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FLIGHT PATH RECOVERY SYSTEM (FPRS)
DESIGN STUDY

By

SYSTECH INCORPORATED
370 7th AVENUE
NEW YORK, NEW YORK

SEPTEMBER 1978

Work performed under Bendix Field Engineering Corporation
Grand Junction Operations Subcontract No. 76-023-5, Project No.
50-51-5022 and Bendix Contract EY-76-C-13-1664

Prepared for
U.S. Department of Energy
Grand Junction, Colorado 81501

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ABSTRACT

The study contained herein presents a design for a Flight Path Recovery System (FPRS) for use in the NURE Program which will be more accurate than systems presently used, provide position location data in digital form suitable for automatic data processing, and provide for flight path recovery in a more economic and operationally suitable manner. The design is based upon the use of presently available hardware and technology, and presents little, if any, development risk. In addition, a Flight Test Plan designed to test the FPRS design concept is presented.

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ACRONYMS AND ABBREVIATIONS

A/A	Air-to-Air
AC	Aircraft
ACMR	Aircraft Combat Maneuvering Range
ADP	Automatic Data Processing
AHRS	Attitude Heading Reference System
BCD	Binary Coded Decimal
BFEC	Bendix Field Engineering Corporation
BPSK	Bi-Phase Shift Keying
CDEC	U.S.Army Combat Developments Experimental Command
CEP	Circular Error Probable
CFE	Contractor Furnished Equipment
cm	Centimeter
CONUS	CONTinental United States
CW	Continuous Wave
dB	Decibel
dbi	Decibel (referenced to input)
DFCS	Drone Formation Control System
DMA	Direct Memory Access
DME	Distance Measuring Equipment
DoE	Department of Energy
DR	Dead Reckoner
EF	Error Factor
ESG	Electrostatically Supported Gyroscope
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FPRS	Flight Path Recovery System
Ft, ft	Feet

ACRONYMS AND ABBREVIATIONS (CONT.)

GD	General Dynamics Corporation
GDOP	Geometrical Dilution of Precision
GFE	Government Furnished Equipment
GHz	GigaHertz (10^9 cycles/sec)
GPS	Global Positioning System
GS	Ground Station
HR, hr	Hour
Hz	Hertz (cycles/second)
IBM	International Business Machines Corporation
INS	Inertial Navigation System
I/O	Input/Output
IU	Interface Unit
K	1000
KB	Kilobits
KBPS	Kilobits Per Second (1000 bits/second)
kg	Kilogram
KHz	KiloHertz (10^3 Hertz)
Km	Kilometer
lbs	Pounds
LINS	Laser Inertial Navigation System
LORAN	Long Range Navigation
LOS	Line-Of-Sight
m	Meter
M	1,000,000
mb	Millibar
MeV	Million electron Volts

ACRONYMS AND ABBREVIATIONS (CONT.)

MHz	MegaHertz (10^6 Hertz)
mm	Millimeter
MSL	Mean Sea Level
MTBF	Mean Time Between Failures
MT/R	Master Transmitter/Receiver
MTTR	Mean Time To Repair
MU	Master Unit
μ sec	Microsecond (10^{-6} seconds)
NBS	National Bureau of Standards
NM	Nautical Mile
NNSS	Navy Navigation Satellite System
ns	Nanosecond (10^{-9} seconds)
NURE	National Uranium Resource Evaluation (Program)
PLRS	Position Location and Reporting System
PN	Pseudo-Noise
PPM	Pulse Position Modulation
PRI	Pulse Repetition Interval
RF	Radio Frequency
RLG	Ring Laser Gyro
RMS	Range Measurement System
RPM	Revolutions Per Minute
RSS	Root Sum Squared
RT/R	Remote Transmitter/Receiver
SCORE	Simulated Combat Operation Range Equipment
sec	Second
sync	Synchronization

ACRONYMS AND ABBREVIATIONS (CONT.)

TACAN	Tactical Air Navigation
T/R	Transmit/Receive (also Transmitter/Receiver)
TTL	Transistor-Transistor-Logic
UHF	Ultra High Frequency
UT1	Universal Time (1)
UTC	Universal Time, Coordinated
UU	User Unit
VAC	Volts Alternating Current
VDC	Volts Direct Current
VHF	Very High Frequency
VOR	VHF OmniRange
W	Watts
WGS	World Geodetic System
Xmt	Transmitter (also Transmits)
(XYZ)	Position Coordinates

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1.0 INTRODUCTION

1.1 Background

The National Uranium Resource Evaluation (NURE) Program has as its major objectives "a comprehensive assessment of the total uranium resources of the United States as rapidly as possible, the identification of areas favorable for uranium resources, and the development of new and improved geophysical and other technology". (1)

One of the major elements of the NURE Program is the Aerial Radiometric Reconnaissance Survey of the conterminous United States and Alaska. The objectives of this survey, which entails the flying of approximately one million line miles by 1981 are: (2)

- (a) To provide data on which to base resource assessment of uranium reserves, and
- (b) To focus industry exploration efforts on broad source * regions of highest uranium favorability.

Flight path recovery is an essential part of the NURE aerial survey. The ground track along which the instrumentation was flown and where on this track specific data were measured must be known. The radiometric and magnetic data corresponding to segments of the ground track must then be correlated with geological

(1) References are listed at the end of this report

* Broad source is defined by specification PMD 1200-A (3) "as having a minimum dimension of 1200 feet".

and other data to make a realistic assessment of uranium resources.

If the radiometric data for some given segment reveals an anomaly which warrants further investigation, it is desirable to return to the midpoint of the anomalous segment as accurately as possible for ground sampling. Accurate flight path recovery is particularly desirable when the ground track segment is located in forested, mountainous, or swampy terrain where ease of movement is restricted. With present flight path recovery practices, position errors ranging from 1/4 to 1/2 mile can occur. Such large errors seriously compromise locating an anomaly within a given search time, and in a safe and cost efficient manner.

