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ACCURACY TEST OF AN AIR-TO-AIR RANGING AND BEARING SYSTEM.(U)
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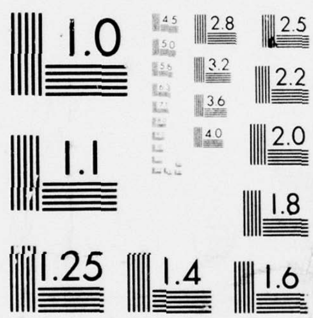

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ACCURACY TEST OF AN AIR-TO-AIR RANGING AND BEARING SYSTEM

Vincent J. Luciani

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

JUNE 1977

FINAL REPORT

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NOTICE

METRIC CONVERSION FACTORS

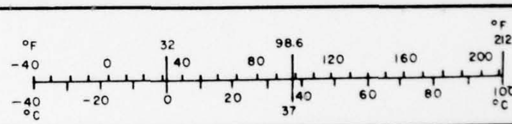
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

This report covers the accuracy test of a system designed to measure, display, and record air-to-air range and bearing measurements between in-flight aircraft. Data acquired from flight tests using reference measurements described in the report showed the estimated standard deviation range of error to be 100 feet, reducible to 60 feet via software smoothing of data. The standard deviation of bearing error was 2.4°. It is concluded that the system is well within specifications.

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PREFACE

This report describes the results of accuracy tests on a modern digital airborne TACAN system designed for air-to-air ranging and bearing. It is believed to be the first such system in which airborne digital TACAN outputs were recorded in detailed quantities and compared against quality reference measurements as provided by the NAFEC phototheodolite system. The results of this work are of interest not only to NAFEC users who require such an independent measurement system, but also to the military in their work to develop a reliable air-to-air rendezvous system. There is also interest evidenced by industry in potential applications such as off-shore drilling site navigation, particularly with use of a rotating airborne TACAN antenna that permits extraction of both distance and bearing from a distance-only ground station.

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INTRODUCTION

PURPOSE.

The objective of this test was to determine the range and bearing accuracies of an airborne digitized Tactical Air Navigation Aid (TACAN) system designed to display and record air-to-air distance and bearing measurements.

BACKGROUND.

Collision avoidance system flight tests have need for an onboard range separation measurement between aircraft. At present, separation has been provided by the National Aviation Facilities Experimental Center (NAFEC) photo-theodolite system over a limited coverage distance. Addressing this need, the NAFEC airborne digital TACAN system, being independent of ground-station requirements, can be operated anywhere and at interaircraft distance separations up to 200 nautical miles (nmi) or more.

AIR-TO-GROUND TACAN. TACAN is an air navigational system operating at ultra-high frequency (UHF) to provide aircraft with continuous range and bearing information to a ground station. The system consists of an airborne UHF transmitter-receiver and a ground beacon station. It has 126 two-way operating channels in the frequency spectrum 962 to 1213 megahertz (MHz). Each channel uses two separate frequencies spaced 63 MHz apart, with adjacent channels separated by 1 MHz.

Both the airborne unit and the ground station contain a receiver and pulse transmitter. The ground station transmits at a continuous rate of approximately 3,600 pulses per second, consisting of randomly spaced pulse pairs, pulse-pair distance replies, and evenly spaced and coded groups of pulse pairs. Due to the antenna configuration and rotation, all of these signals arriving at a given location are sinusoidally amplitude modulated at both 15 and 135 hertz (Hz). A main reference burst is transmitted each time the antenna passes a given azimuth, which establishes zero bearing at Magnetic North.

Whenever the ground station receives a distance interrogation pulse pair from any aircraft, it transmits a pulse pair reply exactly 50 microseconds (μs) later. This 50-μs delay is a system delay that permits response to close-in aircraft which would otherwise be obscured.

The ground beacon antenna consists of a central stationary driven element with a rotating array of one main parasitic reflector element and nine auxiliary parasitic reflector elements to give an antenna pattern that is a combination of a cardioid with nine lobes superimposed on it. Since the pattern is rotating at 15 revolutions per second, an aircraft receives a signal containing pulse pairs amplitude modulated at both 15 Hz (rotational speed of the main parasitic reflector) and 135 Hz (nine auxiliary parasitic reflector elements).

AIR-TO-AIR TACAN. The newer concept of TACAN includes the feature of air-to-air ranging and bearing. Air-to-air ranging is made possible by addition of a transponding function to the airborne equipment and makes special use of the aircraft TACAN frequencies. It does not involve any of the ground TACAN frequencies, nor is the TACAN ground station involved in the air-to-air link. Both ends of the air-to-air link can display distance information simultaneously; therefore, the technique is referred to as bilateral ranging.

Air-to-air bearing is made possible primarily through installation of an airborne rotating TACAN antenna on one of the aircraft. The airborne sets receive frequencies displaced by 63 MHz from their transmitting frequencies. In the air-to-ground link, reception is below transmit frequency for channels 1-63, and above for channels 64-126. For the air-to-air mode, these situations are reversed, and other airborne TACAN sets operating air-to-ground do not respond to air-to-air transmissions regardless of the channel selected.

SYSTEM DESCRIPTION

AN/ARN-84(V) TACAN NAVIGATIONAL SET.

The three air-to-air-capability, AN/ARN-84(V) TACAN sets in use at NAFEC were manufactured by Hoffman Electronics Corporation (serial Nos. (S/N) 15001, 15002, and 15003). This navigational set comprises four major assemblies: receiver-transmitter (TACAN RT-1022), signal data converter (CB-2837), control unit (C-8734), and shock mount base (MT-4354).

