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POSITION MEASUREMENT STANDARD EVALUATION

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16. Abstract

The objectives of the Position Measurement Standard Program were to collect navigation data from three DME receivers and a low-frequency GLOBAL Navigation system, and evaluate their relative performance against a reference radar.

Flight test data during June and July, 1974, established that:

- triple DME was an order of magnitude more accurate than the GLOBAL system
- triple DME accuracy was repeatable, smooth over all flight regions, and insensitive to initial condition, whereas GLOBAL system accuracy varied from run to run, exhibited large random errors and quantum "jumps", and was dependent upon error nulling procedures prior to system initialization.

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PREFACE

During 1972 and 1973, TSC assembled a navigation testbed for the evaluation of radio navigation systems: multiple VOR and DME, and LORAN low-frequency system. These systems were evaluated in a flight test program. Upon completion of these tests, the sponsoring agency requested TSC to modify the navigation testbed for the evaluation of two specific navigation systems: triple-DME ranging and GLOBAL Navigation. Triple-DME uses three independent ground stations and airborne receivers, line-of-sight reception, and a geometric algorithm to compute aircraft position. Global Navigation System uses low-frequency propogation from worldwide stations, and has a self-contained computational subsystem for system outputs.

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1. INTRODUCTION

At the present time, there is no accurate low altitude flight-inspection data available detailing the performance of the VORTAC system. This fact became evident when the FAA was unable to supply data to the Radio Technical Commission for Aeronautics, Special Committee 121 who are evaluating the VORTAC system. Most of the data available today at low altitudes are the ground check-point type whereby the pilotage errors would be the contributing error factor. In addition, the implementation plan to determine the upgrading of the NAVAID ground environment to support narrower route widths due to RNAV routes, as well as STOL operations, cannot be logically developed without a detailed knowledge of the present system accuracy. This empirical data base needed low altitude data as well as fine grain information which allow the determination of the individual components which comprise the route width error budget.

In order to gather this data, a flight test system must be developed for use at low altitudes. One aspect of this development will be an accurate positioning standard to supplement a standard multi-DME technique. TSC was requested to determine the feasibility of modifying the STOLNAV Flight Test System, which was used in previous flight testing, for evaluating two systems for a position standard for the flight test required by the FAA. It was determined that the STOLNAV Flight Test Equipment could be modified for this evaluation and two basic systems were implemented for testing: three DME receivers and a low frequency Global Navigation system. Navigation data was digitally recorded on board for later processing. Flight Tests were flown during June and July, 1974.

2. PROGRAM DEFINITION

The Program Office at TSC was responsible for developing the hardware, software and analysis portions of the flight test system. The goals of the program were:

1. to modify hardware on the STOLNAV pallet so as to collect basic navigation data for three airborne DME receivers and a low frequency Global Navigation system;
2. to develop flight software to record the navigation data; and
3. to evaluate the performance of both triple DME and Global Navigation systems against a reference EAIR radar at NAFEC.

The hardware modifications consisted of adding a third DME receiver and replacing the low frequency LORAN C system with the Global Navigation system. The Air Data Computer was removed from the flight system. The software for the airborne computer was reduced to a simple algorithm to collect the flight data on tape without performing any real time processing. The analysis programs developed for data reduction are described in Section 4. The FAA facilities of NAFEC at Atlantic City, New Jersey, supported the program during flight testing. A convair 580 was fitted with the navigation equipment, and all flights were under coverage of the EAIR radar which recorded position data for later analysis. The aircraft was piloted by NAFEC crews, and a TSC technician monitored the navigation equipment and tape recorder during flight.

3. EQUIPMENT DESCRIPTION

The equipment utilized to evaluate a precision measurement standard was developed primarily in the STOL Navigation & Guidance Program. The STOL program successfully completed flight tests in the fall of 1972. The airborne equipment block diagram is given in Figure 3-1.

The description of the airborne hardware used in the evaluation flight tests can best be presented by separating the equipment into the following five functional groups.

1. Avionics Hardware
2. Computation Subsystem
3. Recording Subsystem
4. Pallet & Control and Monitor Console
5. Support Hardware

3.1 AVIONICS HARDWARE DESCRIPTION

The Avionics hardware consists of:

(3) Distance Measuring Equipment (DME)

Global Navigation VLF System

Time Code Generator (TCG)

(2) Very High Frequency Omnidirectional Receiver (VOR)

Aircraft Heading transmitter

All avionics receivers are located in the System pallet as shown in Figure 3-2. The equipment control boxes and displays are mounted in the Control and Monitor Console to allow ease of access to the system operator. Interconnections are made between the pallet and the C/M console through connectors to facilitate transportation of these two equipment racks.

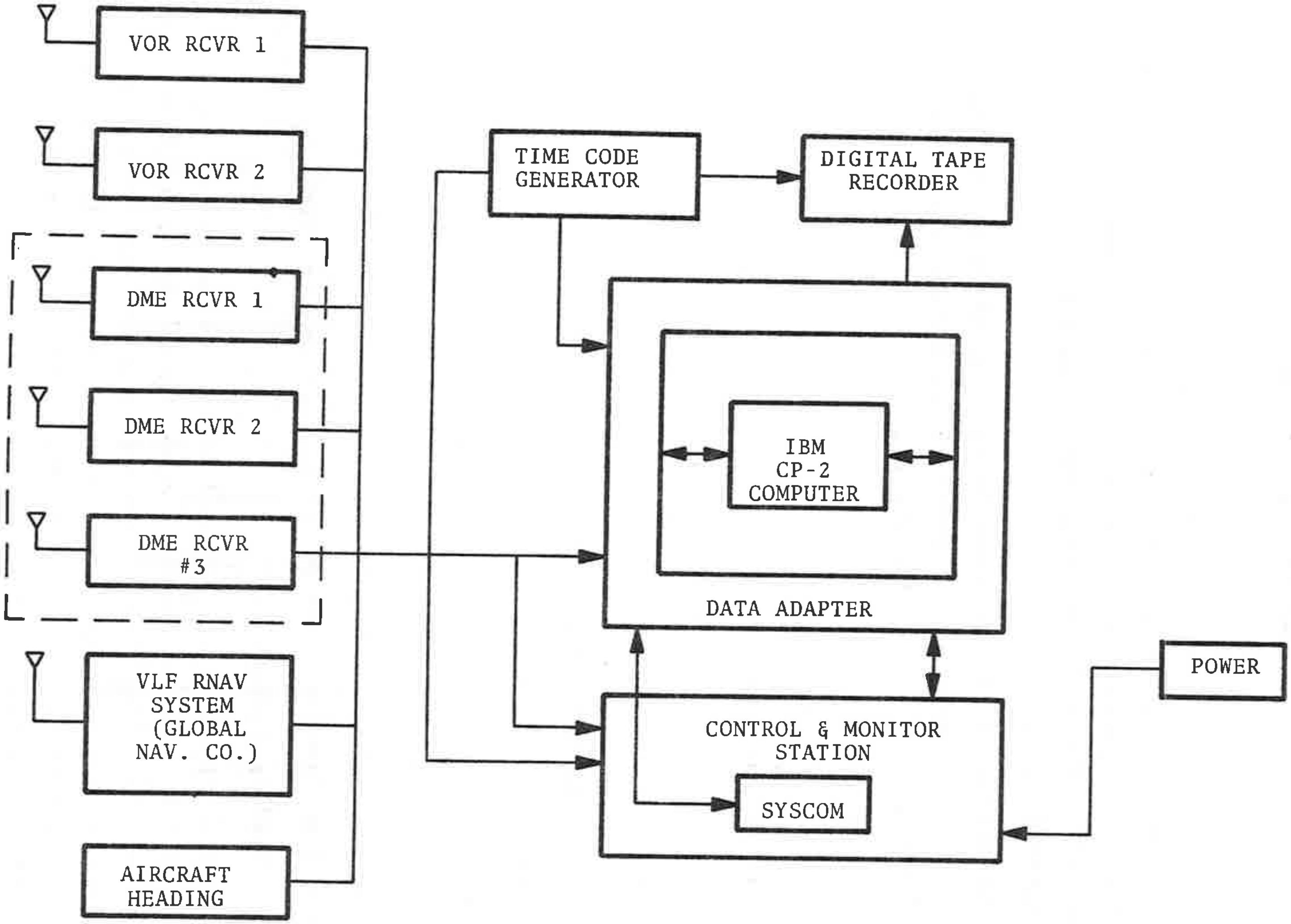

Figure 3-1. Position Measurement Standard Test System

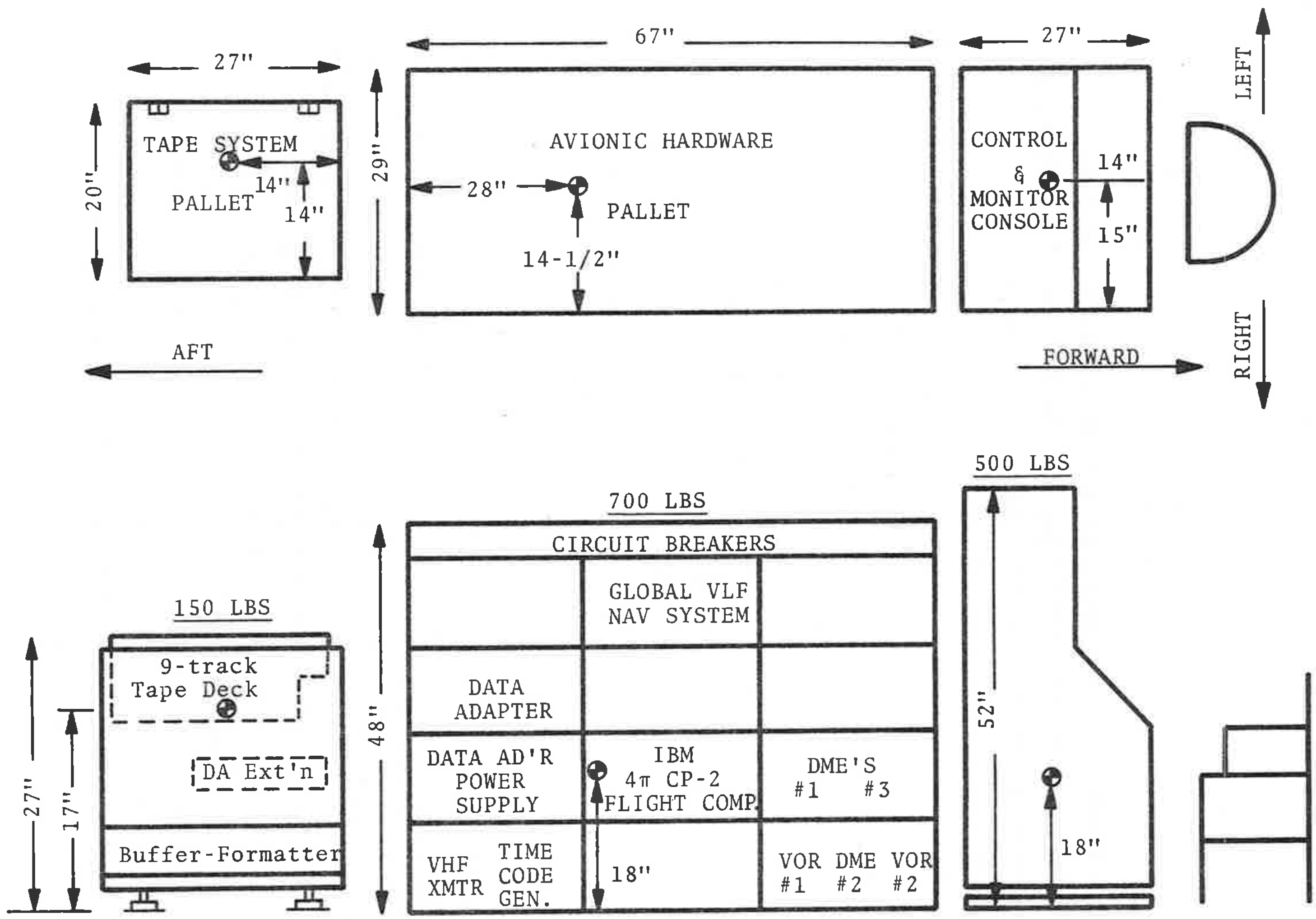

Figure 3-2. System Pallet Configuration

3.1.1 Distance Measuring Equipment (DME)

The DME Subsystem consists of three digital DME receivers with associated remote tuning devices. The tuning devices are accessible to the operator located at the C/M station. The DME receivers are capable of outputting a signal indicating the range and range rate to the station to which they are tuned.

Distance Measuring Equipment is a line-of-sight, pulse-ranging system for aircraft operating in the 960 to 1215 MHz band. The range is determined by a pulse delay measurement. The aircraft transmits pulse pairs at a rate of 30 pairs per sec. in the tracking mode. These pulse pairs, when received by the ground station, trigger the transmission of identical pulse pairs after a fixed delay time. The aircraft equipment subtracts out the delay and measures round-trip time to determine range to be used in the navigation system. The DME receiver is a standard ARINC specified digital DME which provides a serial digital data output defining range to the station. This serial output includes clock, work sync. and data. Data is transmitted at a word rate corresponding to each 0.01 nautical mile change in computed distance up to 30 samples/sec but in no case less than 5 samples per sec. This output is used to drive digital readout devices on the C/M panel and provide an input to the Data Adapter for input to the computer. In addition, the DME receiver provides a warning discrete to indicate power failures, unreliable data output and aural station identification.

The DME receiver is mechanically interfaced with the equipment racks with power being provided through the C/M panel from the aircraft auxiliary power system. Antennas are mounted on the fuselage of the test aircraft with signal leads routed to the receiver. Electrical interfaces include signals routed to the control box, digital display, Data Adapter, and C/M panel. The digital display is mounted in the C/M panel. Standard ARINC interfaces are utilized throughout.

3.1.2 Global Navigation VLF System

The Very Low Frequency Navigation system used in this evaluation was a Global Navigation, Inc. seven-channel system with a Rubidium standard atomic clock. The addition of the clock provides more stable track and distance information by allowing the operator to choose only the two strongest VLF signals, substituting the clock for the third. The navigation system consisted of a seven channel receiver, system controller, antenna and atomic clock.

Very Low Frequency refers to radio signals which fall generally within the band of 3 kHz and 30 kHz. These signals are unaffected by local atmospheric phenomena and can be received at any altitude. Two types of stations provide VLF signals which may be used for navigation. The first includes the stations which comprise the Naval Communication Network. Signals from the higher power stations can actually be received in some instances, more than halfway around the world. These stations were commissioned by the Navy primarily for use in communicating with submarines and ships at sea. It was determined that these stabilized signals could fulfill a number of functions of importance to other users. This stability was achieved by referencing all of these stations to cesium standards, which control the frequency of each of the stations to an accuracy of one part in ten to the twelfth. It is the phase stability of these signals, their frequency and power that make them so useful for VLF navigation. The second set of stations (not utilized in this evaluation) consist of OMEGA Navigation Stations.