Presently, most aerial survey companies use a tracking camera or video tape recorder and an inertial or doppler navigation system. Accuracy claims for this type of system are 500 feet (CEP*) or better. Position errors for both doppler and inertial navigations systems increase with flight time. One measure of performance for these systems is the increase of CEP with respect to time. Typical position error performance for an inertial system is 5 feet or more per second of flight, while that of the best inertial device available today is 1 to 2 feet/ second of flight. Typical position error performance for doppler navigation systems is 5 to 7 feet/second and can be as great as 10 feet/second. The aircraft positional uncertainty would increase 500 feet in 100 seconds

* CEP (circular error probable): Radius of a circle within which the probability of a point being located is 50%.

of flight if we use 5 feet/second as the average performance of these navigation systems. An aircraft flying at 120 knots (200 feet/sec.) would travel 3.3 nautical miles in 100 seconds.

The survey aircraft must obtain a periodic position reference or update due to this increase in positional uncertainty with time. For example, if the error is to be limited to 500 feet, a photograph must be taken at least every 100 seconds. Through the use of an identifiable landmark available in each photograph, the aircraft can fly from landmark to landmark keeping the relative positional errors between landmarks within 500 feet.

The magnitude of the flight path recovery task using this photographic method can be appreciated by considering the following example. The NURE survey requires flying approximately one million line miles. To obtain 500 feet positional uncertainty, a minimum of 303,000 photographs must be taken. The topography and features of the survey area must be such that 303,000 landmarks appear at the appropriate 3.3 NM intervals. Also, it is necessary to note for each photograph an appropriate description of the reference landmark (road crossing, lone tree, etc.) An aircraft whose average velocity is 120 knots requires 8333 hours of flight time to complete one million line miles. This results in taking 36 photos/hour or 288 photos per 8 hour flying day. Thus, each 8 hours of flight requires the recording of 288 landmarks, one for each 100 seconds of flight. And all this is necessary to achieve only 500 foot accuracy during one day of flight using an average inertial system or attitude heading reference/ doppler radar system and photography.

Flight path recovery using photography requires good quality large area aerial photographs. In addition, for ease of identification, there should be no changes in surface features due to fires, logging operations, flooding, etc. between the time these photographs are taken and the radiometric survey flown.

Track recovery, as presently performed using photography, is the most expensive part of data processing - accounting for about one quarter of the total survey cost.⁽⁴⁾ The film must be processed, photos laid down and compared with existing aerial mosaics, and preliminary flight lines plotted to check that they are close enough to the specified lines. More careful analysis is done subsequent to the completion of the field operation.

1.2 Purpose of Study

The purpose of this study is to provide a design for a Flight Path Recovery System (FPRS) which will be more accurate than systems presently used, provide position location data in digital form suitable for automatic data processing, and provide for flight path recovery in a more economic and operationally suitable manner. The technology necessary to achieve such a system presently exists and presents little, if any, development risk.

In addition, a system providing accurate digital navigation and position location data may be used to benefit all types of mineral exploration which involve aerial surveying. For example, the usefulness of high resolution magnetometer measurements is limited by the position accuracy of presently used navigation systems.

1.3 Objective of Study

The objective of this study is to design a system capable of

the following:

- (a) Position location and guidance of a survey aircraft within a survey grid of 100 x 100 nautical miles (NM).
- (b) Recoverable position location accuracy within the survey grid of 100 feet CEP, or less, under conditions of continuous flight operation.
- (c) System operation at low survey aircraft altitudes (nominal terrain clearance is 400 feet).
- (d) System operation in all types of terrain topography (featureless, mountainous, etc.).
- (e) System output suitable for automatic data processing.
- (f) Backup flight path recovery to within 1000 feet CEP.

1.4 Recommended Approach

At the present time, the only position location technique which can meet the above listed goals is multilateration or trilateration whereby the survey aircraft makes radio ranging measurements at line-of-sight (LOS) frequencies (≥ 30 MHz) to ground beacons of known position.

Due to the low altitude of the survey aircraft, there will be some regions where terrain features restrict LOS (e.g., mountains, flat horizon limited terrain). For these situations we recommend the use of a high flying aircraft. The survey aircraft uses the "high flyer" like a ground beacon. At the time of range measurement, the high flyer reports over a digital data link his position to the survey aircraft. The high flyer is at an altitude such that LOS is obtained with enough ground beacons to accurately determine position. The possibility also exists for the high flyer to service more than one survey aircraft. The survey aircraft's position location and dead reckoner data are combined in an on-board computer

for the purpose of providing survey aircraft flight guidance along the pre-planned flight lines.

2.0 FLIGHT PATH RECOVERY SYSTEM (FPRS) DESIGN DESCRIPTION

Sections 2.1 through 2.3 describe and discuss the components of the FPRS subsystems. Section 2.4 discusses the interaction and operation of FPRS subsystems, and provides a description of the basic operation of the FPRS. Section 2.5 describes and discusses the operating modes and FPRS characteristics applicable to survey operations.

For clarity, the FPRS description is presented in four parts:

1. Airborne Subsystem (Survey Aircraft)
2. Airborne Subsystem (High Flyer)
3. Ground subsystem
4. TRANSIT System

2.1 Airborne Subsystem: Survey Aircraft (Rotary Wing)

Figure 2-1 is a block diagram of the FPRS survey aircraft airborne subsystem.

2.1.1 Dead Reckoner (DR)

There are two types of primary DR's commonly found aboard survey aircraft:

- a) Attitude Heading Referencing System (AHRS) and Doppler Radar
- b) Inertial Navigation System (INS)

As a minimum, the FPRS requires that the survey aircraft (rotary or fixed wing) be equipped with an AHRS/Doppler DR.

The following DR descriptions are based upon the use of an AHRS/Doppler.