The AN/ARN-84(V) is a combination transmitter, receiver, decoder, digital computer, and digital-analog converter that can perform the functions of air-to-ground bearing (azimuth) and range (distance), air-to-air bearing and distance, self-test, beacon identity tone, flight computer interface, ground data link, course deviation, and compass. These last five capabilities are not in use on the NAFEC systems at this time.

The AN/ARN-84(V) has the following four basic operations:

1. RECEIVE. In receive, the navigational set processes only bearing from a ground beacon: transmission is inhibited.

2. TRANSMIT/RECEIVE. In transmit/receive, the navigational set processes range and bearing from a ground beacon. The navigational set transmits range interrogations (pulse pairs) to the ground beacon, which transponds with range replies to the aircraft. The aircraft set measures the time lapse between range interrogations and replies and converts the time lapse to range distance in nautical miles.

3. AIR-TO-AIR. In air-to-air, the navigational set processes range and bearing data from another aircraft and can supply range data to as many as five other aircraft. The air-to-air configuration is shown in figure 1, where aircraft A transmits pulse pairs to aircraft B, receives reply pulses from B, and then measures the time lapse between interrogations/replies to determine range.

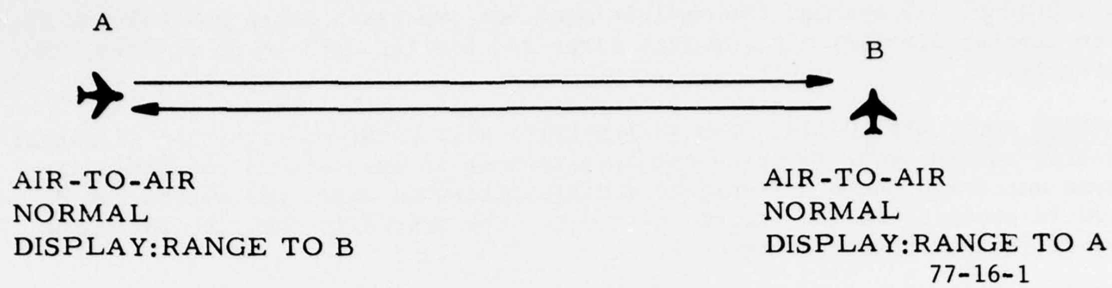

FIGURE 1. AIR-TO-AIR RANGING

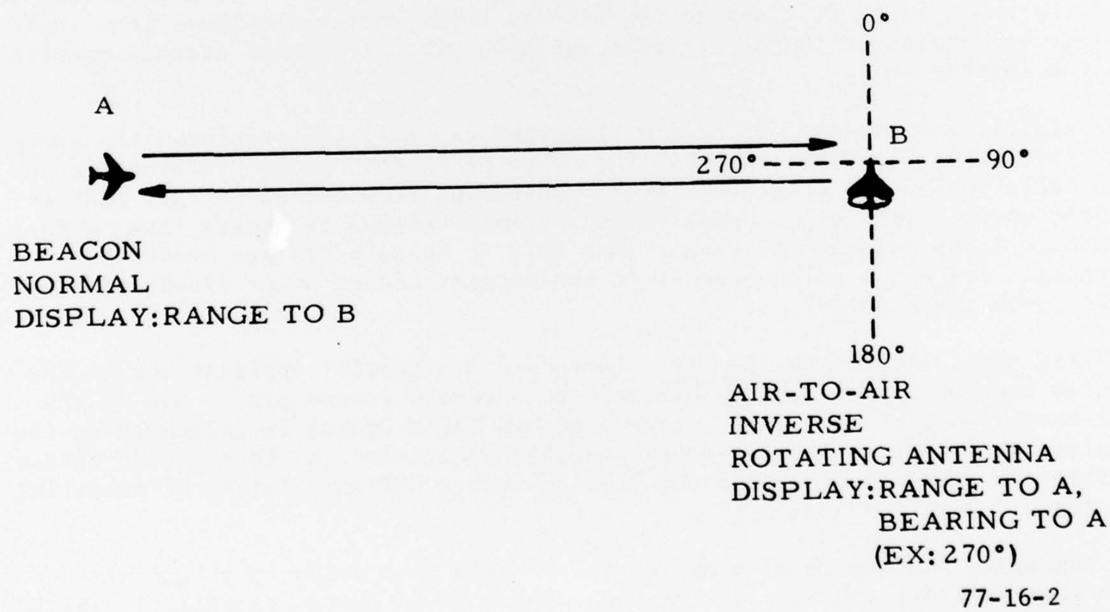

FIGURE 2. AIR-TO-AIR RANGING AND BEARING, INVERSE MODE

4. BEACON. In beacon, the navigational set processes range and bearing data from another aircraft and supplies range and bearing data to up to five other aircraft.

INVERSE MODE, AIR-TO-AIR. The AN/ARN-84(V) also provides selection of normal/inverse antenna mode in which the inverse mode is used with a rotating airborne antenna. There are various configurations in which the system can be used to provide bearing between aircraft. The method in use with the NAFEC system is that shown in figure 2.

In this configuration, the rotating antenna is installed in aircraft B, for example. Aircraft B TACAN is operated in the air-to-air, inverse mode, while aircraft A TACAN is operated in the beacon, normal mode.

In the normal mode of operation, TACAN A receives modulated bearing signals from TACAN B. In the inverse mode, TACAN B does the reverse (or, inverse) by self-generation of the 15-Hz modulated bearing signals via rotation of its own antenna.