The Navigation system as purchased had the capability of flying between two entered "waypoints". Upon reaching the termination of that leg, it was necessary to enter a destination waypoint to continue on the next leg of the trip. Operationally, these inputs can be calculated easily using time difference tables. Global Navigation, Inc. supplied all operational parameters to TSC that were required as system inputs. A buffer box was procured and modified to allow display data to be transmitted in parallel to the recording subsystem.

Since the distance between waypoints was relatively small (40 n mi) the Global system was operated continually in the APPROACH mode. This increased the cross track sensitivity and allowed the DISTANCE TO GO sensitivity increase to ± one-tenth of a nautical mile.

3.1.3 Time Code Generator

The Time Code Generator produces real-time codes which consist of an output of BCD representations of real-time (IRIG-B). The generator provides a time output every millisecond. This is an input to the DA for time correlation of computer data. The Time Code Generator is synchronized prior to each flight test and generates time in a 32-bit parallel digital form for data formatting and recording. Electrical interfaces include those between the components of the timing systems, along with a 32-bit parallel data time to the DA. Provisions are made in the C/M panel for the display of the time and for applying power to the unit.

3.1.4 Very High Frequency Omnidirectional Receiver (VOR)

VOR is a line-of-sight nav aid operating in the 108 to 118 MHz band. The airborne receiver detects and separates the two signals transmitted from the ground station and performs a phase difference measurement. The difference in degrees is then equal to the reciprocal of the magnetic bearing of the VOR station from the aircraft. The magnetic bearing is available for use in the system. Two VOR receivers, each having ILS capabilities, are utilized in the Airborne System.

The Signal output drives the RMI (Radio Magnetic Indicator) mounted on the pallet and provides an aural station identification. Another output in the form of 400 Hz voltages with a phase proportional to sine and cosine of bearing angle is supplied to the DA. In addition, the VOR provides warning discretes to indicate power failures and unreliable bearing and ILS signals. Tuning is accomplished via a separate control unit on the C/M panel.

3.1.5 Aircraft Heading

Current aircraft heading is provided directly from the aircraft heading transmitter in the form of a three-wire synchro. A warning indicator provides indication of erroneous data in the Aircraft Heading Subsystem. Heading is an input to the DA & RMI indicator.

3.2 COMPUTATIONAL SUBSYSTEM

The Computation Subsystem consists of a CP-2 airborne digital computer, a Data Adapter (DA) for the computer I/O interfacing, flight-program software and a systems communication (SYSCOM). The Computational Subsystem is capable of accepting inputs from all of the navigation aids listed above by a selective addressing of any one or more of these devices. The Computational Subsystem is capable of throughputting the output of any navigation aid or aids through the DA to the CP-2 computer. The Computational Subsystem can accept external commands from the SYSCOM and is capable of "snapshooting" the values of the data table five times per second and outputting the formatted data table to tape.

3.2.1 Flight Computer

The airborne computer utilized was a flight-qualified general-purpose computer with 16, 869 16-bit words of core memory. The computer provides direct memory access to external devices through one externally controlled input half-channel and one externally controlled output half-channel. The computer accepts eight external interrupts on two priority levels in order to accommodate inputs from devices which are asynchronous to internal computer operations. One programmed controlled output half-channel is provided. It functions as a stored-program, parallel, fixed-point, binary computer with a 2.5 microsecond storage cycle time.

The CP-2 characteristics are described in detail in applicable CP-2 documents. All data in or out of the computer passes through the DA and will, in most cases, be transferred over I/O channel #1. This channel has two halves: Externally-Controlled Input

(ECI) and Program-Controlled Output (PCO). Each half has 16-bit parallel data nd 12-bit parallel address lines. Aside from the main power and blower excitation, the remaining CP-2 electrical interface is with the Flight DA. This interface consists of data I/O interrupts, discretes and voltages.

The interface of the CP-2 to the DA is as follows: The DA has registers containing continuously sampled digital data that has been obtained from the SYSCOM, C/M Panel, or, after signal conversion, from the navaids (navigational aids). When the CP-2 program requires data from a given register, it reads it into memory using the PCO to control the ECI DMA channel, as follows: The PCO channel sends out a 16-bit word and an 11-bit word plus one parity bit. The 11-bit word goes to the DA and chooses the particular register to be read. The 16-bit data from the DA output holding register is then gated onto the 16-bit ECI parallel data-lines into the computer. Further, the low-order 11 bits of the 16-bit PCO word are routed back onto the ECI 11-bit memory-address lines, to act as the memory address for the holding-register data entering on the ECI data lines. Parity is generated in the DA for the ECI data and address words. Appropriate logic for each register handles the gating, decoding, timing and "data ready". When required, DA hardware and CP-2 software provides "time-tagging" of input data for transmission to the downlink. The "time-tagging" indicates the instant that the data was sampled. The sampling instant is expressed as a time-of-day value (hours, minutes, seconds and milliseconds) that is accurate to within 10 milliseconds and synchronized to the ground Time-Code-Generator. Whenever possible, all input data is verified as good before it is read into the CP-2. This verification consists of parity checks for the SYSCOM and the recognition of "fault" flags from the navaids. In the event that either of these error conditions is recognized, the contents of a DA Flag and Error Register (FER) changes and the change causes the FER to be an additional input to the CP-2. For data output from the CP-2, the DA has registers containing digital data that are sent to the SYSCOM C/M panel or tape recorder. When it is required to output from the program data is transmitted to the DA through the PCO channel as a 16-bit data word and a 11-bit address plus parity bit for the two words. The address word directly selects the DA destination register for data loading. Whenever possible, the destination register is refreshed at a rate that is faster than the minimum signal frequency required by the device connected to the DA. Whenever possible, all parity errors in the CP-2 output data are recognized by the DA. If a parity error occurs, the highest priority external interrupt (No. 1 level 3) is activated. Interrupts and input discretes may originate in the DA itself or within the SYSCOM, the navigation aids, or the C/M panel. Whenever these signals are passed through the DA, they are properly signal conditioned for the computer.

3.2.2 Data Adapter (DA)

The Flight DA allows the CP-2 to select, control, bus, store and monitor input/output data and discretes to and from these boxes. The Flight DA also converts non-digital input signals into digital formats compatible with the CP-2 and the reverse for output signals. Examples of such conversions are analog-to-digital and synchro-to-digital. Since most subsystem boxes interfacing with the DA are asynchronous in their data transfer, the DA must also perform serial-to-parallel, and data holding functions. In addition, the DA accepts, interprets and executes the computer data-transfer sequences, encode and decode addresses for proper data routing check and provide proper parity on transfers, match impedence and voltage levels buffer data for proper timing, and provide proper data bussing.

The DA also contains the Flag and Error Register (FER) to monitor data from the three DME's and to detect "fault" flags, parity loss, etc. from its subsystem boxes.

The DA accepts system mode, navaid selection and data throughout identification inputs from the C/M panel. On receipt, these identifiers are input to the CP-2 on the ECI half-channel. The DA hardware is modularly constructed to be flexible and accept different future system inputs.

The Flight DA is readily removeable as a complete unit from the pallet. Also, consistent with an encasement that meets the environmental requirements, the DA is readily accessible to allow rapid and easy replacement of spare parts.

3.2.3 SYSCOM

The System Communicator (SYSCOM) operates in three modes to provide the means to enter or display data into or from the computer memory. The three modes allow the SYSCOM to operate independently, or as a specialized CP-2 communicator. The latter operation has extra hardware for hexadecimal or decimal entry and display, memory protection address incrementing, and error source identification . This last mode was used exclusively during the evaluation of flight tests. The SYSCOM consists of a keyboard, function switches, signal lights and a set of display digits (Figure 3-3). The SYSCOM panel includes a duplicate of the PICOM panel plus the following: A Storage Protect Key switch, additional Keys (A-F) for hex data, an ERROR/GO light, sixteen lightable pushbuttons for binary data I/O a Reset DA pushbutton, and a four-position switch to select one of the following: PICOM Repeat, SYSCOM Independent Hex or Dec.

3.3 RECORDING SUBSYSTEM

The tape recording subsystem consists of the tape deck, buffered formatter and a tape system interface designated as a data adapter extension.

3.3.1 Digital Magnetic Tape Recorder

The Digidata Model 1709/800 tape transport is a synchronous nine track, 800 lpi, NR-1/phase encoded, IBM compatible machine. The electrical logic interface is DTL. The tape deck is equipped with the necessary electronics for a Read-after-Write operation. The magnetic tape used was 1/2 inch 800 bpi, nine track and the reel diameter was 1 1/2 inch.

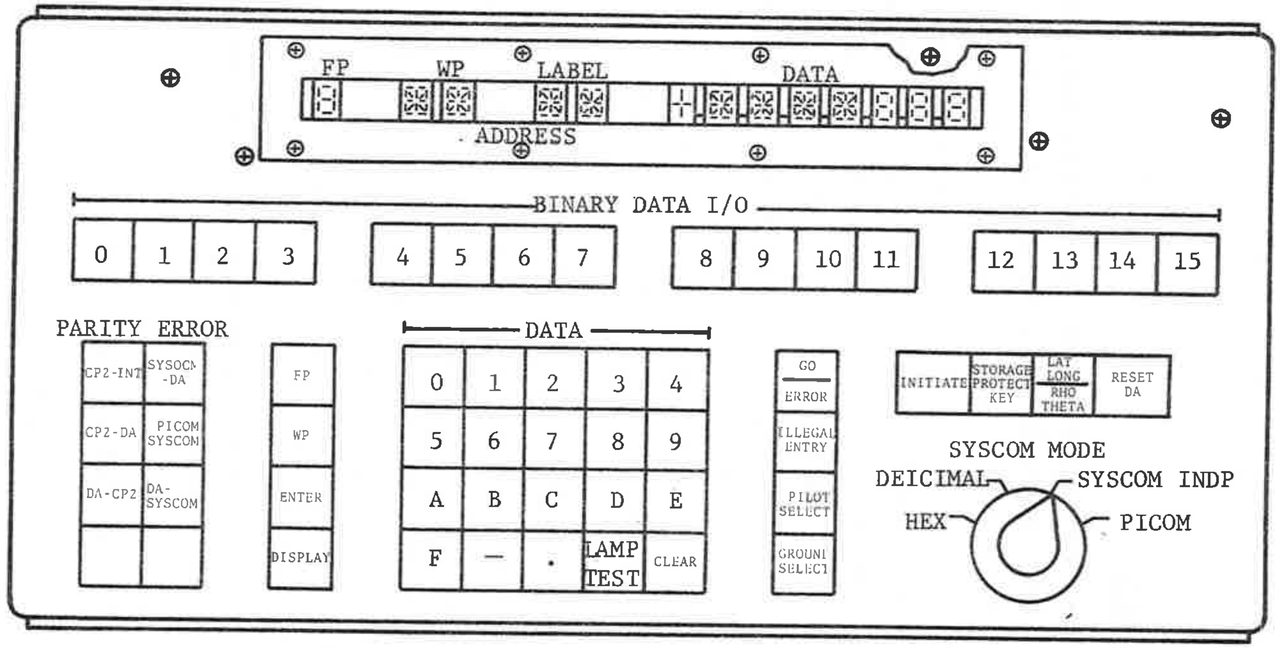

Figure 3-3. SYSCOM Panel Layout

The tape deck was mounted as shown in Figure 3-2 in a horizontal position due to aircraft space constraints. A separate shock-mounted pallet was rised for all the equipment of the Recording Subsystem. Interconnection cables were supplied by Digidata for interface with the buffer/formatter unit mounted just below the tape deck.

3.3.2 Buffer/Formatter

The buffer/formatter contains all the electronics necessary to read or write in IBM compatible formats. There are two buffers to allow continuous recording, each with a 2048 byte capacity. The maximum transfer rate is one MHz in the burst mode. The buffer/formatter and tape deck together form an incremental tape system capable of incrementally transferring data bidirectionally between a controller and IBM formatted magnetic tape. Multiple-error detection circuits are employed for READ transfers while error correction routines may be commanded during WRITE transfers. In this test application, the incremental system was used totally in the automatic write mode with a minimum of control lines.

3.3.3 Data Adapter Extension

In order to utilize existing equipment most efficiently, an extension interface box was designed and built at TSC to act as the interface with the flight computer. This recorder interface box basically functions as the data adapter does and could be considered as a satellite to perform interface functions not possible by the existing data adapter. It primarily operates as a timing and 16 bit/8 bit (2) conversion device for data flow to the tape system from the flight computes.

3.4 PALLET AND CONTROL/MONITOR CONSOLE

3.4.1 Pallet

The pallet is a specifically designed rack to house a variety of standard ATR cases (as described in ARINC specification #404 issued May 1, 1956) and other system components.

The pallet design is adequate to safely house the equipment for the entire spectrum of the anticipated "g" loading. The pallet provides vibration isolated mounting surfaces as required by the various equipments to be mounted. Each component mounted on the pallet is designed such that no pallet RFI shielding is required. The pallet does not provide for generalized cooling or power conditioning. However, several special cases are handled on an individual basis (i.e. cooling air to the CP-2 computer). Fundamental to the design is the consideration that more than one aircraft may be used and the system must be readily adaptable to each new interface.

The pallet provides an enclosure capable of being easily modified and permitting easy accessibility for visual inspection during use. It also provides mounting space for non-standard ATR equipment such as the CP-2 and the Data Adapter.

Pallet Size:	40" high, 66.5" wide, 29" deep
Weight:	670 lbs (loaded) 75 lbs (unloaded)
Power:	3.2 kilowatts (AC and DC).

Equipment locations in the pallet are shown in Figure 3-2.

3.4.2 Control/Monitor Console

A Control and Monitor subsystem is mounted next to the pallet to function as an interface point between the operator, and the entire system on the pallet. From this control point, the operator is able to activate and deactivate all equipment on the pallet, select desired computer modes and data throughput and monitor critical parameters of the system. Suitable alarm and automatic de-energizing circuits is incorporated in the C/M Subsystem to safeguard the equipments. In addition, the operator can insert information into the computer prior to flight, using the SYSCOM (an integral part of the panel), or a separate tape reader unit. The SYSCOM provides the means to enter or display data into or from computer memory.

Control Monitor	Weight:	480 lbs.
	Size:	52" H, 25" W, 27" deep
	Power:	28 Vdc, 500 watts

The control/monitor Console electrically interfaces with all the airborne subsystems. All control panels for selection of system operating modes, frequencies and manual CP-2 computer inputs are located in the C/M panel.

3.5 SUPPORT HARDWARE

Included in the context of support hardware is all equipment not included in the airborne test system which performed an integral function in the operation of the flight tests.

3.5.1 Field Operating Unit (FOU)

The FOU is a stand-alone support machine designed to support the CP-2 computer. It has the following capabilities:

1. Provide power to and operate the CP-2, including running or single-stepping it through a program.
2. Auto-load and auto-verify the computer memory from punched tape.
3. Manual-load and manual-verify any memory location and manual-load or display various computer registers on a large front display panel of lights and switches.
4. Communicate with the computer using a typewriter and utility routines resident in the CP-2.