2.1.1.1 AHRS/Doppler DR Functions

The primary function of the DR in the FPRS is to provide navigation data (latitude, longitude, heading, etc.) allowing the pilot to fly the planned survey flight lines. To accomplish this,

FIGURE 2-1. FPRS AIRBORNE SUBSYSTEM

the AHRS/Doppler provides heading/bearing and true ground velocity data. It also provides these additional functions:

- * It provides "memory" or track of past positions in both the survey grid and the georeferenced grid. The purpose of this function is to allow for post-flight data correction in the event that ground stations have not been surveyed prior to survey flight and also to apply post-flight corrections in certain degraded modes.
- * It provides short term relative position location data. The purpose of this function is to make use of DR position data when there is intermittent line-of-sight (LOS) obstructions or intermittent loss of signal.
- * It provides a source of redundant position location data when ground installations have been accurately surveyed.

2.1.1.2 DR Performance Characteristics

The performance requirements of the DR are dictated by the accuracy with which the aircraft must fly the planned flight lines. Section 5.5 (Flight Line Tracks) of BFEC/GJO Specification No. PMD-1200-A entitled "General Specification for Airborne Geophysical Surveys" dated 8/2/76 dictates that the cross-track error over a flight line segment 4 NM or greater should not exceed 25% of flight line spacing with specified exceptions. Given a flight line of 100 NM in length and spacings of from 2 to 12 NM, the DR cross-track errors are not to exceed 0.5 NM over any segment of flight line greater than 4 NM. For survey aircraft velocities of about 100 knots, this would require a DR whose error growth is approximately 0.5 NM hr. This exceeds the performance capabilities of all commercial or military DR's presently available, making some form of updating necessary.

The requirement for DR updating relaxes the performance requirements on the AHRS/Doppler. A typical AHRS/Doppler may have

a CEP error rate in excess of 2 NM/hr. Thus updating the DR at intervals shorter than once every 15 minutes (for aircraft velocities around 100 knots) would provide the necessary "damping" of the flight line guidance errors. To allow for variations in vendor equipment and calibration errors, we assume an AHRS/Doppler performance of 5 NM/hr. which would require updating every six minutes. See Section 2.4.1 for a discussion of DR updating.

2.1.1.3 DR Interface Requirements

It is assumed that at present the DR output of latitude, longitude, and perhaps velocity and bearing are being recorded by all survey aircraft. In addition to presently recorded data, the FPRS requires that the DR provide output to, and receive position updates from, the FPRS computer.

2.1.1.4 DR Special Requirements

Position updating of the DR is required at least once every six minutes. Maximum error of position update will be equal to the DME trilateration positioning errors.

2.1.1.5 DR Data Output

The data output of the DR to the FPRS computer are:

- a) latitude
- b) longitude
- c) velocity East
- d) velocity North

2.1.2 Distance Measuring Equipment (DME)

The DME discussed in this section is the General Dynamics' (GD) Position Location Reporting System (PLRS) equipment. While other DME's would work just as well, the PLRS is functionally typical of a class of DME suitable for FPRS. It was selected primarily

because of its potential availability as GFE and the cost saving thus realized. For a discussion of DME evaluation and selection see Section 5.2.

2.1.2.1 Position Location and Reporting System (PLRS) Description/Functions

The PLRS equipment was originally designed to meet the requirements of a Marine/Army battlefield Command and Control System. Figure 2-2 is a photograph of a PLRS manpack unit and Figure 2-3 shows a PLRS helicopter installation. The original 17 prototype transceivers manufactured by GD and tested by the DoD are presently stored at Camp Pendleton. These units were extensively tested and are said to have performed satisfactorily with regards to parameters of interest to FPRS * (e.g., ranging accuracy, reliability, data link, operation and airborne operation).

PLRS is a non-synchronous interrogate-respond system which provides both a distance measuring function (ranging) and a secure digital data link.

The ranging accuracy of the DME is the parameter which determines the ultimate flight path recovery accuracy. The PLRS is a pulse interrogate-respond, discrete address system whereby an interrogator unit in the aircraft transmits a coded signal and simultaneously starts a clock. The responder beacon (ground installation) with the appropriate code address transmits a return signal on receipt of this coded signal. This response signal is received by the airborne interrogator unit which then stops the clock. Based on the round trip transit time of the signal, the distance between interrogator antenna and responder antenna is determined. Measurements to three non-colinear responder beacons locate the interrogator

* Private Communications: Army PLRS Project Office.

PLRS R³ UNIT W/USER READOUT

FIGURE 2-2

PLRS MANPACK UNIT

FIGURE 2-3. PLRS HELICOPTER INSTALLATION

in three dimensions. The ranging accuracy of the PLRS is 3 meters (10') over a range of 100 NM. Table 2-1 lists the characteristics (see also Section 5.2.2.1). The primary PLRS DME function is to provide accurate range from the survey aircraft to a ground-based PLRS transceiver or to another airborne transceiver.

2.1.2.2 PLRS Performance Characteristics (Ranging)

The PLRS measures the range between the survey aircraft and a ground installation or airborne responder. A discussion of ranging accuracy and its impact on position location accuracy is given in Section 3.4, "System Performance Analyses".

2.1.2.3 PLRS Interface Requirements

The PLRS DME is required to output range data to the FPRS computer.

2.1.2.4 PLRS Special Requirements

The PLRS equipment as presently manufactured by GD is specified for operation at temperatures above 0° C. For use in the FPRS, the PLRS transceiver will be wrapped in a heater blanket to maintain transceiver temperature above 0° C.

2.1.2.5 PLRS Data Output (DME)

The output of the airborne PLRS transceiver will be range information: i.e., the distance between the airborne transceiver antenna and the discretely addressed ground or high flyer transceiver antenna.