The rotating antenna is aligned along the longitudinal axis of the aircraft so that zero degrees is dead ahead. In this manner, the prime information presently desired by NAFEC users is readily available; namely, that aircraft B needs to know where aircraft A is with respect to B. In figure 2, then, aircraft B would display a bearing to A of 270°. In the air-to-air operation, the desired information is that which answers the question of where to look to see the other aircraft. And in the present NAFEC system configuration, that answer is obtainable in the aircraft equipped with a rotating antenna operated in the inverse mode.

The digital system does not have a "To/From" capability; therefore, the numeric display always shows bearing "To" the other aircraft. Radial information is available to TACAN A simply by TACAN B switching from the air-to-air mode to beacon mode. This is not usually done, simply because it causes TACAN B to transmit 1,350 pulses per second, when only 27 pulse pairs are needed for ranging. The extra pulses result in unnecessary higher power dissipation and lower peak power output.

INVERSE MODE, AIR-TO-REMOTE-SITE. There are two special applications of the system when operating from an aircraft to a remote ground site. One is the air-to-air mode of operation, where a second TACAN system is relocated to the desired ground site, and the other special application is the system's unique ability to extract both range and bearing from a DME-only (distance measuring equipment) site.

In operating the system with one of the TACAN's at a selected ground site, the test aircraft can make use of the onboard TACAN system cockpit display to obtain a direct and precise readout of range and bearing to that site. Such displayed information is useful in permitting tight flight patterns. In addition, as will be described later, the same range and bearing data are recorded on tape for later use as reference measurements.

When working against a ground-located system, the two systems are operated as previously described where the aircraft with the rotating antenna is in the air-to-air, inverse modes, and the ground-located TACAN is in the normal, beacon mode. (If range-only between air and ground is desired, both aircraft would operate their TACAN's in the air-to-air normal modes, and the rotating antenna would not be needed.)

For the case of operation to a commissioned distance measuring equipment (DME)-only site, the aircraft with the rotating antenna is operated in the transmit/receive, inverse mode wherein it modulates the incoming range reply pulses from the DME and self-generates a bearing with respect to the ground site (in addition to the inherent range data). In this manner, complete very high frequency omnirange (VOR)/TACAN (VORTAC) navigational signals are available from a low-cost DME-only ground station. This capability has application in sites where terrain precludes reliable ground-based VOR, or any application where the objective is for low-cost, low-maintenance, ground equipment.

ROTATING AIRBORNE ANTENNA.

The NAFEC 15-Hz airborne mechanical-scan antenna is an International Telephone and Telegraph (ITT) model YN1-112 which was developed specifically for use with the AN/ARN-84(V) TACAN. The antenna's function is to rotate at a very precise 15 revolutions per second and, via a reflecting element attached to a rotating drum, to produce a cardioid radiation pattern that sinusoidally amplitude modulates pulses.

It is necessary for the cooperating aircraft to operate its TACAN in the beacon mode when working against the rotating antenna because, in the air-to-air mode, the pulse rate is only approximately 22 pulse pairs per second. Since the rotating antenna is amplitude modulating these pulses at its rotational speed of 15 Hz, it would result in an attempt to extract a sinusoidal waveform from (22 X 2)/15 pulses, or less than three sample points per sine wave. Instead, the beacon mode is used to add squitter pulses which are randomly generated pulses at a rate of approximately 1,350 per second. This higher pulse rate provides adequate sample points from which the self-generated sine wave is constructed.

The situation is shown in simplified form in figure 3, which shows the cardioid patterns generated by the rotating antenna as it swings through the cardinal points. For aircraft A to the east (at 90°), the amplitude of pulses received by aircraft B in the inverse mode would vary as shown, resulting in a sinusoidal pattern being received. As mentioned, if only three pulse pairs were received within each cycle in the air-to-air mode, the sine wave would be difficult to define and the bearing measurement would show wide fluctuation. But since the beacon mode provides approximately 100 pulses within each cycle, there is adequate capability for reasonably precise definition of the sine wave. (Greater precision could be obtained using a rotating antenna having both 15- and 135-Hz modulation capability, but such a practical airborne antenna is not yet available.)