The FOU must be supplied with 2030 watts of 3-phase, 115/208 60 Hz power. This power circuit should be protected by a 25 amp circuit breaker.

3.5.2 Extended Area Instrumentation Radar (EAIR)

The Extended Area Instrumentation Radar (EAIR) is a tracking radar which is used primarily for tracking aircraft which are not required to touch down. The range of this radar is 200 miles with a beacon-equipped aircraft. The accuracy of the system is:

Azimuth:	±1.0 milliradians (±6.1 ft/mile)
Elevation:	±1.0 milliradians (±6.1 ft/mile)
Range:	±60 feet

The precision tracking radar of the EAIR Facility measures, displays, and records the slant range, azimuth and elevation angles of an aircraft. Maximum tracking distance of the EAIR Facility is 100 nautical miles when operated in its primary (skin tracking) mode, or 190 miles when in secondary (beacon tracking) mode. Minimum tracking distance is one nautical mile. Digital output data consisting of slant range, azimuth angle, elevation angle and realtime are recorded on magnetic tape in IBM 7090 compatible format. Analog data in X-Y, X-Z coordinates are recorded in real-time on 30-inch plot paper. Other performance features of the radar system include automatic tracking, aided range tracking and raster scanning. Automatic tracking, once the aircraft is acquired, enables the radar antenna and range system to automatically follow aircraft movements. The aided range tracking features enables a range gate to be set at target (aircraft) velocity to facilitate angle lock-on or tracking during poor signal conditions. Raster scanning is used to assist in target acquisition. The radar system has the capability of providing or receiving synchronizing and slaving information to or from other radars, optical trackers and programmers, both in angle and in range. Radar data is supplied in both analog and digital forms for slant range, azimuth and elevation angle. The following data is the output from the system.

1. <u>Plots</u>

   An X-Y, X-Z ink-trace plot of aircraft trajectory and precise timing marks is available on a 30 inch x 30 inch plotting board. Timing marks to be available at selectable rates of one per second or one per ten seconds. The plotting board range is continuously adjustable from 6,000 yards to 1,200,000 yards.

2. Digital Data Formatting

This system extracts data from the radar, adds a time-word from a terminal timing unit and organize the data into a suitable format that is recorded onto magnetic tape for subsequent entry into a 7090 computer.

4. ANALYSIS AND DATA REDUCTION PROGRAMS

One program objective was to establish whether triple DME or Global Navigation system is more accurate as a position measurement standard. To this end, the analysis programs were designed to format the navigation data from both systems to allow comparison over the same regime of flight.

The flight path chosen is shown in Figure 4-1. Legs 1 through 5 were flown at even thousands of feet +500, and legs 6-7 at odd thousands +500. Eight circuits of this path were planned, from 2500 feet to 16,500 feet plus a 25-mile orbit of ACY VORTAC at 1500 ft. to record low-level data. This configuration was chosen because it afforded well-defined flight path segments between VORTAC stations, that were easy for the pilot to navigate in the absence of any onboard guidance system. The three DME stations (SIE, MIV, CYN) used for navigation were chosen for coverage over the flight and good geometry for the triple DME algorithm. They also are shown in Figure 4-1. The heavier segments shown on each flight path segment represent the portions where reduced data is presented graphically in Section 6, to demonstrate relative navigation accuracy.

4.1 TRIPLE DME ALGORITHM

The line-of-sight characteristics of the DME ranging system mandate their operation within a fairly restricted geographic area for example, at 1500 feet altitude the radio horizon is less than 50 miles. Therefore, the selection of DME ground stations is limited, and the processing algorithm designed accordingly. A full description of the coordinate conversion algorithm used to convert three DME ranges to latitude and longitude is contained in Appendix A: basically, it uses the principles of shperical and plane geometry applied to a geocentric earth model, with compensation for variations in the geodetic earth model.

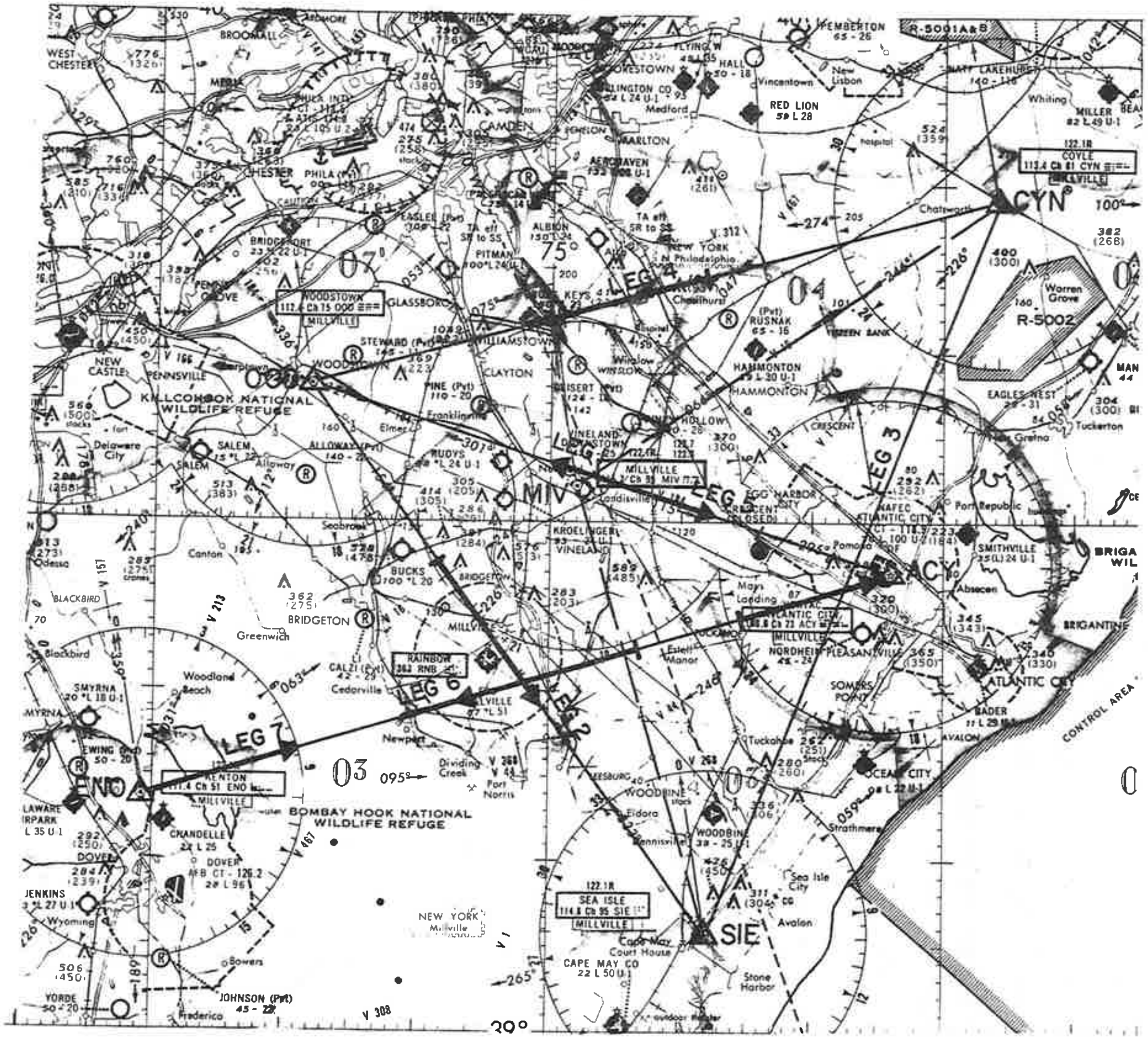

Figure 4-1. Flight Path

4.2 GLOBAL SYSTEM OUTPUTS

The Global Navigation System is intended to operate as a self-contained sensor-computation-output device dependent only upon low-frequency ground stations on the earth's surface. The principle of operation is the phase differential between pairs of stations, which set up parallel grid lines. Using two sets of station pairs, crossing grid lines can be established running essentially parallel and perpendicular to the intended flight path. These grid lines, when referenced to Ahead-Behind and Left-Right pairs of stations, yield cross track deviations and distance-to-go measurements which are as accurate as the quantum measurement for each grid. This is further exemplified in the discussion of Global Navigation, Inc. contained in Section 6.

4.3 DATA REDUCTION PROGRAMS

The data reduction process is depicted in Figure 4-2. The EAIR radar site collected time-tagged range, azimuth and elevation data on tape for processing at TSC. The data was smoothed, converted to latitude, longitude and altitude and written on tape as reference data for the triple DME and Global Navigation quantities.

The navigation data collected by the airborne tape recorder went through a multi-stage reduction process. The 9-track tapes were first re-recorded onto 7-track tapes on an IBM 360 computer at MIT, then formatted on an XDS 9300 computer at TSC. The formatting program stripped out the data from each record, matched MSB and LSB portions of words back together, scaled date to the proper units and performed limited data error checking.

Using the reference radar data tape, errors in the received DME ranges were computed and statistics generated for each leg of the flight path. The three time-tagged DME ranges and the time-tagged Global Crosstrack (CT) and distance-to-go (DTG) quantities were written on tape for further processing, at the recording rate of five samples per second.

The final phase of the data reduction process involved converting the three DME ranges into latitude, longitude, and altitude

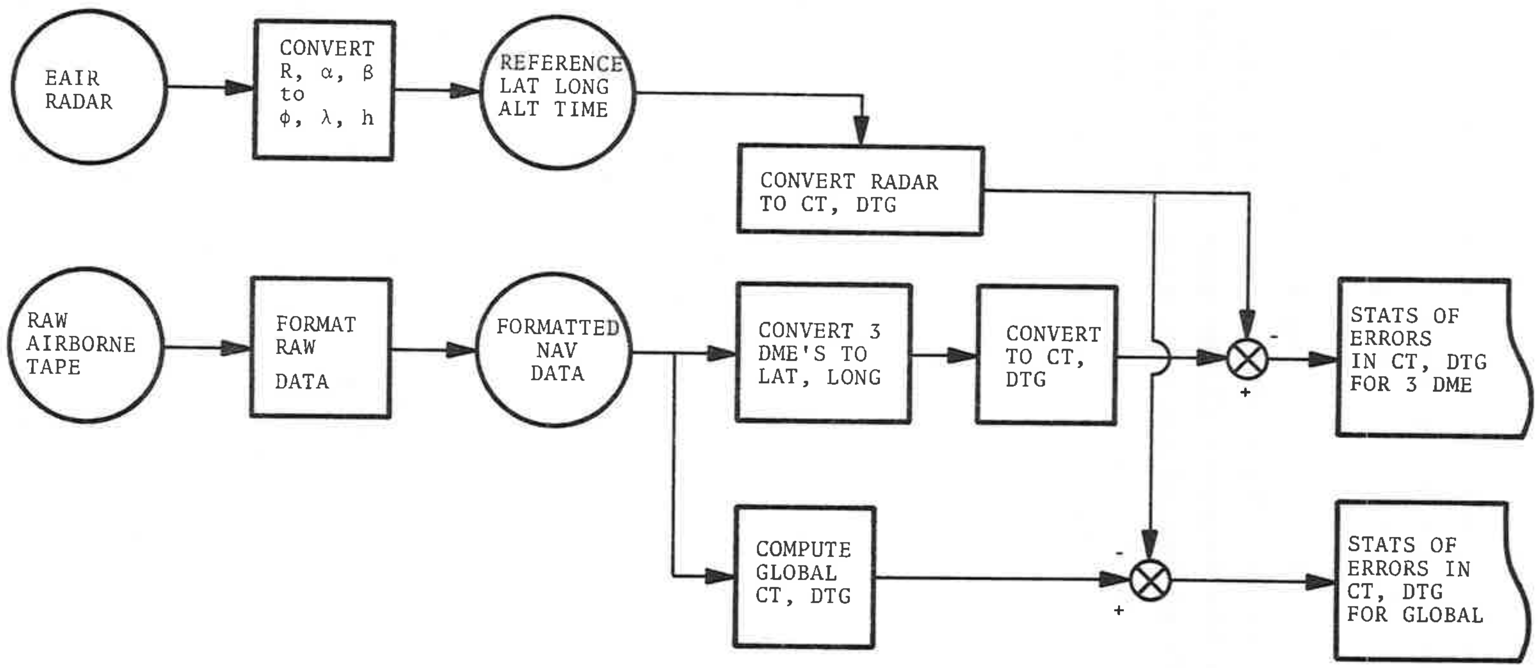

Figure 4-2. Data Reduction Processing Program

using a triple DME algorithm, then converting these to crosstrack and distance-to-go data with respect to fixed waypoints. The radar latitude and longitude are also converted to crosstrack and distance-to-go with respect to the same waypoints and compared to the triple DME data.

The natural coordinates of the Global Navigation system are crosstrack and distance-to-go with respect to fixed waypoints, so the same references radar-derived data are used to establish errors in the Global outputs.

The errors for both the triple DME system and the Global Navigation system are processed cumulatively so as to yield mean error and one-sigma standard deviation at the end of each leg of the flight path. These can also be processed to yield one cumulative statistic representative of the entire flight. The error data is strip-charted during processing, to show graphically the nature of the errors.

5. FLIGHT TESTING AND DATA PROCESSING

The test equipment was delivered to NAFEC in April, 1974, installed on the test aircraft (Convair 580) and given ramp testing and shakedown flights. The data collection flights commenced May 6, 1974 for three days, at which point the data tapes were returned to TSC for preliminary evaluation and the aircraft underwent maintenance. It was determined that the navigation hardware was working properly, and the flights resumed on June 4, 1974.

During the second phase of testing, it was observed that the airborne tape recorder was "running away" periodically, thereby eliminating data collection. The tape recorder manufacturer serviced and replaced the unit, which as it turned out, possibly continued to malfunction during the remaining flights. All of the flight data recorded in June exhibited several random "jumps" of the data words during the course of each flight. A summary of each days flights, written by Mr. William Moloney of TSC who monitored the onboard equipment throughout the flight tests, appears in Appendix B.

An attempt was made to correct for these anomolies in the data reduction software, but because the sporadic randomness of the occurrence, the data reduction software could not be modified to eliminate their effects. The data from flights 1 and 3 yielded the best statistical samples over large portions of flight and are presented in the following section. The qualitative data from the remaining flights supports the conclusion made based upon flights 1 and 3. The relative accuracy and data patterns exhibited in the first few flights were preserved in later flights, and any conclusions reached are supported qualitatively if not quantitatively.

6. TEST RESULTS

The quantitative data presented herein was collected during flights 1 and 3. Flight 1 was flown at 12,500 feet for legs 1 through 5 and at 13,5000 feet for legs 6 and 7. Flight 3 was flown 2000 feet higher on corresponding legs. Table 6-1 contains the statistics (mean error and one-sigma standard deviations) for errors in cross track deviation and distnace-to-go (to the waypoint), for both the triple DME and Global Navigation systems, along each leg of the flight path and over the entire flight.