TABLE 2-1PLRS CHARACTERISTICS

RANGE:	100 NM
RANGING ACCURACY:	3 M (10)
FREQUENCY:	435 MHz
BANDWIDTH:	8 MHz
DATA TRANSMISSION:	TWO WAY DISCRETE ADDRESS
TRANSMISSION RATE (BURST):	150 KBPS
WEIGHT:	16 KG
SIZE:	31 x 10.2 x 19.9 CM ³

2.1.3 PLRS Data Link

The following discussion of the data link component identifies the General Dynamics' Position Location Reporting System (PLRS) which performs both ranging and digital communication functions.

2.1.3.1 PLRS Data Link Description/Functions

PLRS was designed for a network of 370 User Units (UU) with a Master Unit (MU) controlling the network. Depending on the given message received by the UU, it can perform a number of operations such as:

- * Make range measurements to as many as four UU's and report these range measurements back to the MU;
- * Relay a message to some other UU. In the communications mode a message may be relayed through as many as three relays (also referred to as 3 levels of relays) to reach its destination;
- * In the special data mode, send back data (e.g., dead reckoner outputs) to the MU;
- * Respond to an interrogating range pulse with its return range pulse.

With reference to FPRS, the network would consist of a number of ground installed UU's, an airborne UU on the high flyer, and a MU on the survey aircraft.

The data link provides two way discrete address digital communi-

cations with the following being a typical sequence for three ground stations (UU_1 , UU_2 , and UU_3), a high flyer (UU_4), and a MU aboard the survey aircraft:

- (a) MU sends message to UU_4 (high flier) which instructs UU_4 to range to UU_1 , UU_2 and UU_3 and report these ranges to MU;
- (b) UU_4 sends message (which includes a range pulse) to UU_1 , telling UU_1 to respond with a range pulse;
- (c) UU_4 stores the round trip time;
- (d) UU_4 repeats steps (b) and (c) for UU_2 and UU_3 ;
- (e) UU_4 sends all this range data plus his altitude to MU;
- (f) MU sends message to UU_4 requesting other data (e.g., dead reckoner data);
- (g) UU_4 sends requested data;
- (h) MU then ranges (similar to b and c above) on UU_4 and any ground stations in line-of-sight.

2.1.3.2 PLRS Data Link Performance Characteristics

The following summarizes the leading PLRS data link performance characteristics. Further details are given in Sections 3.3.3 and 5.5.

- * Two way discrete address communications with all network control under the direction of a master station.
- * Burst transmission rate-150 kilobits/sec.
- * Pulse position modulation (2 bits/pulse pair)
- * Parity checking at destination; retransmission upon error.
- * Spread spectrum type waveform using surface acoustic wave device.

2.1.3.3 PLRS Data Link Interface Requirements

PLRS is required to interface with the FPRS interface unit (IU). The PLRS master unit receives serially transmitted data from some other UU. This data will be buffered in the IU and then transferred to the computer memory via the computer's I/O bus. In the high flyer, an interface unit will be required to bring data (other than altitude) to the UU when it is operating in the special data mode (see Section 2.1.3.5).

2.1.3.4 PLRS Data Link Special Requirements

See Section 2.1.2.4

2.1.3.5 PLRS Data Link Output

Pulse position modulation is used for coding data bits - the time increment (either 10, 11, 12 or 13 μ sec) between a pulse and the preceding pulse represents 2 bits. The message contains a three pulse preamble. The first pulse is used to set the automatic gain control. The second pulse is 10 μ sec later and the third is 13 μ sec from the second. The preamble is followed by a 12 bit address, then a 12 bit "function and mode word". Two bits of this 12 bit function and mode word specifies the function as: The UU is either a responder, reporter (makes range measurements and reports them back), a first level relay, or a second level relay. Another three bits of the function and mode word specifies the modes as: the modes "ranging", "send data to", "send data from" and "special data mode" (other available modes are not pertinent to FPRS). The function and mode word is then followed by additional addresses and (in the communications mode) the data and parity bits. Parity is checked at the destination unit.

2.1.4 Computer

Selection considerations for an FPRS computer, along with the characteristics of some computers considered, are discussed in Section 5.4.

One of the important considerations is that the computer operate reliably onboard either a fixed wing or rotary aircraft. For this reason we recommend that the computer meet military specifications. Of the whole spectrum of such computers, we recommend the subset containing a commercial version to insure continued vendor support (hardware and software) and lower cost.

Therefore, we recommend either ROLM or NORDEN who make militarized versions of the Data General and DEC (Digital Equipment Corp.) computers respectively. At this time (early 1977) of this study, NORDEN has not yet delivered any systems. Hughes has also undertaken to build a militarized version of the Interdata computer.

Before any buy decision, the status of this Hughes' program, as well as the availability of any militarized airborne GFE computers, should be checked.

2.1.4.1 Computer Functions

The FPRS computer must perform the tasks listed below. We assume that the aircraft has some type of navigation computer coupled to the dead reckoner (AHRS/Doppler or INS). The design goal, regarding computer determination of the flight path in real time, is that maximum use be made of all available sensor data (e.g., ranges, altitude, DR).

The FPRS computer must:

- * Control the system during all modes of operation
- * Perform system and self tests
- * Process all sensor data
- * Solve the navigation equations for the primary position location mode and any submodes
- * Perform data smoothing and filtering of redundant navigation data and estimate system errors
- * Perform data formatting for output and/or display.

Table 2-2 gives estimates of memory storage for the various software tasks.

2.1.4.2 Computer Performance Characteristics

Table 2-3 lists the characteristics of one of the recommended computers (ROLM 1602). The characteristics of the other recommended computer (NORDEN PDP 11/34 M) are given in Section 5.4.