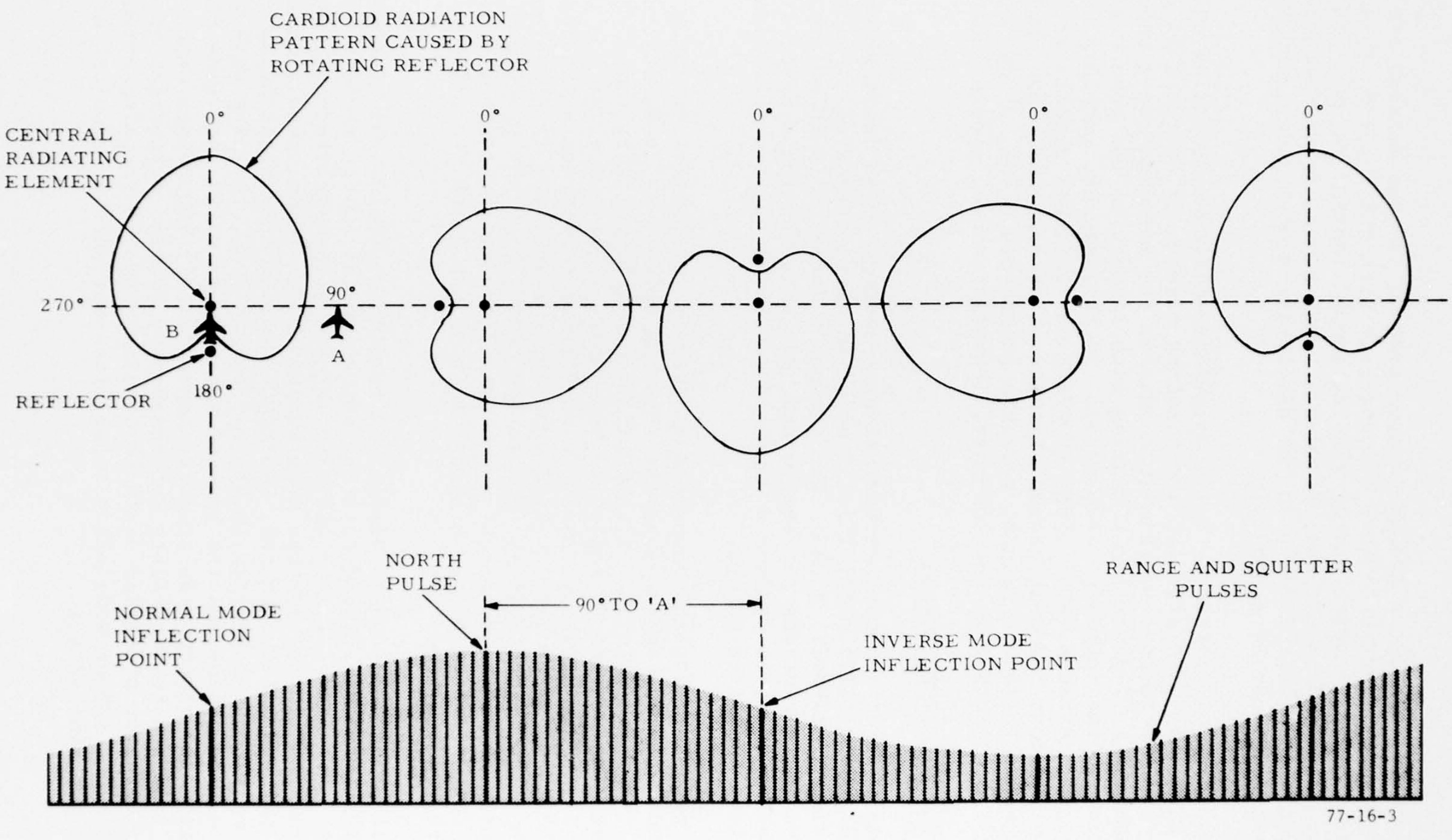

FIGURE 3. AIR-TO-AIR BEARING PATTERNS

The "north" reference pulses are generated when the antenna (on the NAFEC system) points ahead along the longitudinal axis of the aircraft, and this is the point from which phase displacement (bearing) of the received signal is measured with respect to an inflection point (zero crossover of the sine wave). The inflection point is on the positive-going swing for normal mode, and on the negative swing for inverse mode.

EQUIPMENT.

The NAFEC TACAN air-to-air ranging and bearing system is pictured in figure 4. The TACAN digital system and the basic system block diagram is shown in figure 5. Two digital racks have been assembled and are designated the "digital" TACAN. There is a third unit contained on a single shelf that has only aircraft-type displays of range and bearing, and this latter is commonly referred to as the "analog" rack.

Power requirement of the AN/ARN-84(V) is 28 volts direct current (V d.c.) and 115 volts alternating current (V a.c.), 400 Hz. Other equipment in the racks require 60-Hz power. The analog shelf is portable and contains a 28-V d.c. power supply and a 400-Hz inverter so that its only power requirement for remote operation is 60 Hz.

Functions of the TACAN set are performed at the control head and include channel selection (channels 1 to 126), operating mode (receive, transmit/receive, air-to-air, or beacon), bearing mode (normal or inverse), X/Y TACAN submode selection, and built-in test.

Serial digital outputs from the AN/ARN-84(V) consisting of range and bearing words are applied to a formatter. The formatter also accepts clock pulses and a time-of-day code from an Incredata model SP305 time code generator. Controls on the formatter are (1) selection of data rates from 1 sample per second to 10 samples per second, (2) thumbwheel switches to insert and record run numbers, (3) numeric displays of range and bearing. Resolution of the displays is two decimal places for range in nautical miles and one decimal place of bearing in degrees. Resolution of the digital data on tape is 0.0125 nmi in range and 0.25° in bearing.

Six switches located on an events module are connected to the formatter to permit manual insertion of a mark on tape for any real-time event. Energizing any of the switches results in a printout in that channel identified at the precise time the switch was operated. The formatter also has a connector that permits operation of up to two additional range/bearing displays remotely, one of which is generally located in the cockpit of the test aircraft. Another capability built into the formatter is the provision for accepting up to eight channels of analog data.

Formatter output signals are applied to a Kennedy model 1708 digital tape recorder. Tape data are processed through system software in the NAFEC computer complex.