These overall statistics demonstrate that triple DME system has a mean error of .06 nautical miles whereas the Global Navigation system mean error was .6 nautical mile. This one order-of-magnitude difference in the basic accuracy of each system was demonstrated throughout the entire flight test series. The Global Distance-to-Go data consistently exhibited the phenomena depicted in Figure 6-1. The system readout was accurate to the nearest .1 nautical mile, which accounts for the small "jitter" on the output. There was also, however, a jump of .5 nautical miles which occured approximately every eight (8) seconds or for every .4 nm flown. This jump is most probably due to the tracking algorithm within the Global computer, as it appears throughout the entire testing, on all legs at all altitudes. On the other hand, the Global cross-track data is smooth, which supports the theory that is an inherent problem in the algorithm to compute only distance-to-go.

The triple DME data, obtained from the three independent DME measurements through the conversion algorithms, exhibits the basic smoothness of the raw DME inputs, and has no algorithm anololies due to station geometry (e.g. flying along baseline between station pairs).

The following discussion is based upon the data graphically presented in Figures 6-2 through 6-14. An attempt was made to present the data from two different flights over the same portions of corresponding legs, so that comparisons could be made. All the

TABLE 6-1. SUMMARY OF QUANTITATIVE ERRORS

Flight Path Segment		FLIGHT 1				FLIGHT 3			
		3 DME		GLOBAL		3 DME		GLOBAL	
		ΔCT	ΔDTG	ΔCT	ΔDTG	ΔCT	ΔDTG	ΔCT	ΔDTG
1 ACY-OOD	MEAN	-.013	-.207	.040	.070	-.033	-.202	.491	-.192
	1σ	.020	.056	.093	.206	.071	.098	.209	.409
2 OOD-SIE	MEAN	-.120	.074	.519	-.402	.071	.012	-.248	.355
	1σ	.049	.080	.201	.364	.030	.076	.084	.255
3 SIE-CYN	MEAN	.079	-.013	.587	-.292	.050	-.127	.558	.098
	1σ	.059	.091	.248	.357	.039	.320	.330	.467
4 CYN-OOD	MEAN	-.134	-.114	.673	.810	-.132	-.134	.567	-.280
	1σ	.027	.124	.288	.815	.023	.064	.410	.304
5 OOD-ACY	MEAN	.026	.145	.086	.427	.041	.071	.649	.625
	1σ	.016	.069	.136	.253	.072	.064	.250	.242
6 ACY-ENO	MEAN	.078	.189	.898	.875	.065	-.128	.868	-.088
	1σ	.066	.126	.372	.694	.016	.150	.555	.550
7 ENO-ACY	MEAN	.075	.104	1.014	-.101	.066	.017	1.423	-.688
	1σ	.041	.095	.539	.361	.018	.045	.701	.401
SUMMARY	MEAN	-.029	-.055	.579	.234	-.027	-.083	.610	-.063
	1σ	.092	.162	.460	.723	.081	.175	.583	.548
RSS	MEAN	.062 nm (379 ft.)		.624 nm (3794 ft.)		.087 nm (528 ft.)		.614 nm (3728 ft.)	

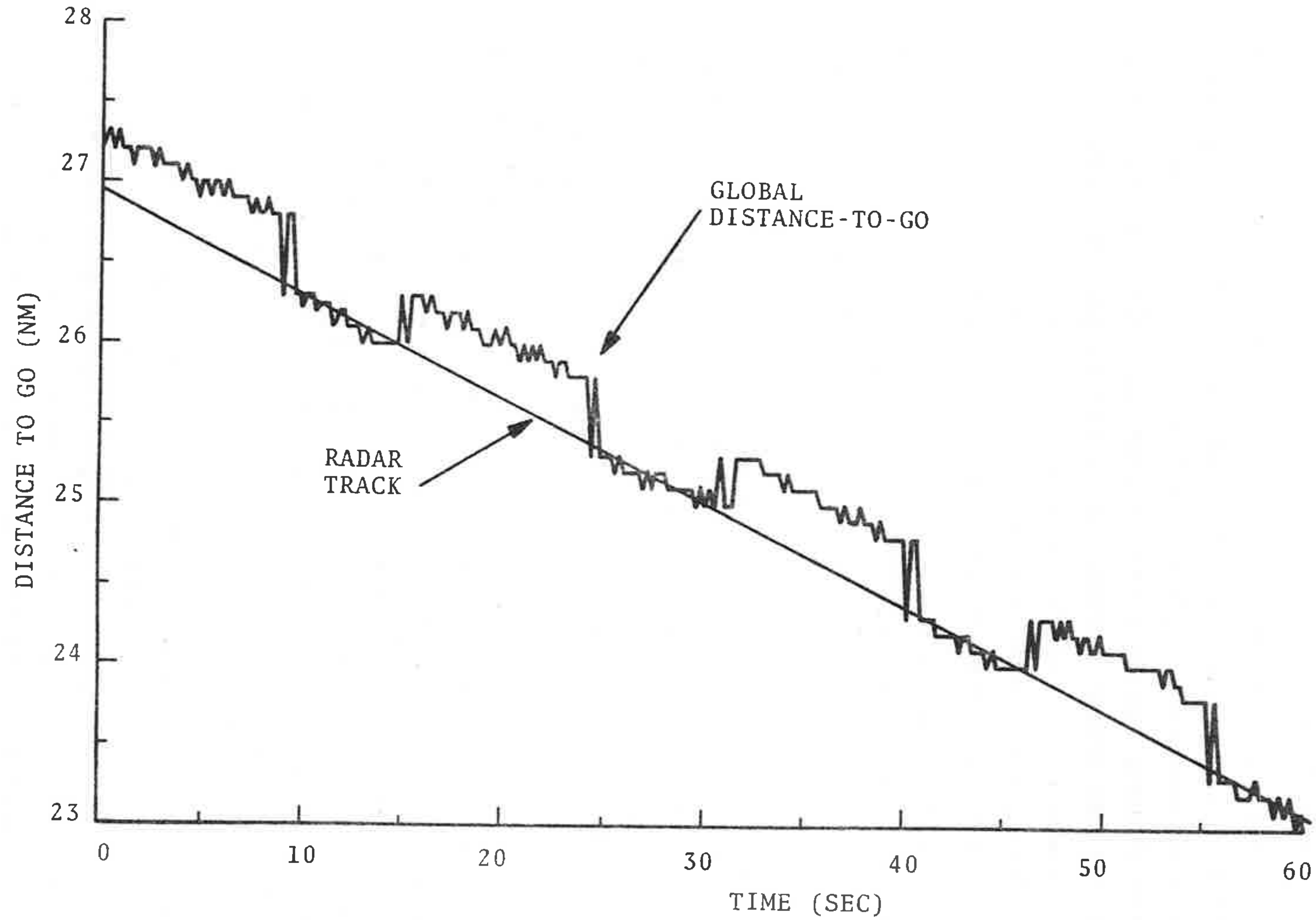

Figure 6-1. Errors in Crosstrack Deviation and Distance-To-Go

figures depict error in crosstrack versus distance-to-go to the waypoint. All error quantities are with respect to the EAIR radar reference crosstrack data.

Figure 6-2 shows a portion of Flight 1, leg 1 which was aborted because of cloud cover at the altitude flown, 10,500 feet. Figure 6-3 shows the same portion at 2,000 feet higher. Although no parameters were changed during reinitialization, note the lack of repeatibility for the Global system, while the triple DME outputs are similar. Figure 6-4 shows the same portion during Flight 3 at 14,500 feet. Again, the Global outputs are non-repeatable, this time exhibiting twice as large an error in crosstrack.

Figures 6-5 and 6-6 depict a portion of leg 2 for Flights 1 and 3 respectively. The triple DME crosstrack error is consistent between flights, but the Global System crosstrack error shifts both sign and magnitude.

Figures 6-7 and 6-8 depict a portion of leg 4 for both flights. The triple DME error repeats itself between flights, but the Global System crosstrack error is large in magnitude and drifts more off-scale as distance to go decreases for both flights.

Figures 6-9 and 6-10 depict Global System repeatability to a certain extent. As seen on Figure 4-1, legs 1 and 5 are the same flight path, flown in opposite directions. The similarities between the outputs for legs 1 and 5 on each flight indicate that there is some repeatability. It should be noted, however, that although the magnitudes of the errors are similar, the left-right sense of the errors are inconsistent, being north of the flight path on leg 1 and south of it for leg 5. Note that the triple DME errors do reverse their left-right sensing when flying in opposite directions on the same path.

Figures 6-11 and 6-12 show portions of leg 6. Again, the Global System errors are consistently compared to the triple DME errors. The fact that the errors are larger than on previous legs has no ready explanation, as all other parameters are constant except for the direction of flight. It should also be noted that this segment of leg 6 intersects the segment of leg 2 which was depicted in Figures 6-5 and 6-6. The errors are different by a factor of 2 or greater, indicating that parameters such as direction of flight affect the errors more than just the position in space.

Figures 6-13 and 6-14 show different portions of leg 7 one at the beginning of the waypoint leg and the other at the end. Position along the flight path apparently does not affect errors, which are consistent along the entire length of any given leg.

One possible explanation for the inconsistency of Global errors is that the Global System is sensitive to initial conditions along each leg. Prior to passing over each waypoint defining the beginning of a flight path, the pilot would line up with the intended path, and the system operator would center the crosstrack needle and set the distance to go display. The crosstrack needle had a scale of ± 1.5 nm. and nulling procedure probably introduced a 10% (.5 nm) error. This in itself would not explain the wide range of errors observed, but if the Global crosstrack algorithm were especially sensitive to initial conditions, this might explain some of the inconsistencies. Other factors such as station pair selection and grid shifts apparently had no effect, as the same stations pairs, recommended by Global as optimal, were always used, and no discernible shifts occurred in the Global grid network during the test duration.

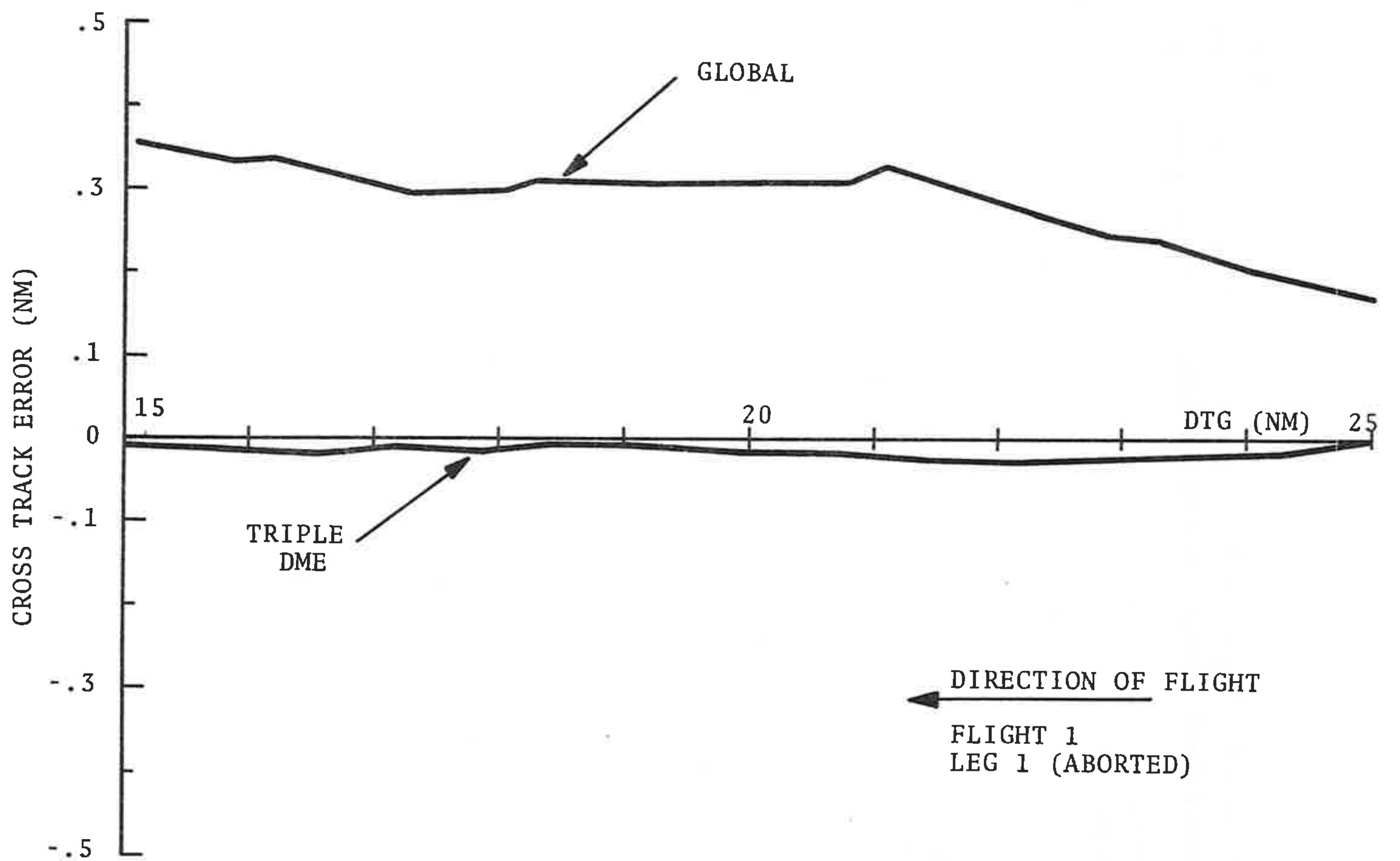

Figure 6-2. Flight 1, Leg 1 (Aborted). Error in Crosstrack Vs. Distance-To-Go to the Waypoint

