic Treaty Organization
NEXRAD	Next Generation Weather Radar
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
PPI	Plan Position Indicator
PRD	Polytechnic Research and Development Co. (Brooklyn, N.Y.)
PSI	Plan Shear Indicator
RVI	Range Velocity Indicator
SASC	Systems and Applied Sciences Corp.
STRADAP	Storm Radar Data Processor
UHF	Ultra High Frequency
VAD	Velocity Azimuth Display
VHF	Very High Frequency

Appendix A
Civilian Personnel

We have attempted to include in the following list all individuals who have been affiliated with the weather radar program as members of the federal civil service, except student employees. Where pertinent to that affiliation or of interest in a broader context, we have included prior and subsequent affiliations. We have endeavored to verify the dates, but we welcome corrections.

Aoyagi, Jiro, engineer, 1964-1965
    Meteorological Research Institute, Tokyo, 1955-1964, 1965-present

Armstrong, Graham M., engineer, 1953-present

Atlas, David, scientist and chief, 1948-1966
    All Weather Flying Division, 1945-1948
    The University of Chicago, 1966-1972
    National Center for Atmospheric Research, 1972-1976
    National Aeronautics and Space Admin., 1976-1985
    University of Maryland, 1985-1987

Banis, Kenneth J., engineer, 1971-1983
MIT Lincoln Laboratory, 1983-present

Banks, Harold, scientist, 1949-1951

Barnes, Arnold A., Jr., scientist, 1972-1974
Meteorological Development Laboratory, 1961-1962
Upper Atmosphere Branch, 1962-1972
Cloud Physics Branch (chief), 1974-1987
Atmospheric Structure Branch, 1987-present

Bedard, Gloria, secretary, 1962

Bishop, Alexander W., engineer, 1967-present
MIT Lincoln Laboratory, 1951-1966
Northeastern Univ., 1966-1967 *

Bohne, Alan R., scientist, 1980-1987
Systems and Applied Sciences Corp., 1979-1980 *
Atmospheric Prediction Branch, 1987-1989
Titan Systems, Inc., 1989-present

Børresen, Jan A., visiting scientist, 1968-1969

Boucher, Roland J., scientist, 1967-1986
Blue Hill Meteorological Observatory, 1952-1956 *
Allied Research Associates, 1956-1967 *

Browning, Keith A., scientist, 1962-1966
British Meteorological Office, 1966-present

Chmela, Albert C., scientist, 1952-1986
Cloud Physics Section, 1951-1952

Daly, Paul, engineer, 1960-1961
Electronics Research Directorate, ?-1960
Meteorological Development Laboratory, 1961-?

Donaldson, Ralph J., Jr., scientist, 1953-1981
Electromagnetic Propagation Laboratory, 1949-1952;
Systems and Applied Sciences Corp., ST Systems Corp.,
1982-present *

Duquette, Edward F., Jr., technician, 1963-present
Air Weather Service (Great Blue Hill), 1955-1956
Allied Research Associates, 1961-1963 *

Dyer, Rosemary M., scientist, 1967-1976
Atmospheric Sciences Division (other branches), 1976-present

Fitzgerald, Donalc R., scientist, 1976-1983 **
Cloud Physics Branch, 1961-1976
Optical Physics Division, 1983-1987

Gibson, Frank W., engineer, 1960-1961
Meteorological Development Laboratory, 1961-1964
Optical Physics Division, 1964-present

Glover, Kenneth M., scientist, 1962-present; chief, 1974-present

Goldberg, Beverly, secretary, 1962-1963

Hardy, Kenneth R., scientist, 1963-1974; chief, 1966-1974
Environmental Research and Technology, Inc., 1974-1981
Satellite Meteorology Branch (chief), 1981-present

Joss, Jurg, visiting scientist, 1970-1971

Katz, Ludwig, scientist, 1950-1951
Space Physics Laboratory, 1951-1976

Kessler, Edwin, III, scientist, 1955-1962
Travelers Research Center, 1962-1963
NOAA National Severe Storms Laboratory, 1963-1986

Kraus, Michael J., scientist, 1968-1980
Atmospheric Sciences Division (other branches), 1980-present

Lamkin, William E., technician, 1955-1972
Meteorology Division (other branches), 1972-1980