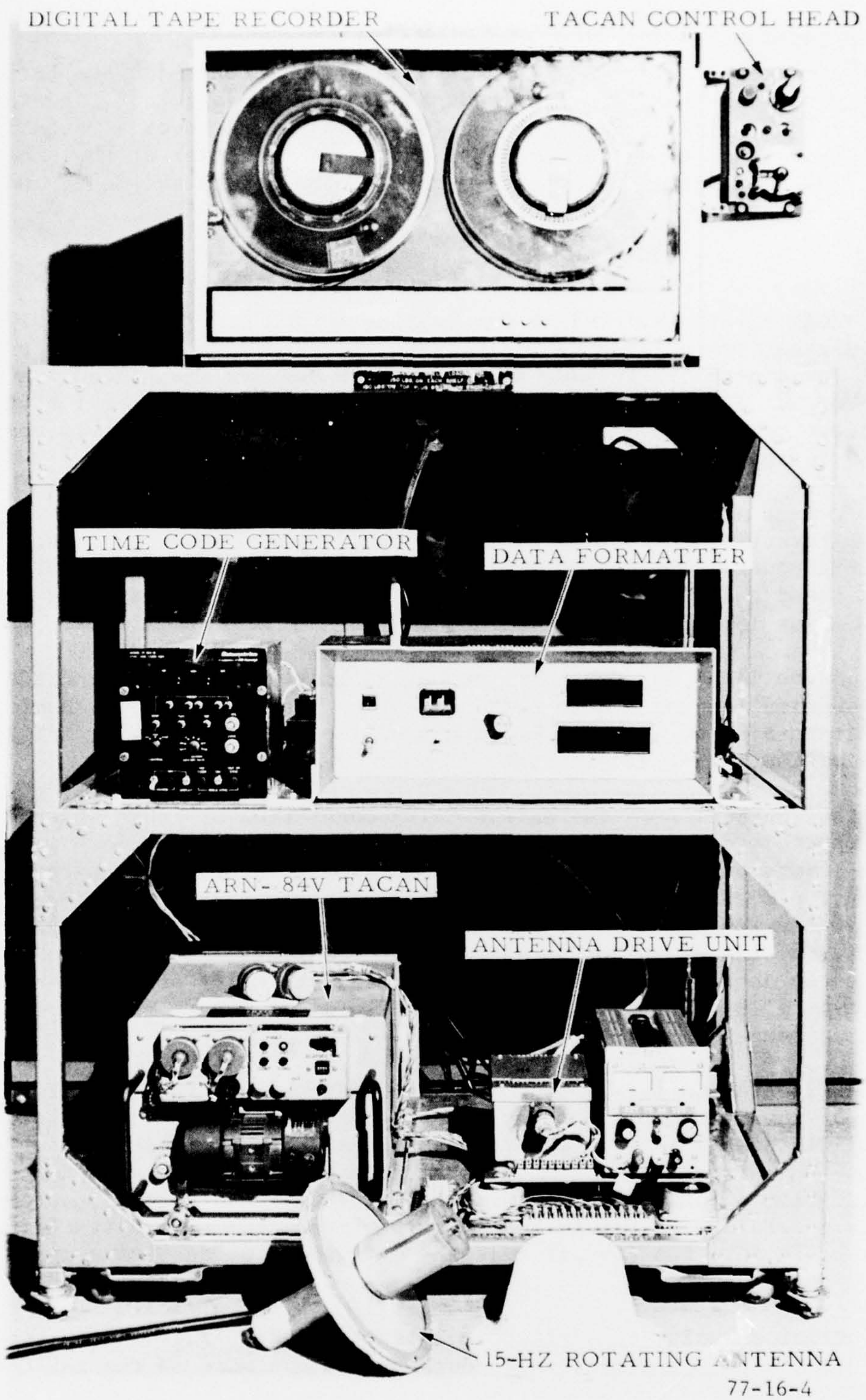

FIGURE 4. TACAN DIGITAL SYSTEM

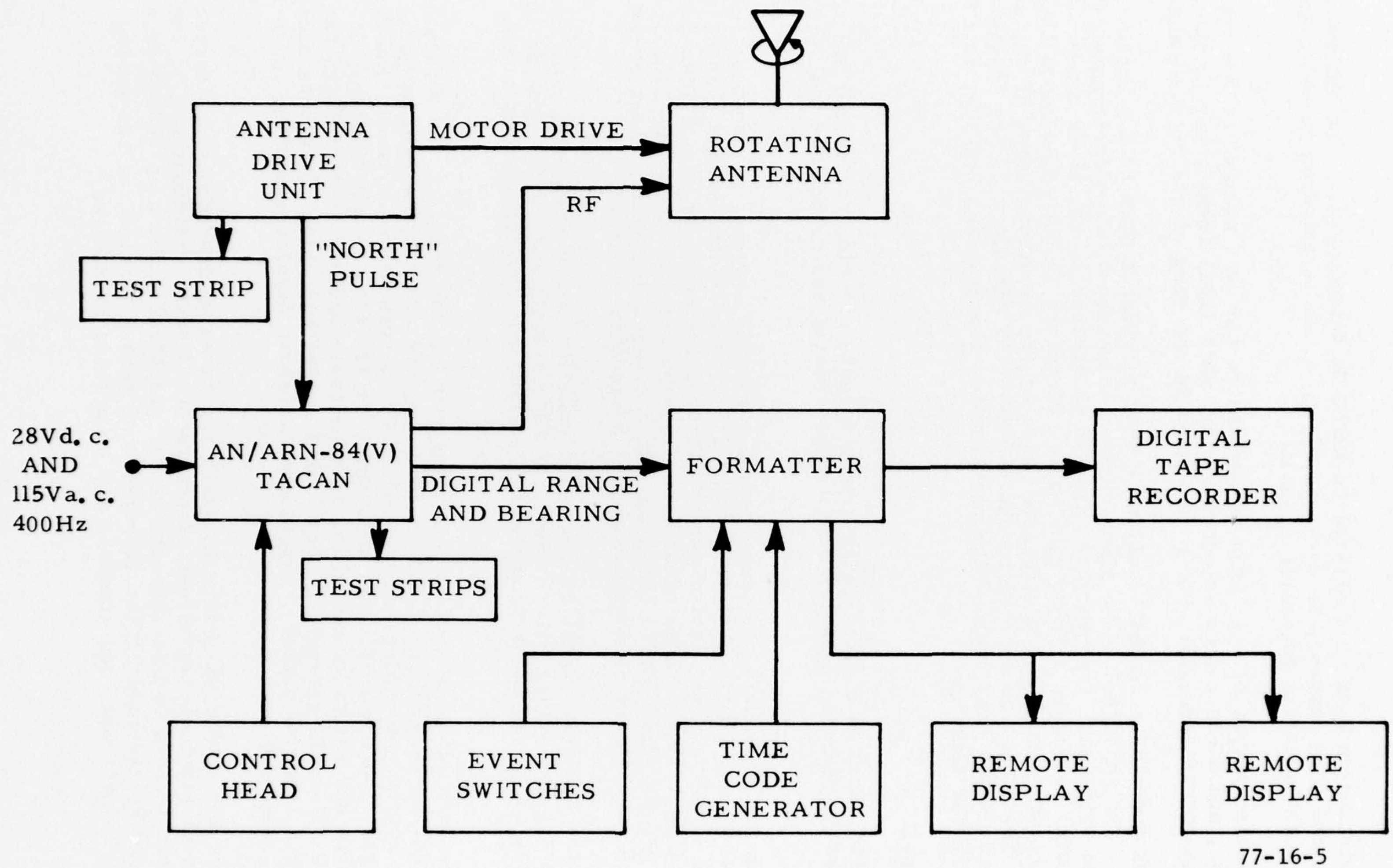

FIGURE 5. TACAN DIGITAL SYSTEM BLOCK DIAGRAM

The rotating antenna is installed in NAFEC Gulfstream N-47. The antenna, with fiberglass dome removed, is shown in figure 4, as is the drum on which is printed the rotating parasitic element.

Transmitter output of the TACAN is applied to the feed element of the rotating antenna, and a cable from an antenna drive unit (ADU) feeds power to the antenna motor/alternator, which is housed in the stem of the antenna mount.

The ADU contains a crystal oscillator that is counted down to a precise 60 Hz. The amplified 60-Hz signal drives a hysteresis motor/alternator the precise rotational frequency of which is maintained by the 60-Hz drive. The alternator output is a 15-Hz sine wave. Circuitry in the ADU accepts the 15-Hz return signal and generates a pulse at the crossover point of the sine wave. This pulse is applied to the AN/ARN-84(V) circuitry as its "north" reference pulse input from which phase angle, representing bearing, is computed in the TACAN set.

SOFTWARE.

The NAFEC airborne digital TACAN system outputs are time correlated and recorded on magnetic tape for computer processing and comparison with project data.

TACAN system tape data are processed on the NAFEC computer to provide listings of time, range, bearing, status of the six event switches, range change, and bearing change. These latter two are first differences in consecutive data points (i.e., line 1 range minus line 2 range, line 2 range minus line 3 range, etc.). First differences provide a convenient quality check of data by which unrealistic data changes could be readily detected.

Should the received signal be faulty, a validity bit accompanying each range and bearing word drops out. Absence of the validity bit is detected in the software, and an asterisk is printed alongside the invalid word as a flag to users.

Software capability includes a smoothing routine for reducing the variability and effective resolution of data. In range, the practical effect of judiciously applied smoothing has been observed to reduce system resolution from 0.0125 nmi (least significant bit), which is 75 feet, to approximately 10 feet. The choice and extent of smoothing is a software option. For example, recording at a 10-sample-per-second rate with 10-point smoothing represents smoothing over a 1-second period. Experience has shown 5-point smoothing to be the optimum value for most purposes.