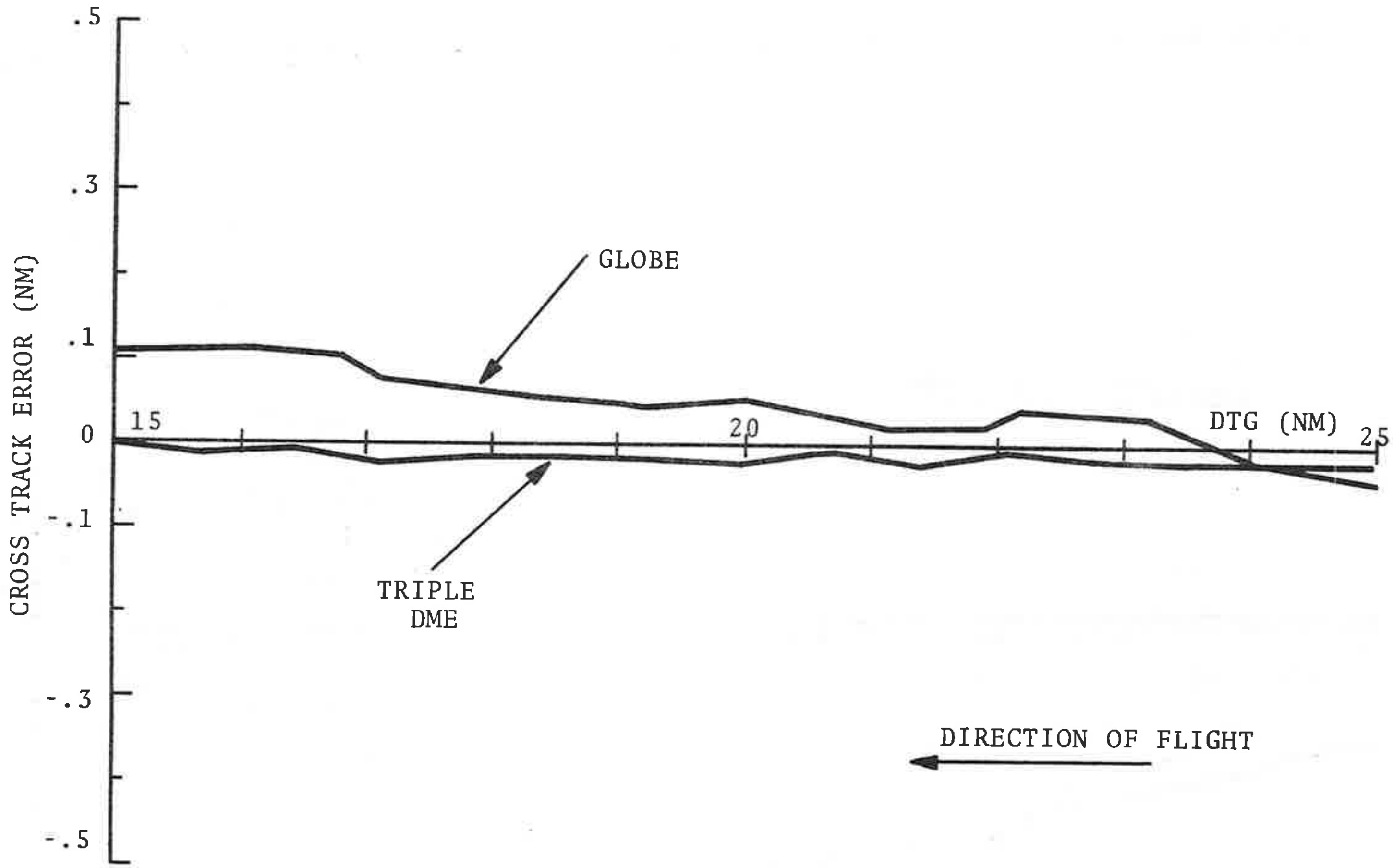

Figure 6-3. Flight 1, Leg 1. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

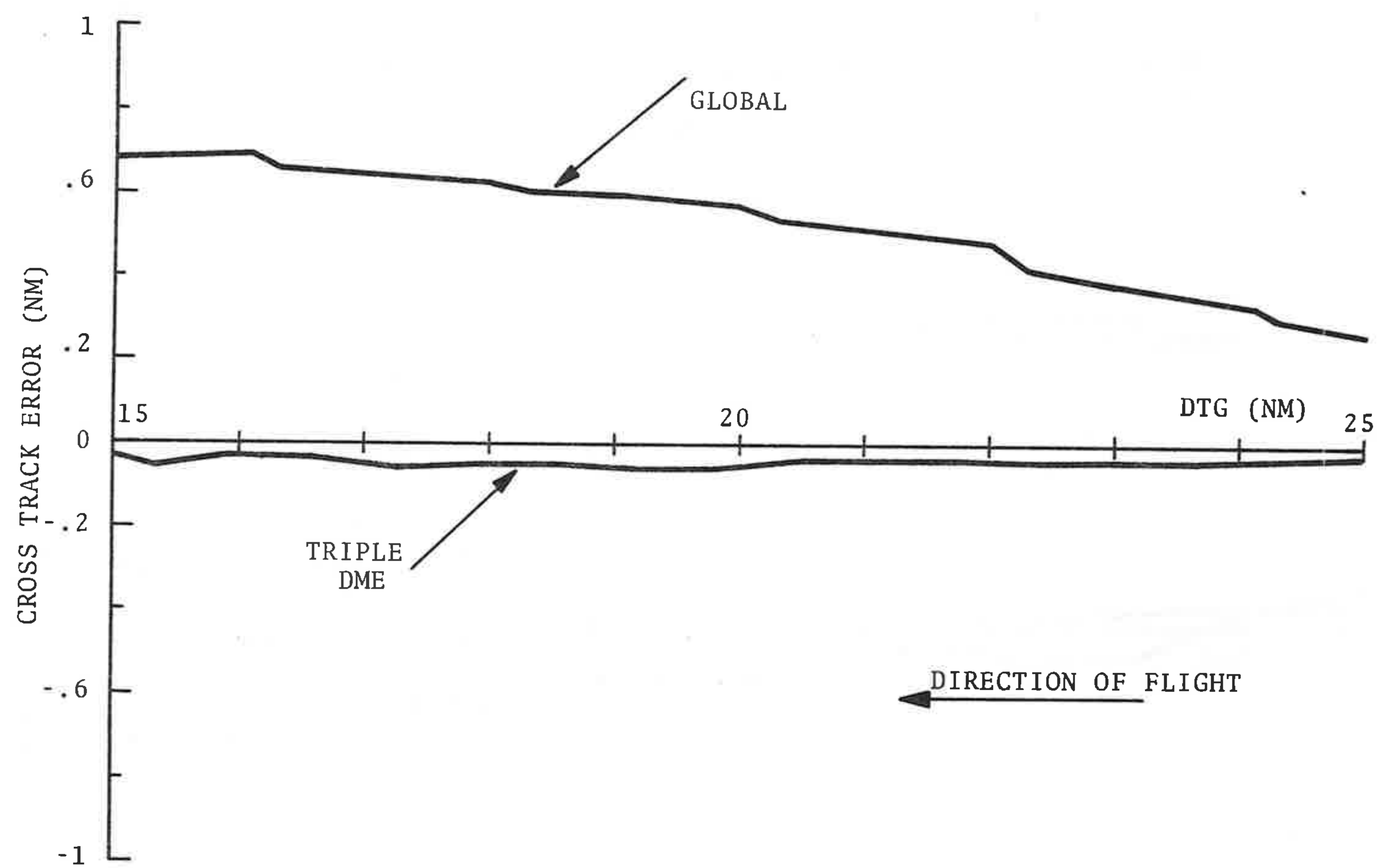

Figure 6-4. Flight 3, Leg 1. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

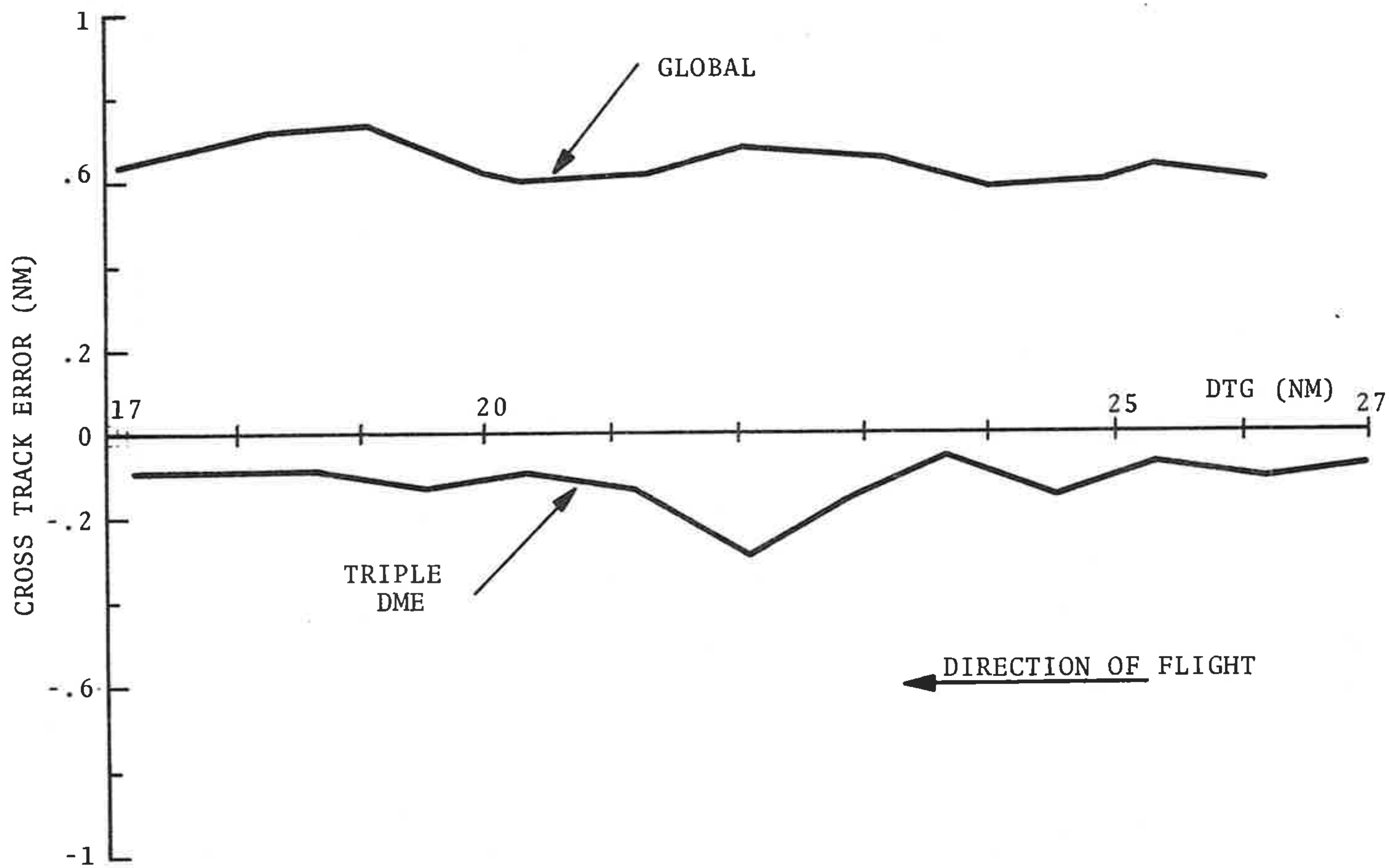

Figure 6-5. Flight 1, Leg 2. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

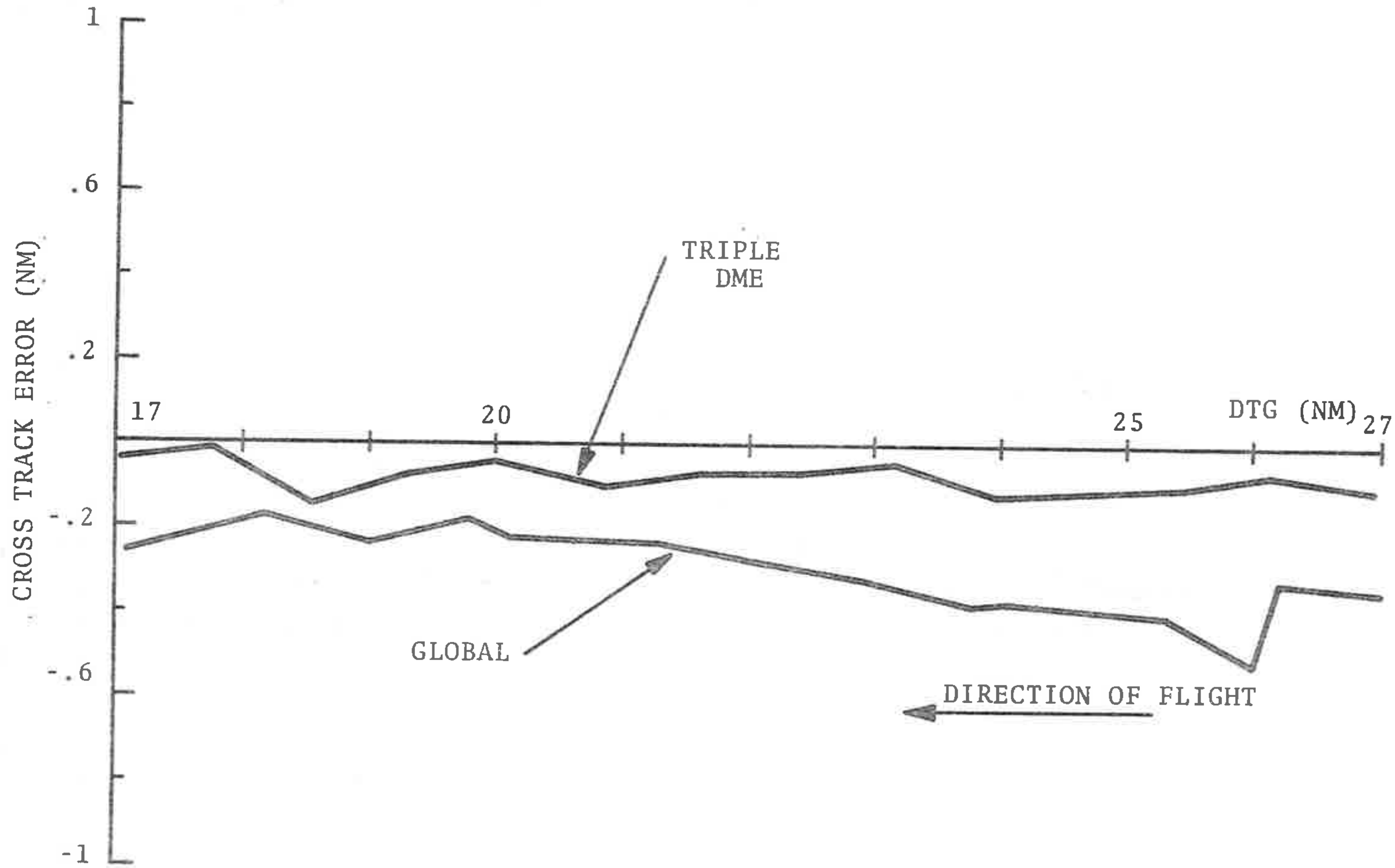

Figure 6-6. Flight 3, Leg 2. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