Landry, Claude R., physical science technician, 1964-1969
Wentworth Institute, Allied Research Associates, 1962-1964 *

Leviton, Robert, scientist, 1974-1976
Meteorology Laboratory (other branches), 1953-1974

Lhermitte, Roger M., engineer, 1961-1963
Blue Hill Meteorological Observatory, 1956 *
Sperry Rand Research Center, 1963-1964
NOAA National Severe Storms Laboratory, 1964-1966
NOAA Wave Propagation Laboratory, 1966-1970
University of Miami, 1970-present *

Metcalf, James I., scientist, 1981-present
Georgia Institute of Technology, 1975-1981 *

Moroz, Eugene Y., engineer, 1981-1983 **
AFCRL (other laboratories), 1961-1970
Meteorology Division (other branches), 1970-1981
Optical Physics Division, 1983-1985

Morrissey, James F., scientist, 1987-present
Aerospace Instrumentation Laboratory, 1961-1971
Atmospheric Sciences Division (other branches),1971-1987

Novack, Ruben, technician, 1954-present
Research Services Branch, 1948-1954

Ottersten, Hans, scientist, 1966-1970
Cooperative Institute for Research in Environmental Sciences, 1970-1971

Paulsen, Wilbur H., engineer, 1950-1954, 1958-1961, 1973
Meteorological Development Laboratory, 1954-1958, 1961-1964
Aerospace Instrumentation Laboratory, 1964-1973
Cloud Physics Branch, 1973-1980

Petrocchi, Pio J., scientist, 1958-1961, 1973-present
Meteorological Development Laboratory, 1955-1958, 1961-1964
Aerospace Instrumentation Laboratory, 1964-1973

Plank, Vernon G., scientist, 1950-1953
Cloud Physics Branch, 1953-1987
Atmospheric Structure Branch, 1987-present

Queijo, June, secretary, 1967-1972, 1974-1981

Reynolds, Geraldine, secretary, 1962-1963

Ritscher, George, engineer, 1974-1979
Meteorological Development Laboratory, 1955-1963
Cloud Physics Branch, 1963-1974

Ruggiero, Frank H., scientist, 1986-present
ST Systems Corp., 1984-1986 *

Shodin, Leonard, technician, 1953-1954

Smethurst, Edward G., technician, 1968-1970

Smith, William A., technician, 1967-present
Northeastern Univ., 1965-1967 *

Sweeney, Hugh J., engineer, 1960-1974
Cloud Physics Branch, 1974-1985

Vallerand, Suzanne (Tourville), secretary, 1972-1974

Velardi, Donna (Ruble), secretary, 1981-present

Wood, Alice, secretary, 1964-1967

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* Performed work under contract in support of weather radar program.

** Involved in lidar remote sensing and other programs outside the scope of this narrative.

Appendix B
Military Personnel

We have attempted to include in the following list all individuals who have been affiliated with the weather radar program while on active duty in the Air Force. We have endeavored to verify the dates, but we welcome corrections.

Bjerkaas, Carlton L., weather officer, 1976-1982

Chanley, Richard C., technician, 1985-present

Curl, Richard Dale, technician, 1987-present

DiMascolo, Anthony W., technician, 1987-present

Douglas, Scott C., technician, 1981-1982

Forsyth, Douglas E., weather officer (attached), 1977-1982

Freeman, Gerald L., weather officer, 1986-1987

Glover, Kenneth M., technician, 1952-1955

Klein, Charles, technician, 1978-1983

Kowalsky, John W., technician, 1977-1978

Landry, Claude R., technician, 1960-1962

Legg, Franklin D., technician, 1975-1977

Lewis, Philip, technician, 1983

Metcalf, James I., physicist, 1972-1975

Niedzwiecki, Joseph J., technician, 1978-1979

Potter, Gregory S., technician, 1986-1987

Pryor, William M., technician, 1976

Rolader, Daniel, technician, 1964-1965

Sadoski, Paul Allan, electronics engineer, 1983-1988

Snapp, Michael R., weather officer, 1982-1983

Sycuro, Stephen J., weather officer, 1984-1986

Willis, John T., electronics engineer, 1961-1963

Whittaker, Robert, technician, 1956-1957

Wood, Travis, technician, 1988-present