TABLE 2-2

COMPUTER MEMORY SIZING ESTIMATES

<u>TASK</u>	<u>WORDS (16 BIT)</u>
MONITOR/ CONTROL	3000
INITIALIZATION	500
FILTERING/ ESTIMATION	3000
DATA CORRECTION (REFRACTION,...)	800
SELF-TEST	500
SYSTEM-TEST	1500
INPUT	500
DATA LINK (FORMATTING, ERROR CORR.)	700
OUTPUT (DISPLAY, RECORDER)	1500
ARITHMETIC ROUTINES	1000
DATA BLOCKS	2000
	<hr/>
	14200
INERTIAL PLATFORM MANAGEMENT OR DOPPLER NAVIGATION	SEPARATE COMPUTER
AIR DATA	SEPARATE COMPUTER

Characteristics of ROLM 1602 Computer

Word length	16 bits
Fixed point operand length	16,32 bits
Instruction length	16,32 bits
Number of basic instructions	81
Storage type	core
Cycle time	1.0 μ -sec
Access time	0.5 μ -secs
Maximum memory capacity in main chassis (maximum expansion)	8K (256K)
Storage protection	optional
Number of accumulators	4
Number of index registers	2
Number of directly addressable words	64K
Number of addressing modes	5
Hardware stack capability	standard
Control storage	ROM (2K x 32 bits)
Add time	1 μ sec
Hardware multiply/divide	standard
Floating point	optional, implemented in firmware (24 bit precision)
Floating point add (multiply) time	4.6-10.1 (18.1-18.3) μ -sec
Hardware byte manipulation	standard
Real time clock	optional
Direct memory access channel	standard
Maximum I/O rate	1M words/sec
Number external interrupt levels	16

Characteristics of ROLM 1602 Computer (Cont.)Environmental

Case temperature	0° to 65°C standard -25° to 75°C optional -55° to 95°C optional
Vibration	10g, 5-2000 Hz, with vibration isolators (MIL-E-5400, Curve IV) 2g, 5-2000 Hz, hard mounted (MIL-E-5400, curve II)
Shock	15g, 11 m-sec (MIL-E-5400) 400 lb. hammer, with isolators (MIL-S-901)
Humidity	95% Relative
RFI	MIL-STD-461
Altitude	80,000 feet
Power	400 Hz, 115VAC, single phase, per MIL-STD-704A, Category B (47-440Hz or ± 28 VDC optional) 175 watts typical (CPU + 8K core) 275 watts maximum (per chassis)
Size	ATR chassis (7.62 x 13.12 x 15.91"

2.1.5 Barometric Altimeter

All survey aircraft are equipped with an air data sensor which measures static and dynamic air pressure and air temperature, from which the vehicle's true airspeed and barometric altitude are derived.

2.1.5.1 Barometric Altimeter Function

The function of the barometric altimeter is to provide height or altitude above a horizontal reference datum (usually mean sea level), accomplished by calibrating the free-stream static pressure in terms of pressure altitude and using a standardized temperature-altitude profile of the air. All aircraft altimeters permit the setting of sea level barometric pressure while in flight to correct for local pressure fluctuations.

With reference to FPRS, the purpose of the pressure altitude is:

- * to provide a position location solution for minimal data cases [e.g., range to 2 ground stations plus pressure altitude]
- * to provide redundant data when three or more range measurements are available.

In addition, the static pressure and air temperature data can be used to make atmospheric refraction corrections on the range measurements.

2.1.5.2 Barometric Altimeter Performance Characteristics

The pressure altitude performance as quoted by one manufacturer [Bendix, Navigation and Control Division] follows (no accuracy statistic was listed).

<u>Accuracy (ft)</u>	<u>Altitude (ft)</u>
13	0
18	5000
20	10000
25	15000
30	20000

2.1.5.3 Barometric Altimeter Interface Requirements

FPRS will interface with the existing barometric altimeter through the FPRS IU as shown in Figure 2-1.

There are no required inputs from the IU to the baro-altimeter. For some aircraft the baro-altimeter is not a stand-alone system, but part of an air data sensor group coupled to an air data computer. Control signals, such as "ready" and "self-test" signals, will be used by FPRS.

The altitude data, although expected to be slowly varying, will be time correlated to the FPRS range measurement data. When the high flyer aircraft and survey aircraft are both operating, the high flyer's altitude and other data will be transmitted to the survey aircraft.

2.1.5.4 Barometric Altimeter Data Output

The available data output(s) is usually in analog form, necessitating an analog-to-digital converter module in the FPRS IU.

2.1.6 PLRS Antennae

2.1.6.1 Antenna Functions/Descriptions

The PLRS airborne antennae are standard blade antennae typical of those used with airborne TACAN receivers. It is expected that all survey aircraft will have an already installed blade antenna on the underside of its fuselage. The function of the antennae is to radiate signals to, and receive signals from, the FPRS ground and high flyer subsystems.

2.1.6.1.1 Upper Antenna

All survey aircraft must be equipped with an "upper" blade antenna situated atop the aircraft fuselage. The purpose of this antenna is to radiate signals to, and receive signals from, the high flyer aircraft, or ground installations located higher than the survey aircraft.

2.1.6.1.2 Lower Antenna

All survey aircraft must be equipped with a "lower" blade antenna situated on the underside of the aircraft fuselage. The purpose of this antenna is to radiate to and receive signals from FPRS ground stations.

2.1.6.2 Antenna Special Requirements/Interface

Special interface is required between the FPRS IU and the upper and lower antennae. Those FPRS operating modes which require the survey aircraft to operate with both ground stations and a high flyer will require appropriate antenna switching. Antenna switching is discussed in Section 2.1.9 (Controls/ Displays). Both automatic and manual control over the operation and sequencing of the upper and lower survey aircraft PLRS antennae are required.

2.1.7 Tape Recorder

There are two possible system configurations with regard to the magnetic tape recorder: (a) a separate recorder for the flight path data and (b) a single recorder for both radiometric data and flight path data. In option (a), which would be the choice in the FPRS flight test phase, the flight path data would be time tagged with the same real time clock that is used to tag the radiometric data. In option (b) which may be less costly, the method of synchronizing the flight path and radiometric data depends on the radiometric instrumentation system. We will assume that, at least for any flight test, option (a) will be implemented.