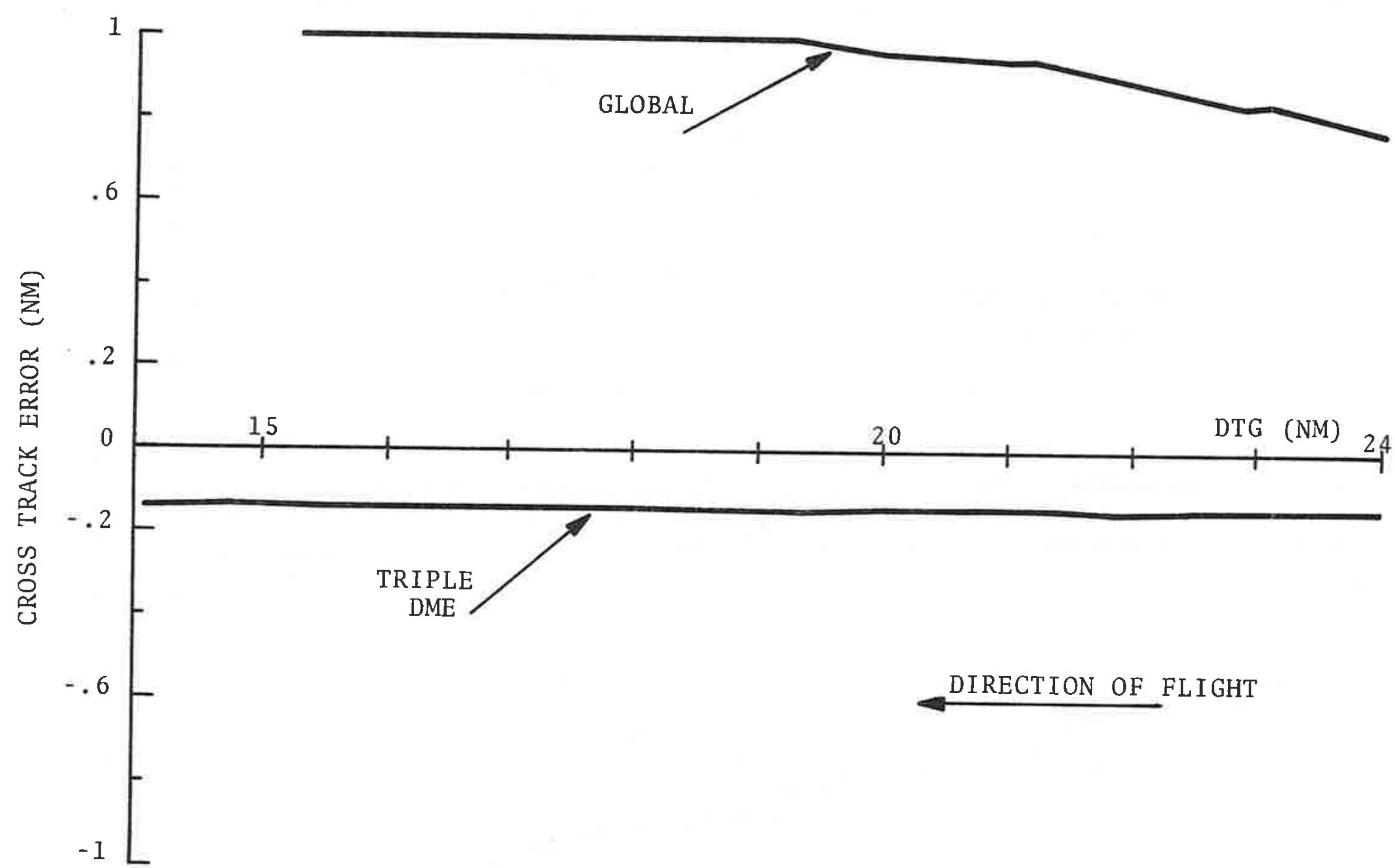

Figure 6-7. Flight 1, Leg 4. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

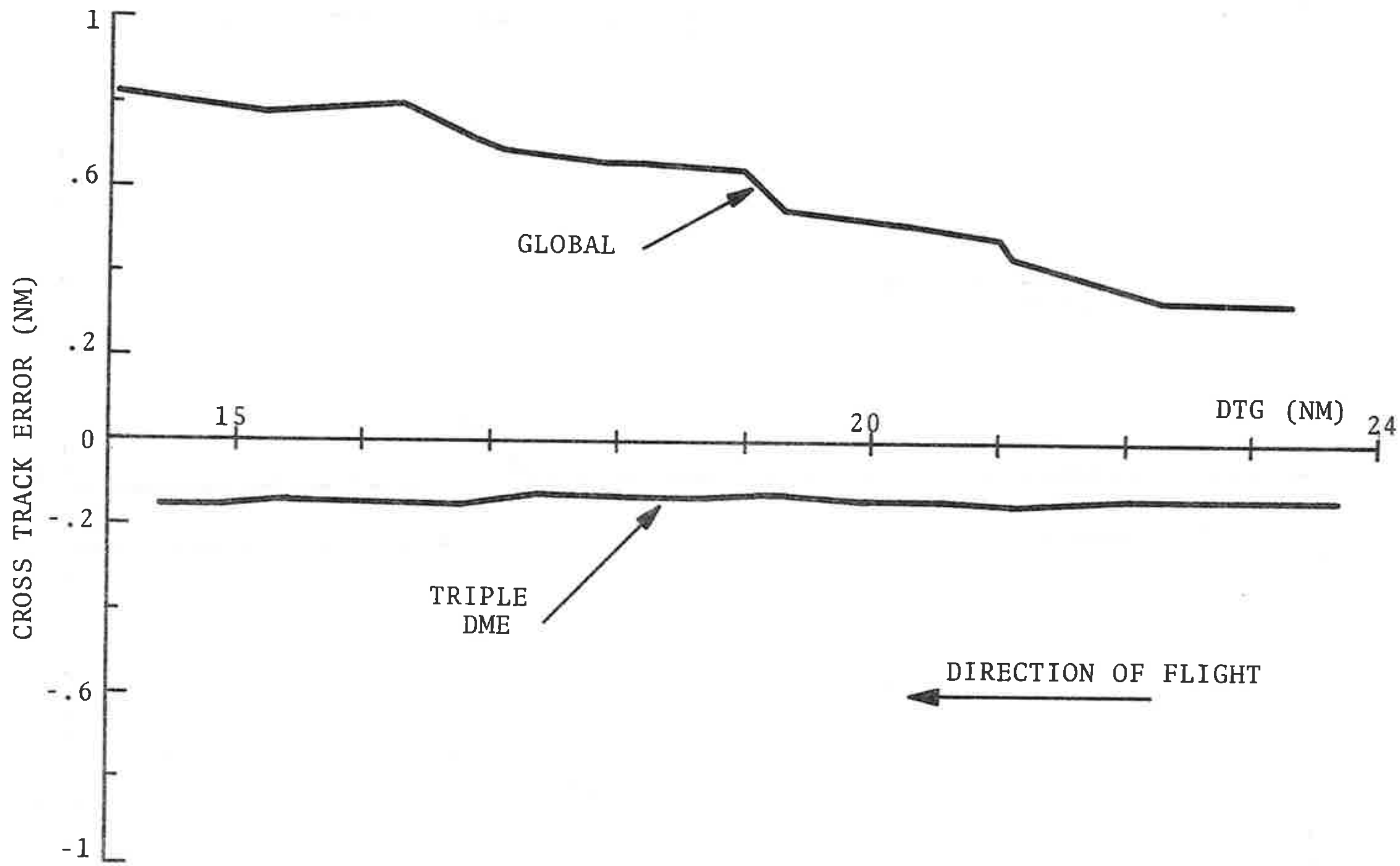

Figure 6-8. Flight 3, Leg 4. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

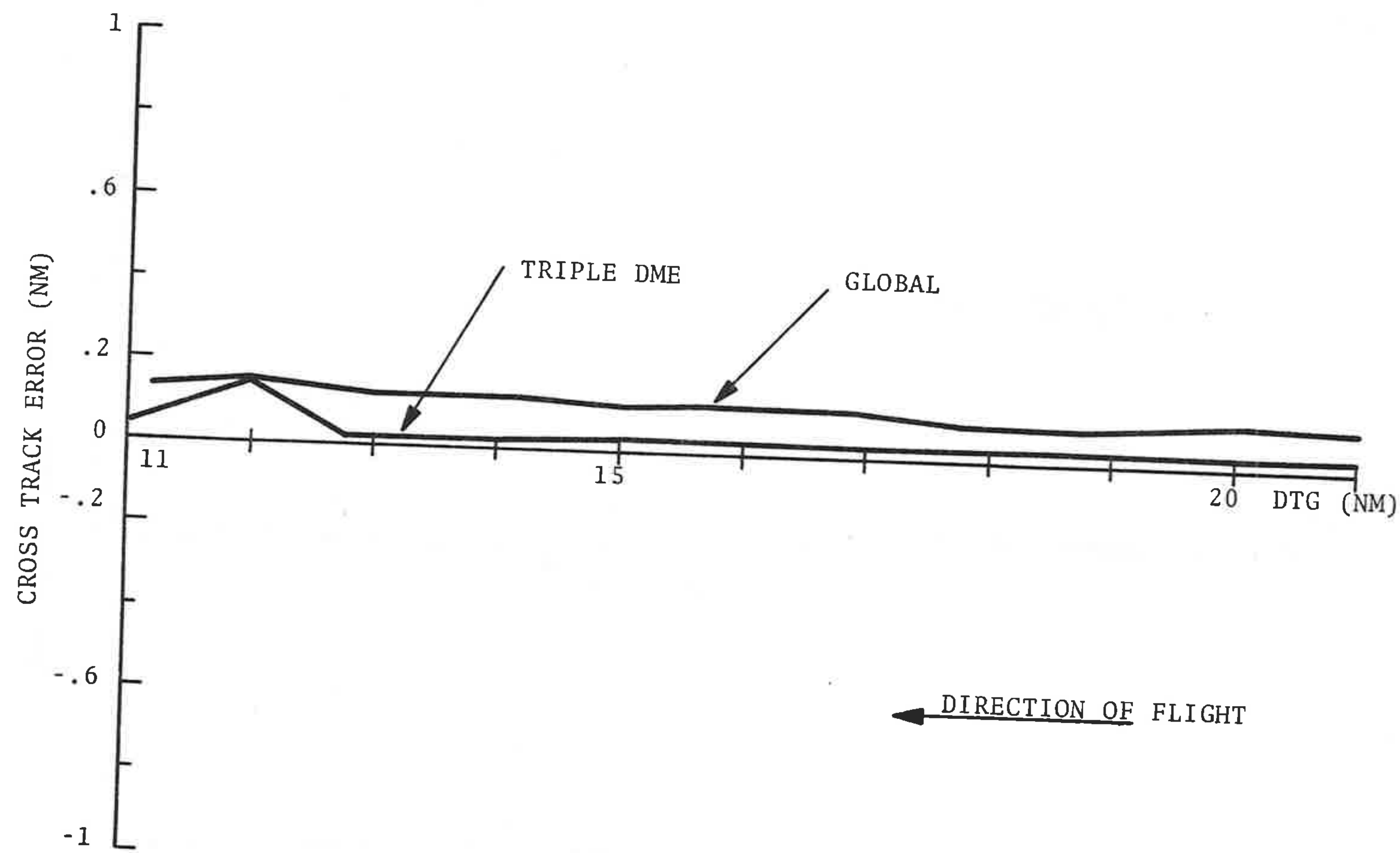

Figure 6-9. Flight 1, Leg 5. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

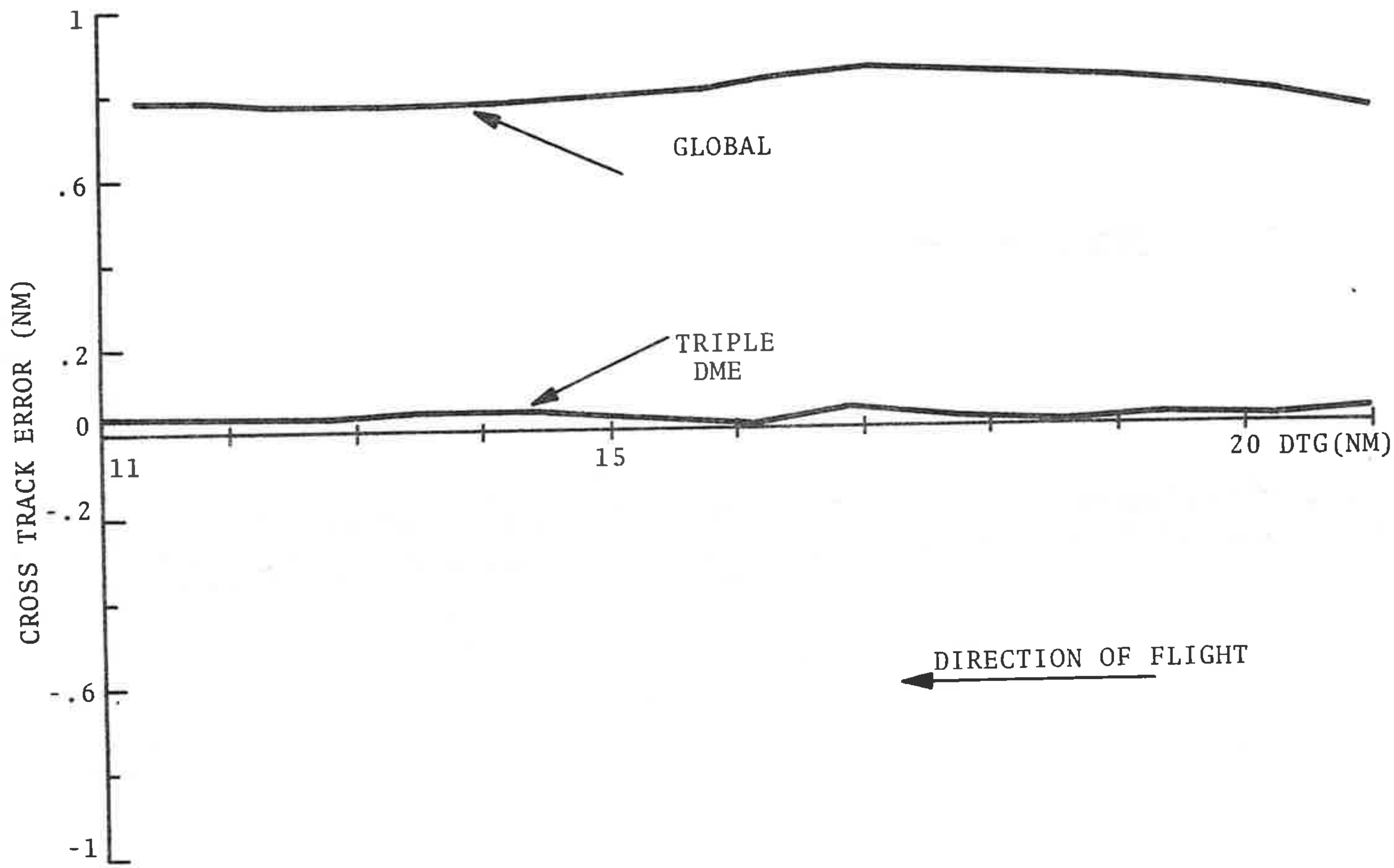

Figure 6-10. Flight 3, Leg 5. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