To reduce the amount of printout, another program option permits selection at any rate of printout regardless of the recorded rate. Printout can be one sample per second, one per minute, or any practical rate, even though data are generally recorded at the 10-per-second rate. Printout of the analog channels is optional, and channels may be printed as desired.

A binary tape of TACAN data, useful for merging with other project data, is also optionally available.

IMPROVEMENTS.

Flexibility of the system has been enhanced by various modifications and improvements, one of which was a recommended modification in the bearing circuitry of the AN/ARN-84(V) TACAN's to improve its automatic gain control (AGC) response in the air-to-air bearing mode.

Also, in early use of the system, implausible data jumps were observed on the printout, and this fault was traced to the tape recorders. Corrective action has improved the recorder performance, but the problem is unpredictably recurrent with this type recorder.

Since the least significant bit in range of 0.0125 nmi was not available at the serial data terminal which feeds the formatter, a modification was made to pick up this bit internally and route it through the various subchassis and internal connectors to where it was gated out from the AN/ARN-84(V) computer circuitry. Otherwise, in early use, the least significant bit in range was 0.025 nmi.

As a manufacturer-recommended precaution, external blower motors were mounted in back of the rack for added cooling when the TACAN was operated in the beacon mode.

Test units were installed on each TACAN system rack, with plugs that mate to front connectors on the TACAN's. A similar test unit was made for the ADU. With several test points openly available, in-flight performance was readily monitored, and trouble analysis was more convenient.

Failure of the mechanical-scan antenna to rotate was twice caused by wearout of miniature ball bearings used in the motor mount. Such very low MTBF (mean time between failure) has prompted research into availability of low-cost electronic-scan antennas, which should represent a future potential improvement in reliability.

Other problems encountered were; (1) failure in the power supply module of one of the TACAN's, (2) problems with the mount mating connectors because of frequent and often unavoidable plugging and unplugging of the TACAN's into their mounts, (3) a defective range computer module, and (4) a serious burnout of one TACAN set when ramp power failed briefly and apparently restarted with a large surge voltage.