2.1.7.1 Tape Recorder Functions/Description

The function of the tape recorder is to record flight path data (and radiometric data) for the purpose of correlating the radiometric data with the actual ground track. The data to be recorded according to the BFEC/ERDA "General Specification for Airborne Surveys" (PMD 1200-A, August 1976) are:

1. Record identification number
2. Latitude in degrees (four decimal places)
3. Longitude in degrees (four decimal places)
4. Time of day
5. Total magnetic field intensity data
6. Terrain clearance (ft.)
7. Barometric pressure reading
8. Outside flight level air temperature

9. Quality flag code (for radiometric data)
10. Raw count data for all channels (0-3MeV)-4π detector
11. Dead time counting period (secs) for each sample-4π detector
12. Raw count data for all channels (0-3MeV)-2π detector
13. Dead time counting period (secs) for each sample-2π detector
14. Cosmic spectral summed data (3-6 MeV)-4π detector
15. Cosmic spectral summed data (3-6 MeV)-2π detector

We would suggest that, instead of recording latitude and longitude for every record, all the data necessary to calculate latitude and longitude be recorded. This data would include:

1. Ranges to all ground stations from survey aircraft plus corresponding identity codes
2. Survey aircraft altitude (already recorded)
3. Outside flight level temperature (already recorded)
4. Survey aircraft dead reckoner data

and, if in the high flyer mode:

5. Ranges to all ground stations from high flyer plus corresponding identity codes
6. Range from survey aircraft to high flyer
7. High flyer dead reckoner data
8. High flyer altitude and outside flight level temperature

We did not survey, as part of this contract, magnetic tape recorders for use in FPRS. The recorders presently being used will most likely suffice and, if not, there are a number of standard units which meet MIL-E-5400 Class 1 (Airborne Equipment). Examples are Ampex ATM-13 and Miltope Airborne Tape Transport.

2.1.7.2 Tape Recorder Interface Requirements

The magnetic tape recorder will interface, via a magnetic tape

controller, to the FPRS computer. This is a standard unit if configuration (a) of Section 2.1.7 is chosen.

2.1.7.3 Tape Recorder Special Requirements

With configuration (b), both the FPRS computer and the radiometric system would have to be interfaced to the magnetic tape recorder unless there was first a transfer of all radiometric data to the FPRS computer.

Configuration (a) would require some modification to the interface unit such that: (1) the contents from a block of FPRS computer memory, containing flight path data, be written via the input data lines on magnetic tape and then (2), the radiometric data from, for example, the multichannel analyzer be written on magnetic tape.

It is critical that the system verify that data is actually being written on tape with no errors. Therefore, the tape transport/controller should have error checking/correcting capability (e.g., parity checking, longitudinal redundancy check character, cyclic redundancy check character, and read-after-write heads).

2.1.8 FPRS Airborne Power Supply

2.1.8.1 Power Supply Functions

Power is required to operate the PLRS DME Data Link, the FPRS computer, the IU, FPRS Controls and Displays and the FPRS Tape Recorder. The PLRS has in existence the necessary interfacing to use aircraft power and thus is part of the required GFE. It is considered that the use of aircraft power for digital computers, recorders etc. is so standard at this time that powering of the airborne FPRS does not present any problems other than the eventual

selection of standard aircraft power conditioning equipment.

2.1.8.2 Power Supply Special Requirements

For the purpose of cost reduction, it is recommended that the power supply and power conditioning equipment (designed and built for PLRS airborne use) be made an essential item of GFE.

2.1.9 Controls/Displays

2.1.9.1 Controls: Manual

The following discussion assumes a separate FPRS control panel to be operated by a pilot or technician.

2.1.9.1.1 FPRS Mode Switch

A four position FPRS mode switch is recommended. The four positions and the purpose of each are as follows:

1. "Off" Position: The purpose of this control is to shut down the FPRS system operation.
2. "Stand-By" Position: The purpose of this control is to turn on all components of FPRS, but not initiate the ranging operation. The system would be ready to radiate. System pre-flight and post-flight testing occurs in this mode.
3. "Non-High Flyer" Position: The purpose of this control is to initiate survey ranging operations and to initiate all ground-station-only, FPRS-position-location modes.
4. "High Flyer" Position: The purpose of this control is to initiate survey ranging operations, using both upper and lower antennas, and to initiate computer controlled high flyer modes of position location.

2.1.9.1.2 FPRS Computer Input and Control

A keyboard control to allow the manual input (to the FPRS computer) of the identity and position location parameters of each ground station used in the survey is required. The keyboard will be used for other control functions.

2.1.9.1.3 Present FPRS Aircraft Position Location Call-Up

A switch or keyboard control is required to enable the pilot or technician to request the display of the FPRS/DME-determined present aircraft position. This function is used for in-flight validation of FPRS status.

2.1.9.1.4 Ground Station Position Location Call-Up

This control instructs the FPRS computer to display the stored position location of a designated ground station. This control can be part of the control keyboard discussed in Section 2.1.9.1.2.

The keyboard can be used to input the identity of the station. A predetermined code or special key can be used to command the computer operation. The purpose of this control is to allow for the pre-flight, in-flight, and post-flight test of the FPRS.

2.1.9.1.5 Antenna Selector Switch

This control manually overrides the "four position" mode switch (Section 2.1.9.1.1) and allows for the use of the upper antenna only for DME radiation.

The purpose of this control is to allow for the pre-flight testing of the upper antenna only and to allow for the special survey mode, where the ground stations are placed at higher altitudes than the survey aircraft, eliminating the need for use of the down antenna.

2.1.9.1.6 Computer Ground Station Location Command

This control instructs the computer to compute and display the position location of a designated ground station. It can also be an integral part of the computer input control keyboard (Section 2.1.9.1.2).

It is used only in pre-flight testing, and permits the testing of the computer program and the validity of the ground station positions entered into the computer.