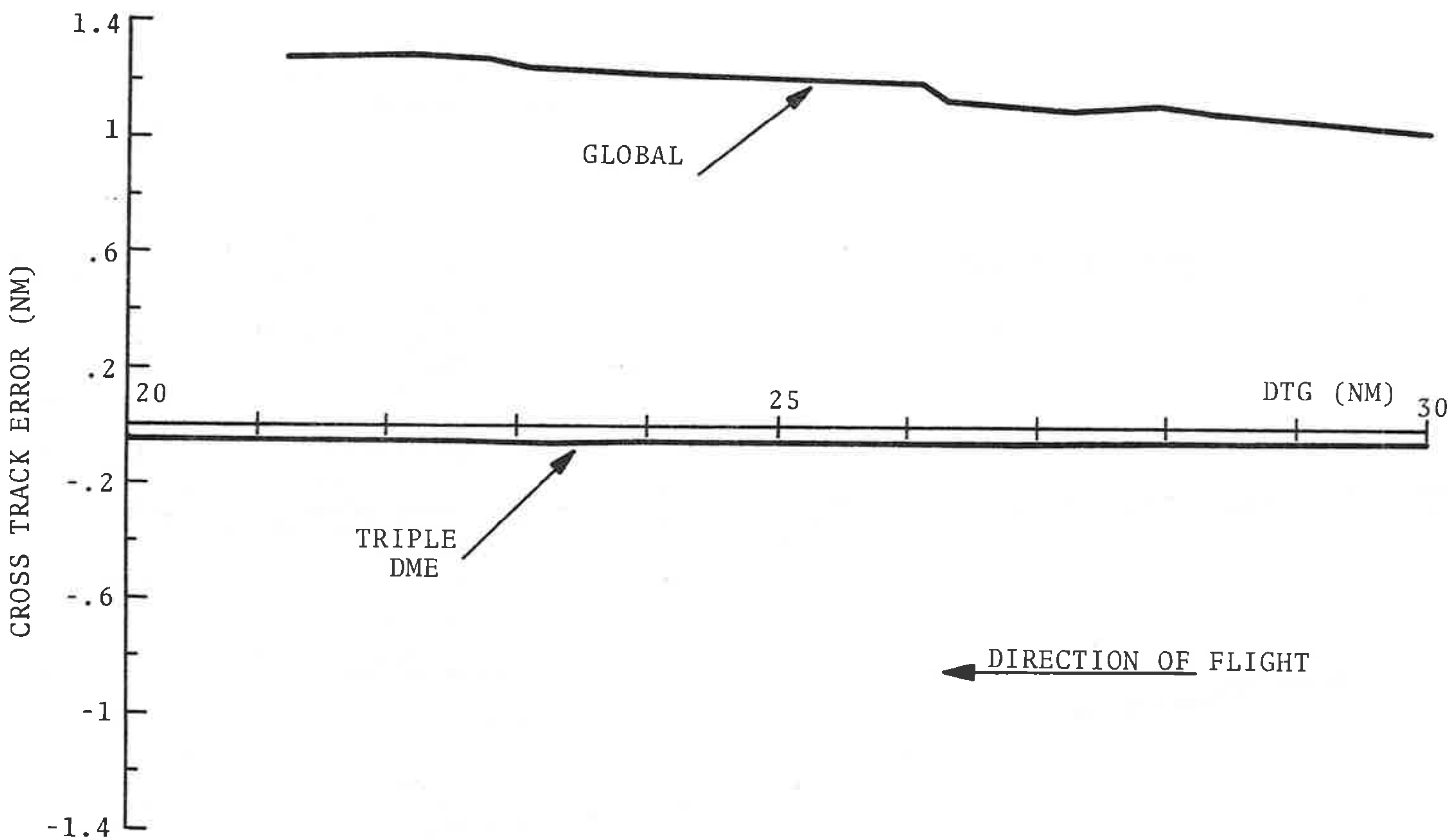

Figure 6-11. Flight 1, Leg 6. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

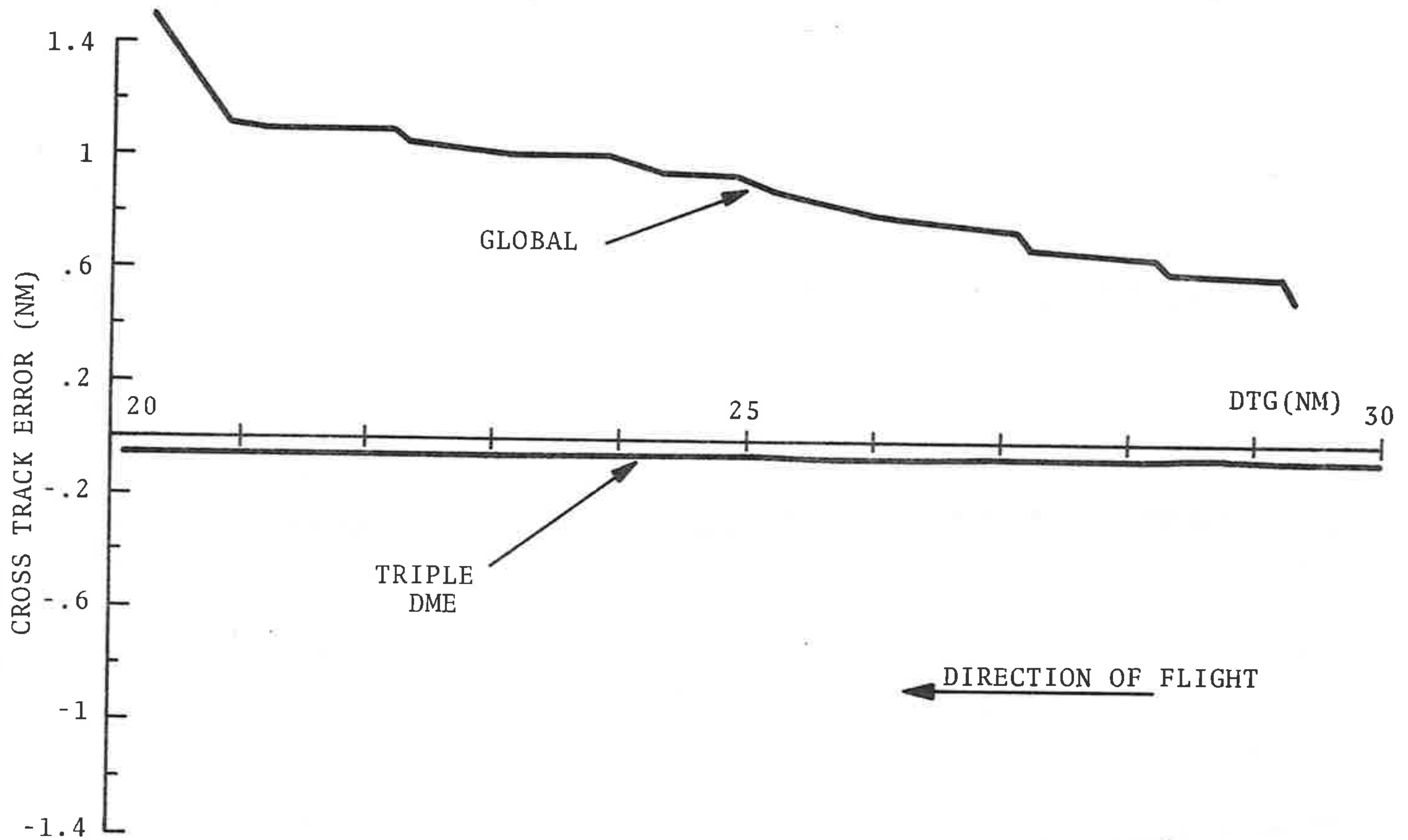

Figure 6-12. Flight 3, Leg 6. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

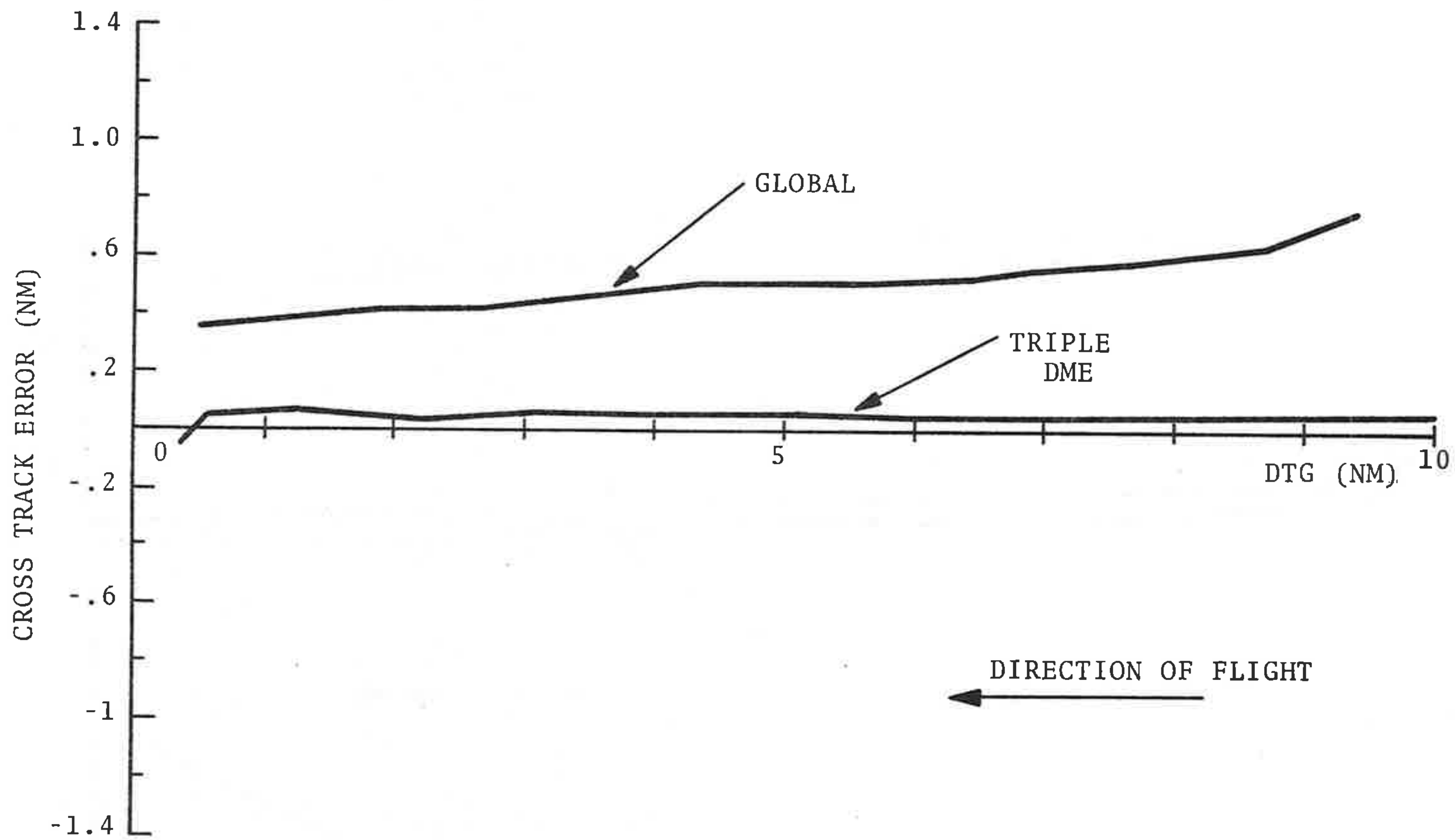

Figure 6-13. Flight 3, Leg 7. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

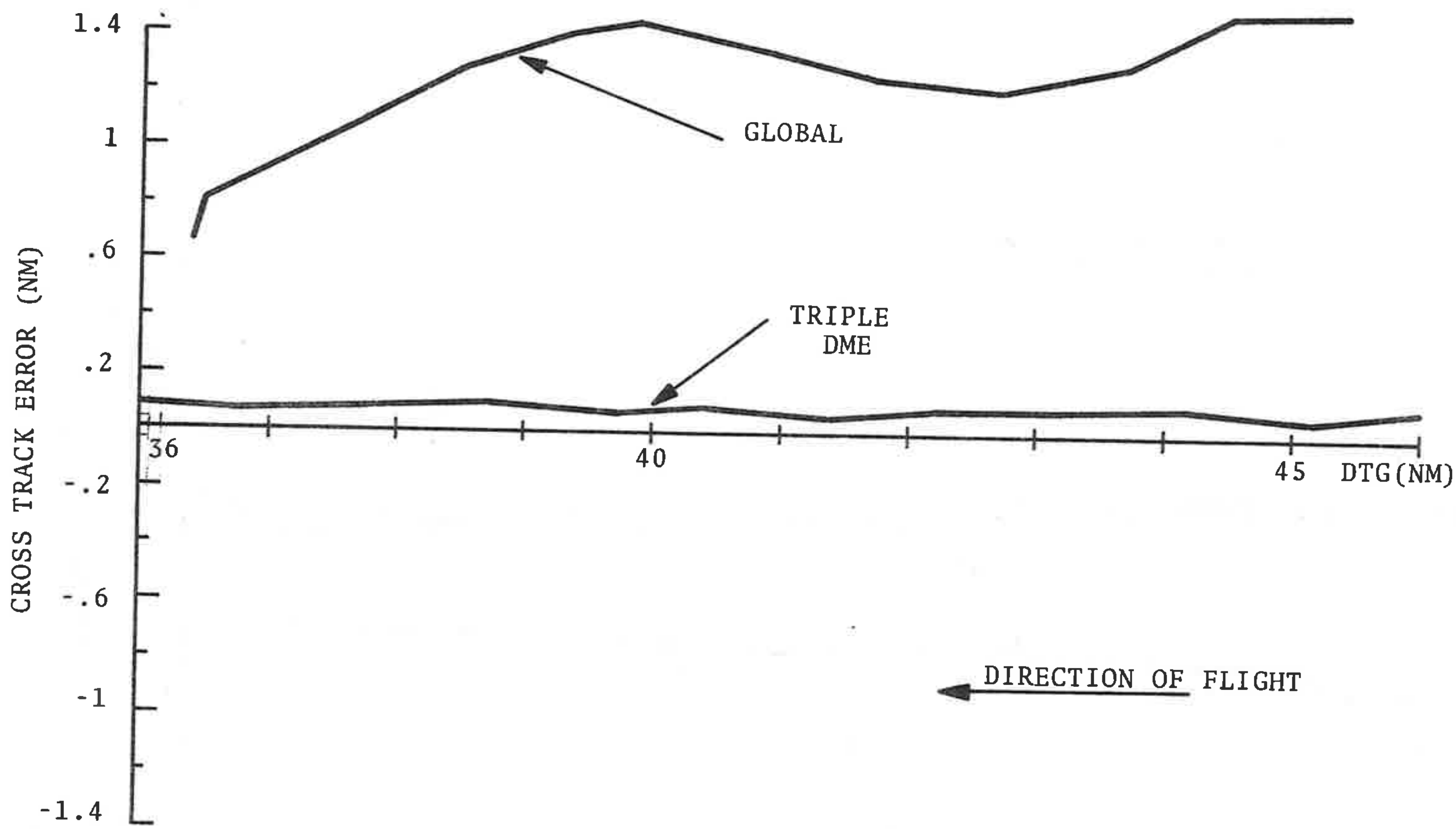

Figure 6-14. Flight 1, Leg 7. Error in Crosstrack Vs. Distance-To-Go to the Waypoint

7. CONCLUSIONS

The major conclusions presented below are drawn from the quantitative and qualitative data discussed in Section 6 and are summarized by category:

System Accuracy: triple DME system is an order of magnitude more accurate than the Global System, exhibiting a mean error of .062 versus .624 nm over seven flights and seven flight path segments.