Due to the extent of damage, this last failure was corrected by the manufacturer. The manufacturer also performed the previously mentioned bearing AGC modification.

Recent improvements include permanent display and recording of AGC, installation of an automatic antenna changeover relay to permit diversity application in selection of lower or upper aircraft antenna, and installation of paired, high-gain directional TACAN airborne antennas for use in long-range flights. Planned are modifications to improve ranging under conditions of interference. Another formatter chassis is under construction, to serve either as spare or as basis in conversion of the analog system to digital.

ACCURACY TEST

REFERENCE MEASUREMENTS.

Two separate systems were employed to individually measure the range and bearing accuracy of the TACAN system. For range reference measurements, the NAFEC phototheodolite system was used. For bearing reference measurements, a periscopic sextant was installed in the N-47 aircraft.

PHOTOTHEODOLITE SYSTEM. The NAFEC phototheodolite system is a four-station system located at the four corners of an approximate rectangle that encloses the NAFEC runway. Phototheodolite range errors for the data used in this report are estimated to average less than 20 feet.

Each phototheodolite provides an azimuth and elevation angle measurement to the aircraft being tracked. These signals are encoded and transmitted in digital form to range control center, where they are recorded. The raw data tape is processed on the NAFEC computer complex in any of several formats, including position coordinates in XYZ, slant range, azimuth and elevation angle, or geodetic coordinates. Program options include translation and rotation of origin, smoothing of data, and merging with other project data tapes via generation of a phototheodolite binary tape.

For the TACAN accuracy test, two two-station solutions, one of each test aircraft, provided the slant range separation distance against which the air-to-air TACAN range measurements were compared.

Range control provided the precise time source with which all NAFEC instrumentation facilities were correlated to project data including the TACAN digital system time code generator.

PERISCOPIC SEXTANT. A Kollsman aircraft periscopic sextant was used to provide in-flight reference bearing measurements. The sextant was mounted in a special overhead hatch door on NAFEC Gulfstream N-47. It is conveniently removed from its mount after use, so that it is not permanently maintained in position.

The sextant has a dial resolution of 2°, with interpolation to 1°. Initial calibration of the installation was made by backsighting a transit down along the longitudinal axis of the aircraft to assure zero degrees dead ahead. The sextant was set to zero degrees when the transit showed the aircraft was pointing directly at it. Since the centerline of the sextant was precisely in line with a forward antenna and the aircraft tail, calibration thereafter was a simple matter of setting up on these two projections each time the sextant was installed. Both the sextant and the rotating antenna are mounted on top the fuselage, with the sextant forward of the rotating antenna.

Various tests were conducted on the ramp to estimate the accuracy and repeatability of measurements with the sextant. These included tests where the angles between various structures about the field and within sight of the ramp were repeatedly measured. From these tests, it was estimated that the total error in the sextant, including operator error, was less than 1°. Reference bearing measurement from the sextant could not be recorded; therefore, all bearing reference data were acquired manually.

The test flight consisted of positioning the cooperating aircraft about the lead aircraft. At each of these points, the cooperating aircraft was sighted through the sextant, at which time simultaneous readings were made of sextant bearing and TACAN bearing.

BEARING ERROR.

STATIC TEST. Initially, a static error test of the rotating antenna was conducted in which the antenna installation in Gulfstream N-47 was operated in the air-to-air mode against the analog TACAN system located in Bldg. 156 (approximately 0.7 nmi distant), and in the inverse receive/transmit mode against a DME-only site off runway 31 (approximately 0.3 nmi distant).

Measurements were made on the aircraft at the ramp, while the aircraft heading was changed to enable measurements at six different headings. Reference bearing measurements as made with the sextant compared to the TACAN-displayed bearing measurements were:

	Mean Error	Standard Deviation
Bldg. 156 TACAN	1.2°	2.0°
Ch. 28 DME	1.7°	1.4°

The average sextant error was estimated to be 0.7°. Statistics from each set of data indicated a slight clockwise bias with a variation in measurements from 0.09° to 4.74°. The larger values were from data taken off the nose or tail, where shadowing evidently occurred.

FLIGHT TEST. On a subsequent two-aircraft flight test in which the aircraft were flown in the same direction spaced at separations of 3 to 5 nmi, bearing data were collected at several relative headings.

Two of the test patterns included head-on flights, but it was impractical to operate and record the sextant at very high rates of change. Of 15 sets of measurements made, there were four occasions the TACAN bearing drifted off abruptly for no apparent reason, a condition that had not been previously experienced. Statistics from those four errant sets of data are listed below in table 1, but they are not included in the computation of the summary statistics. Subsequent test flights substantiated these statistics.

TABLE 1. TACAN SYSTEM AIR-TO-AIR BEARING ERRORS

Nominal Heading (Degrees)	Mean Error (Degrees)	Standard Deviation	Sample Size
62	-0.29	2.75	7
72	1.0	1.79	6
310	-1.2	1.82	15
286	-0.5	1.29	4
236	-2.89	1.62	7
110	-0.14	2.85	7
98	0.0	2.45	8
111	-0.2	1.10	5
111	0.57	1.62	7
198	-1.32	1.89	19
197	-1.90	1.10	10
Summary:	-0.79	2.40	95
74*	7.17	6.49	6
271*	-1.79	6.34	15
111*	-4.20	5.88	10
134*	0.0	4.69	6
H**	-0.50	5.80	4
H**	2.01	5.04	17

* TACAN drift.
** Head-on patterns.

Direction of subtraction for data was the TACAN bearing measurement minus the sextant bearing measurement.