2.1.9.1.7 FPRS Component Test

Controls necessary to accomplish the test and calibration of the integrated FPRS have been listed. The test and calibration of the FPRS components (e.g., DR, Doppler, PLRS) will be conducted using vendor supplied operating instructions and manuals.

2.1.9.1.8 FPRS System Test Command

This control may be a coded digital instruction entered on the "Input Keyboard" which activates a software/computer controlled FPRS system test operation. This control operates only when the FPRS is in the "stand-by" mode. There should also be a "System Test Terminate" coded instruction.

2.1.9.2 Displays

In the following discussion, a separate FPRS display panel is assumed.

2.1.9.2.1 Present DR Aircraft Position

It is assumed that all survey aircraft will have a "present position" display driven by the aircraft navigation computer. This required display may be analogue or digital, but is not a part of the FPRS display panel.

2.1.9.2.2 Present FPRS Aircraft Position

This displays the FPRS/DME computed aircraft position. This

display function and that described in Section 2.1.9.2.3 may be incorporated in a single display.

2.1.9.2.3 FPRS System Status Light

This light indicates FPRS is either in "stand-by" or "operating" mode (green), or is not ready to operate (red).

2.1.9.2.4 FPRS System Component Status Lights

These lights indicate that the interface between the airborne FPRS sensors, the DR, PLRS and the altimeter, are operating and that data from these sensors is arriving at the IU.

2.1.9.2.5 Survey Mode Indicator

This display indicates the number of ground stations responding to survey aircraft interrogations and can be in the form of a single digit display or lights.

2.1.9.2.6 Degraded Mode Alert

This indicator (light/sound) alerts pilot and crew that the FPRS is operating with positional errors between 100 and 1000 feet.

2.1.9.2.7 Failure Mode Alert

This indicator (light/sound) alerts the pilot and crew that the FPRS is operating either with insufficient data to compute position or with errors greater than 1000 feet.

2.2 FPRS Airborne Subsystem: High Flyer (Fixed Wing)

2.2.1 FPRS High Flyer Subsystem Functions/Description

The High Flyer Subsystem Block Diagram is shown in Figure 2-4. Based upon our experience with military flight profiles, it is unusual for a helicopter to be flown above altitudes of 5000-6000 feet for any length of time. Thus, throughout this report, we have shown the high flyer as a fixed wing aircraft to permit higher operational altitudes and thereby to take advantage of the 100 NM range of PLRS. The primary function of the high flyer subsystem is to extend the line-of-sight of the survey aircraft to ground stations that are located in rugged terrain, or when natural or other obstructions make line-of-sight acquisition to ground stations from the low flying aircraft impossible or unfeasible.

The high flyer aircraft will always have line-of-sight acquisition to at least two ground stations and usually more. The survey aircraft will measure its range to the high flyer while, at (or very close to) the same time, receiving over the PLRS data link the barometric altitude of the high flyer and his position data with respect to the ground stations. Thus, the survey aircraft, operating with only one ground station and in line-of-sight with the high flyer will be able to determine its position in the survey grid.

Note that it is possible for the high flyer to act as an airborne reference beacon to more than one low flying survey aircraft.

2.2.2 FPRS High Flyer Subsystem Performance Characteristics

The high flyer subsystem performance characteristics are the same as for the survey aircraft subsystem performance except as

FIGURE 2-4. FPRS HIGH FLYER SUBSYSTEM

noted in Section 2.2.4.

2.2.3 FPRS High Flyer Subsystem Special Requirements

The high flyer subsystem must operate at an altitude of approximately 10,000 feet and must relay position data to the survey aircraft.

2.2.4 FPRS High Flyer Subsystem Component Special Functions

2.2.4.1 Dead Reckoner

The high flyer subsystem DR functions are the same as those indicated for the survey aircraft subsystem in Section 2.1.1.

2.2.4.2 DME

The FPRS DME, when operating in a high flyer, will always operate with another airborne FPRS system (the survey aircraft) and a minimum of two ground stations. Thus the high flyer DME will interface with more stations than the survey aircraft (a minimum of three). It will have different multipath conditions and somewhat different ranging errors based upon long range operational characteristics of the PLRS or other suitable DME.

2.2.4.3 Data Link

The high flyer subsystem must transmit its present position data to the survey aircraft. Position location is reported in latitude and longitude. In addition, high flyer baro-altitude data must be transmitted to the survey aircraft. This data cycle is to be accomplished once every half second (0.5 sec.) and is to be time correlated (annotated) with the corresponding position data being acquired by the survey aircraft.

2.2.4.4 Processor/Interface Unit

It is not necessary for the high flyer to perform any computations. (All computations will be performed in the survey aircraft

FPRS computer.) An interface unit (IU) is required to transfer dead reckoner data and barometric altimeter data to the PLRS for transmission to the survey aircraft. A micro-computer can be incorporated into the IU for controlling and/or sampling the high flyer subsystems.

2.2.4.5 Baro-Altimeter

In the high flyer mode the FPRS airborne subsystem must transmit barometric altitude data to the survey aircraft FPRS subsystem. Thus, an interface with the FPRS IU and the aircraft baro-altimeter is required.

2.2.4.6 Antenna

The high flyer subsystem antenna will always operate using the "down" antenna.

2.2.4.7 Controls/Displays

In the high flyer mode, it is required that a control be provided to insure operation with "down" antenna only. This mode selection may be accomplished automatically and/or with manual controls.

No special requirements related to displays are noted.

2.3 FPRS Ground Subsystem

Figure 2-5 is a block diagram of the FPRS ground subsystem. For purposes of description the FPRS ground subsystem has been divided into five (5) parts as follows:

- a) Ground Subsystem DME
- b) Ground Subsystem Antenna
- c) Ground Subsystem Power Supply
- d) Ground Subsystem Controls/Displays
- e) Transit Satellite System

2.3.1 Ground Subsystem DME

The ground subsystem DME is considered to be the same as, and interchangeable with, the airborne DME operating in a slave or responder mode.