Repeatability: triple DME system accuracy repeats itself on successive passes over the same point in space, independent of direction of flight, whereas the Global system accuracy varies on successive runs for all conditions.

Smoothness: triple DME system exhibits a smooth processed signal, with small deviations on the order of .02 nm, whereas Global system outputs have more "random noise" and the Distance-To-Go output exhibits quantum "jumps" of .5 nm.

Initial Conditions: triple DME accuracy is consistent from run to run, but Global system accuracy is dependent upon the nulling procedure prior to initiating navigation on any flight path segment.

APPENDIX A
TRIPLE DME ALGORITHM

A geocentric earth model was assumed with geodetic earth corrections. The physical constants were:

equatorial radius	$a = 3443.93$ nm
polar radius	$b = 3432.38$ nm
eccentricity	$e^2 = .006696$

The fixed inputs for each set of 3 DME stations ($i = 1, 2, 3$) are:

ϕ_i = geodetic latitude (rad)

λ_i = longitude (rad)

h_i = altitude above sea level (nm)

from which the following are computed:

$c\phi_i$, $s\phi_i$, $t\phi_i$ are cosine, sine, tangent of ϕ_i

$c\lambda_i$, $s\lambda_i$ are cosine, sine of λ_i

Compute the geocentric latitude of each station:

$$\phi c_i = \tan^{-1} (b^2 \tan \phi_i / a^2)$$

and their trig functions: $C\phi c_i$, $S\phi c_i$ are cosine, sine of ϕc_i

Compute the geocentric earth radii:

$$RE_i = b/\sqrt{1-e^2 \cos^2 (\phi c_i)}$$

Compute the coordiantes of each station in an earth centered rectangular coordinate frame:

$$\overline{X}s_i \begin{Bmatrix} X_s \\ Y_s \\ Z_s \end{Bmatrix}_i = \begin{bmatrix} RE_i \; C\phi c_i + h_i \; c\phi_i \; c\lambda_i \\ -(RE_i \; C\phi c_i + h_i \; c\phi_i \; s\lambda_i) \\ RE_i \; S\phi c_i + h_i \; s\phi_i \end{bmatrix}$$

and $S_i = \sqrt{(Xs_{i+1} - Xs_i)^2 + (Ys_{i+1} - Ys_i)^2 + (Zs_{i+1} - Zs_i)^2}$

Compute normal vector at origin:

$$\overline{V}_i \quad \left\{ \begin{matrix} Xs_2 - Xs_1 \\ Ys_2 - Ys_1 \\ Zs_2 - Zs_1 \end{matrix} \right\} ; \qquad \overline{V}_2 = \left\{ \begin{matrix} Xs_3 - Xs_1 \\ Ys_3 - Ys_1 \\ Zs_3 - Zs_1 \end{matrix} \right\}$$

$$\overline{N} = \overline{V}_1 \times \overline{V}_2 = \left\{ \begin{matrix} V_1Y \cdot V_2Z - V_1Z \cdot V_2Y \\ V_1Z \cdot V_2X - V_1X \cdot V_2Z \\ V_1X \cdot V_2Y - V_1Y \cdot V_2X \end{matrix} \right\}$$

$$N_2 = \sqrt{N_x^2 + N_y^2}$$

$$N_3 = \sqrt{Nx^2 + N_y^2 + N_z^2}$$

$$C\phi_N = N_z/N_3 \qquad S\phi_N = N_2/N_3$$

$$C\lambda_N = N_x/N_2 \qquad S\lambda_N = N_y/N_2$$

Define $\hat{\lambda}$ matrix:

$$\hat{\lambda} = \begin{bmatrix} C\lambda_N & S\lambda_N & 0 \\ -S\lambda_N & C\lambda_N & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Define $\hat{\Phi}$ matrix

$$\hat{\Phi} = \begin{bmatrix} C\Phi_N & 0 & -S\Phi_N \\ 0 & 1 & 0 \\ S\Phi_N & 0 & C\Phi_N \end{bmatrix}$$

Compute vectors $\overline{X}_1$, $\overline{X}_2$:

$$\overline{X}_1 = \{X_{s1}, Y_{s1}, Z_{s1}\}; \; \overline{X}_2 = \{X_{s2}, Y_{s1}, Z_{s2}\}$$

$$\overline{\omega}_1 = \hat{\lambda}\, \overline{X}_1; \qquad \overline{\omega}_2 = \hat{\lambda}\, \overline{X}_2$$

$$\overline{\omega}_3 = \hat{\Phi}\, \overline{\omega}_1; \qquad \overline{\omega}_4 = \hat{\Phi}\, \overline{\omega}_2$$

$$\overline{W} = \overline{\omega}_4 - \overline{\omega}_3 = \hat{\Phi}\, \hat{\lambda}\, \overline{X}_2 - \hat{\Phi}\, \hat{\lambda}\, \overline{X}_1$$

Set $\hat{\psi}$ matrix:

$$SQ = \sqrt{W_1^2 + W_2^2}\; ; \; CS = W_1/SQ; \; SS = W_2/SQ$$

$$\hat{\psi} = \begin{bmatrix} CS & -SS & 0 \\ SS & CS & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Redefine $\hat{\lambda}$, $\hat{\Phi}$ matrices as their transpose:

$$\hat{\lambda} = \hat{\lambda}^T \quad ; \qquad \Phi = \Phi^T$$

The above computations are valid for each set of 3 unchanging DME stations. The following computations yield latitude, longitude of the aircraft as a function of each new measurements: DME ranges R_1, R_2 R_3 and altitude h_o, all in nm.

$$\begin{bmatrix} (S_1^2 + (R_1 + R_2)(R_1 - R_2)/(2S_1) \\ S_3^2\ (S_1 - XR_1) + S_1(R_1 + R_3)(R_1 - R_3) - XR_1(S_1 + S_2)(S_1 - S_2) \\ R_1^2 - XR_1^2 - XR_2^2 \end{bmatrix}$$

where $F = 4\sqrt{s(s-S_1)(s-S_2)(s-S_3)}$

and $s = (S_1 + S_2 + S_3)/2$

(and XR_3 set = 0, if $R_1^2 - XR_1^2 - XR_2^2 < 0$)

compute $\overline{\omega}_1 = \hat{\psi}\ \overline{XR}$, $\overline{\omega}_z = \hat{\Phi}\ \overline{\omega}_1$, $\overline{\omega}_3 = \hat{\lambda}\ \overline{\omega}_2$

i.e., $\overline{\omega}_3 \quad \hat{\lambda}\ \hat{\Phi}\ \hat{\psi}\ \overline{XR}$

and
$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \overline{\omega}_3 + \overline{X}_{s1}$$

Compute

$$Q = \sqrt{X^2 + Y^2} \quad , \quad C = (a + h_o)/(b + h_o)$$

which yield lat = $\tan^{-1}\{C^2 Z/Q\}$
long= $\tan^{-1}\{-Y/X\}$

This algorithm contains no computational anomalies along baselines between stations, and does not diverge on solutions outside the triangle formed by the three stations.

APPENDIX B
PRECISION MEASUREMENT FLIGHT TESTS

FLIGHT NOTES

May 6, 1974
Pilot: Al Bazer
Co-Pilot: John Ryan

Weather information indcated that any altitude above 9,000 feet would allow VFR conditions to prevail. These conditions are necessary in order to fly unimpeded over the Woodstown VORTAC station. Since Woodstown comes under the jurisdiction of the Philadelphic Traffic Control Area, flying conditions other than ideal would, in all probability, force deviations in our intended flight paths as well as altitude changes and holding patterns to be effected. The altitude chosen for the first test circuit was, therefore, 10,500 feet. With approximately 7.5 miles to go to Woodstown on leg #1, we entered heavy cloud cover and were informed by Philadelphia Control that we would not be allowed into the area at that altitude. This caused the first leg of the flight plan to be aborted and a return to Atlantic City to try another, higher, altitude. Twelve thousand and five hundred (15,500) feet was then chosen to be safely above the cloud cover. The flight was completed at this altitude except for legs 6 and 7 which were at 13,500 feet according to plan. Observations indicated that the Global crosstrack indicator would start out centered, but would become progressively more off-center as the terminal stations were approached. After the flight, the pilot related that VOR radials as given in our instructions caused him to miss the VORTAC terminal points by 2 or 3 miles. This is probably what caused the cross-track indicator to become increasingly deviant. Afterward, it was decided to allow the pilot to use whatever method he chose to arrive at the terminal points with greater accuracy.

May 7, 1974
Pilot: Al Bazer
Co-Pilot: Dick Lamprecht

Since the weather was ideal, the pilot opted to fly at our highest altitude reasoning that, generally, it is easier to get in the lower altitude flights when weather conditions are less conducive. Legs #1 through #5 were, therefore, flown at 16,500 ft. while legs 6 and 7 were flown at 17,500 ft. It was observed while taxiing that the time code generator (TCG) had lost synchronism, probably due to a power transient. It was reset by wristwatch which had been previously synchronized with NAFEC range control time. Partway through the first leg, the pilot relayed information that radar tracking had been lost due to an antenna problem. It was decided to continue flying the route with the hope of again reacquiring radar coverage. Near completion of the second leg, the radar station resumed tracking. It was later reported that a malfunctioning relay had caused the ground based antenna problem. The flight was completed with no further major difficulties.

May 8, 1974

Pilot: Dick Lamprecht

Co-Pilot: Jess Terry

Since the weather was again very good, it was decided to fly at out next maximum altitude for reasons previously given. The TCG has been left on internal battery power from time of calibration until well after takeoff (approximately 45 minutes) to avoid any unnecessary power transients. When it was again switched on to A-C power, it read 34:52:08. A time check countdown was obtained from radar control and the TCG was reset to 15:10:00. The tape recorder unit had also gone off as it does in case of momentary power outage. This was restarted using the procedure described in the T.R. manual. Flight was completed at 14,500 feet for legs #1 through #5 and 15,500 feet for legs 6 and 7.

May 9, 1974

Pilot: Bob Grace

Co-Pilot: Jess Terry

Weather conditions were poor with a very low ceiling. Pilot's weather advisories indicated it would be impossible to fly to the

Woodstown VORTAC. It was considered a possibility to complete legs #6 and #7 at our lowest designated altitude (3,500 ft.) and this trip was initiated. Again, the time code generator did not retain synchronization while using the same procedure as in the previous flight. A time countdown was received from EAIR radar and the TCG was reset. At approximately two-thirds of the distance to Kenton (leg #6) heavy overcast and rain was encountered along with reports of thunderstorms and turbulence in the vicinity. The Kenton control area would not allow us in at that altitude. They advised us to climb to 4,000 feet and assume a holding pattern until further notified. At this point in time, the flight was aborted, radar tracking was discontinued and a return to Atlantic City was effected.

June 3, 1974

Captain: Ken Johnson
1st Officer: John Ryan

Arrived at NAFEC at 13:00 hours. Calibrated and installed time code generator and checked all electronic systems. All systems were operational so flight crew prepared for flight. The Captain, Ken Johnson, experienced difficulty in starting the right engine. When finally started, he could not accelerate it to the required 10,000 RPM. Mechanics were called out and diagnosed the problem as a malfunctioning valve in the right engine. At 14:30, flight was cancelled to allow for repairs to be made.

June 4, 1974

Captain: Ken Johnson
1st Officer: Al Bazer

A complete circuit was flown with legs 1 through 5 at 10,500 feet and legs 6 and 7 at 11,500 feet. Throughout the flight, the tape recorder (T.R.) ran intermittantly. The tape advance mechanism would often increment in a very erratic manner. In addition, the recorder would frequently stop advancing entirely, necessitating a manual restart procedure. Because of this problem, it was decided that the flight data acquired would be inadequate and that the entire flight would have to be repeated.

June 5, 1974

Captain: Jess Terry
1st Officer: Ken Johnson

Prior to the flight, the entire buffer-formatter section of the T.R. was replaced with a stand-by unit. This procedure appeared to remedy the problems encountered with the T.R. on the previous day. Legs 1 through 5 were then completed at 8,500 feet. In addition, legs 6 and 7 were flown at 9,500 feet, 7,500 feet and 5,500 feet. All electronic systems appeared to be functioning in a normal manner.

June 6, 1974

Captain: Ken Johnson
1st Officer: Irv Budoff

Legs 1 through 5 were flown at two different altitudes, 6,500 feet and 4,500 feet. Some minor problems were again experienced with the T.R. unit. On the first circuit, the T.R. had to be manually restarted about 4 times. On the second circuit, a passenger, Tom Sheridan, offered to continually monitor the tape recorder. He reported on three (3) occasions, he had to re-initialize the T.R. manually.

June 7, 1974

Captain: Ken Johnson
1st Officer: Al Bazer

This was the first and only day that TSC was scheduled for both morning and afternoon flight times. Before the flight began, all T.R. connectors were taken off and reseated. The morning flight consisted of legs 1 through 5 at 16,500 feet, and two trips from Atlantic City to Kenton, Del. and return (legs 6 and 7), first at 17,500 feet and second, at 11,500 feet. Throughout this flight DME #3 did not operate despite recycling a-c power and reseating all connectors. Because of this failure, it was subsequently decided that this flight would have to be repeated.

Prior to the afternoon flight, a new DME unit was obtained from Matt Naimo and installed in place of the inoperative DME #3.

Legs 1 through 5 were twice completed, first at 10,500 ft. and then at 2,500 feet. Except for the DME failure in the morning flight, all other electronics, including the T.R., functioned without problems throughout both flights.

June 10, 1974

Captain: Al Bazer
1st Officer: Irv Budoff

Today's flight was behind schedule since flight crew claimed they were unaware that TSC would fly today, despite the fact that it was posted on the CAD board. An additional delay was caused when EAIR radar was also unprepared and had to set up their tracking facilities. Takeoff was thus delayed until 13:40 instead of the scheduled time of 12:45. Despite the late starting time, a complete day's flight was obtained. Legs 6 and 7 were flown at 11,500 feet, legs 1 through 5 at 16,500 ft. and finally legs 6 and 7 again at 17,500 feet. No electronic anomalies were observed during this day.

June 11, 1974

Captain: Dick Lamprecht
1st Officer: Jess Terry

The final flight to complete TSC's flight test plan was completed, Atlantic City to Kenton and return (legs 6 and 7) at 3,500 feet. In addition, a low altitude orbit of Atlantic City VORTAC was executed. The radius of the orbit was 23 nautical miles at an altitude of 1,500 feet. As a byproduct of this orbit, additional data was obtained for legs 1 and 5 at 1,500 feet. Again, there were no apparent problems with any of the electronic equipment.