RANGE ERROR.

Two test flights were conducted on another NAFEC activity for which the test design included use of the phototheodolites and TACAN systems. Data collected on these flights were suited for a range error analysis of the TACAN's. Phototheodolite tracking data on the two aircraft were converted into reference slant range separation for comparison with time-correlated TACAN air-to-air range data. Some of the TACAN data collected on these flights were unusable, due to recorder malfunction. (There have been flights in which well over 100,000 consecutive samples have been recorded without a single malfunction. The problem has been the unpredictable nature of the malfunctions, rather than consistent malfunction.)

On the first flight of June 23, 1976, flight patterns were limited in range rates to values below 200 knots. The second flight of July 7, 1976, provided for collection of certain data at the higher range rates but, again, there was a recorder malfunction that limited the quantity of data for analysis.

Range error statistics for the June 23 flight are shown in table 2. The table is divided into three parts, the first of which lists the individual runs as collected.

Runs 2 and 4 were collected while the aircraft were banking in turns preparatory to coming up on the next crossing pattern over the field. Fortunately, phototheodolites remained on track during this maneuvering period, which provided unexpected data on TACAN characteristics during bank and turn. As expected, the standard deviation error during these periods was greater than that of runs 1, 3, and 5 where the aircraft were in level flight.

The second part of table 2 lists all level-flight statistics separately from all maneuvering data, and the third part of table 2 lists the statistics from all data combined. This last statistic is the quoted value of system error.

The average error of 0.001 nmi is well below the phototheodolite error, therefore the TACAN bias is considered to be zero biased in that its mean error is effectively zero. The standard deviation of 0.016 nmi (97 feet) is well within specifications for TACAN range measurements.

These same statistics are repeated in table 2 for a program-smoothing factor of 5. That is, data collected at a rate of 10 samples per second were processed for smoothing over 1/2-second (5-point) rates. There are significant reductions to be noted in already low variabilities as evidenced by the lower standard deviation errors of all runs, and of the total of all data. Smoothing resulted in a standard deviation error of 0.010 nmi, or 60 feet.

(There are fewer samples in the smoothed data due to a situation in which bit drops by the recorder sometimes resulted in bad range values that retained the validity bit. Since the TACAN was supplying good data into the recorder, the validity bit was present, but bit dropping by the recorder sometimes retained the validity bit with misplaced bits in the range word. Also, the computer program included these bad bits in the smoothing, with the result that large jumps in recorded range caused data following for several seconds to be adversely affected by the smoothing. A later program modification tested first the differences in range, and if the range jump between 0.1-second intervals was an improbable value, the smoothing computation was interrupted, and the raw range printed.)

The data of the July 7 flight were reviewed and found to have the same characteristics of the June 23 test. For the July 7 data, the unsmoothed mean error was 0.003 nmi, with standard deviation error of 0.016 nmi, and with sample size of 1,222 samples. These data included flights in which the aircraft were both converging and diverging at range rates of approximately 100 knots.

TABLE 2. TACAN SYSTEM AIR-TO-AIR RANGE ERRORS

Run	Raw Data $\overline{X}$	Raw Data S	Raw Data N	Smoothed Data $\overline{X}$	Smoothed Data S	Smoothed Data N
1. Diverging, 50 knots	0.002	0.009	880	0.002	0.005	880
2. Banking	0.002	0.021	787	0.002	0.014	667
3A. Converging, 150 knots	0.010	0.013	765	0.010	0.007	635
3B. Diverging, 150 knots	-0.005	0.013	1,060	-0.005	0.005	1,050
4. Banking	0.001	0.028	800	0.006	0.017	800
5A. Converging, 50 knots	-0.001	0.012	981	-0.001	0.006	914
5B. Diverging, 50 knots	-0.001	0.011	1,289	-0.001	0.005	1,289
Runs 1, 3, and 5 combined	0.001	0.013	4,995	0.001	0.007	4,768
Runs 2, 4 combined	0.001	0.025	1,587	0.002	0.017	1,467
All Data	0.001	0.016	6,582	0.001	0.010	6,235

NOTE:

$\overline{X}$ = mean error in nmi, S = standard deviation, N = sample size.
Direction of subtraction was TACAN range minus phototheodolite range.

TACAN S/N 15001 had been used in the aircraft (N-47) to obtain the data and statistics described in table 2. At this time in the analysis it was of interest to review statistics from TACAN data (S/N 15002) simultanously acquired in the cooperating aircraft N-48 in the June 23 and July 7 flights. This was when some bias was noted. Discussion with the manufacturer provided assurance that this bias could be removed by careful alignment, which normally was not done on production models, simply because user requirements were not as precise as those in the NAFEC application.

Along with the bias correction potential, modifications are planned that should further reduce variability of measurements by compromising other unneeded features such as the range rate tracking capability up to 4,000 knots.

SUMMARY OF RESULTS

The primary results obtained from the data were:

1. Air-to-air ranging measurements exhibited zero bias, with a standard deviation error of 97 feet for raw data and 60 feet for smoothed data.

2. Air-to-air bearing measurements exhibited essentially zero bias, with a standard deviation error of 2.4°.

CONCLUSIONS

The standard of comparison for range error was military specification MIL-N-81207A(AS), which states the digital error in distance measurement for the AN/ARN-84(V) TACAN navigational set shall not exceed ±0.05 nmi (300 feet). Contract specifications for the airborne rotating antenna specified that the error should not exceed ±5.0°.

Based on test data defined in this report, the standard deviation of errors in range of 0.016 nmi (97 feet) and in bearing of 2.4° are within specifications.