2.3.1.1 Ground Subsystem DME Functions/Description

The ground subsystem DME (GS DME) functions as a responder. Upon receipt of the airborne interrogator signal and recognition of its unique address it will radiate a respond signal to the interrogator. In this manner, the distance between the GS DME antenna and the airborne DME antenna can be measured. The function of a GS DME is to mark a stationary point of reference on the surface of the earth to which the survey aircraft can reference itself. This is necessary so that, given a sufficient number of GS DME's, the survey aircraft may uniquely determine its position relative to the distribution of GS DME's.

2.3.1.2 Ground Subsystem DME Performance Characteristics

GS DME performance characteristics are the same as for the

FIGURE 2-5. FPRS GROUND SUBSYSTEM

airborne DME and are shown in Table 2-1.

2.3.1.3 Ground Subsystem DME Special Requirements

The PLRS DME, as presently manufactured and described by General Dynamics, is designed to operate at temperatures of 0° C to 50° C. As it is expected that the GS DME will be required to operate at temperatures below 0° C, some form of heater is required to maintain the GS DME operating temperatures at or above 0° C.

2.3.1.4 Ground Subsystem DME Interface

The GS DME has two subsystem interfaces:

- a) A power supply interface.
- b) An antenna interface.

The present PLRS manpack configuration provides an existing power supply/DME interface. The power is supplied by batteries. This type of power supply is assumed to be adequate for survey operation.

The PLRS manpack configuration provides for an existing whip (dipole) antenna. While it is expected that this DME antenna will prove suitable for most survey operations, a discussion of other or special antenna requirements is presented in Section 2.3.2.

2.3.2 FPRS Ground Subsystem Antenna

2.3.2.1 Ground Subsystem Antenna Functions/Description

The GS antenna functions are; (1) to receive interrogation signals from and (2) to radiate respond signals to an airborne FPRS subsystem. The antenna for the GS DME is the PLRS manpack whip antenna presently configured in the PLRS manpack unit.

2.3.2.2 Ground Subsystem Antenna Special Requirements

The design of antennas and the prediction of antenna fields is not an exact science. It is expected that conditions will arise wherein the present whip antenna configuration will not suffice. A most obvious requirement is the ability to raise the antenna higher than is presently possible. In consideration of this potential problem, the Flight Test Plan (Section 4) imposes tests whose purpose is to gather data concerning GS antenna performance as a function of antenna height and obstructions. This consideration of antenna performance is not intended to suggest either serious or insurmountable ground station antenna problems. It is, however, intended to call attention to a problem that may exist and to justify consideration of this problem in the Flight Test Plan since data obtained during a flight test will be more valuable than any other data presently available.

2.3.3 FPRS Ground Subsystem Power Supply

Ground station power requirements for the different DME systems are given in Section 5.1. As can be seen, input power requirements are not large. Input power could be supplied by one of the following:

- * Battery
- * Battery plus motor generator
- * Battery plus propane fueled thermoelectric generator
(one gallon/day for 24V, 80 amp-hour battery)
- * Battery plus solar panel

The choice of powering methods will depend on the permanency of the installation (i.e., time required to perform survey within survey grid) and the accessibility to the area. Figure 2-6 shows the flying time required to cover a 100 x 100 NM survey grid at an

FIGURE 2-6. SURVEY FLYING TIME

aircraft velocity of 100 knots as a function of line spacing. This shows it can take from several days to about one week, depending on line spacing, to overfly a 100 x 100 NM survey area. For short time emplacements, a battery is the most convenient method. To increase battery life, the DME can remain in a "receive only mode" until alerted by the survey or high flyer aircraft to turn on the transmitter.

2.3.4 FPRS Ground Subsystem Controls/Display

No controls or displays other than those presently available on the PLRS manpack system are required.

2.3.5 TRANSIT SYSTEM (5,6,7)

2.3.5.1 General Description

The TRANSIT System, also referred to as the Navy Navigation Satellite System (NNSS), was originally conceived as a navigational aid for naval vessels, and has been used for this purpose since 1964. The system was made available to civilian users in 1967.

The present system consists of 6 satellites in circular polar orbits at altitudes of approximately 600 nautical miles. The orbital period is about 104 minutes. Four tracking stations determine satellite orbital data. New orbit data is transmitted by ground control to satellites every 12 hours and stored. The satellites transmit their orbital data (ephemeris data), using phase modulation coding, at precisely controlled intervals of two minutes.

A stationary user determines his position by measuring the Doppler shift in the signals transmitted by the satellite. The user's receiver references the received signal against a stable internal oscillator, thereby generating a beat frequency. The number of cycles of the beat frequency (Doppler count) is measured over a convenient time interval by utilizing time marks which are impressed on the satellite signal. Two coherently related transmission frequencies (150 MHz and 400 MHz) are used to calculate a first order correction for ionospheric refraction effects. The ephemeris data plus the Doppler counts collected over the duration of the pass constitute all of the information required to position the user.

The single pass error budget for TRANSIT System, surveyors is as follows:⁽⁵⁾

1. Uncorrected propagation effects (3rd order ionospheric and neglected tropospheric effects)		1-5 m
2. Instrumentation (navigator-satellite oscillator phase jitter)		1-6
3. Geodesy (uncertainty in geo-potential model)		5-10
4. Incorrectly modeled surface forces (secular error growth due to incorrect period, drag, and radiation pressure)		10-25
5. Unmodeled UT1-UTC effects and incorrect coordinates of the pole		1
6. Ephemeris rounding error (last digit of ephemeris is rounded)		5

RSS 12-28m

The error contribution for item 3 above is based on use of the 1972 World Geodetic System (WGS-72). (The TRANSIT system has been on WGS-72 since December 1975.)

WGS-72 is the datum or system of reference in which a TRANSIT system user positions himself, and in which ephemeris positions of the TRANSIT satellite are maintained. The WGS-72 system also provides data conversion formulas for relating major datums of the world to WGS, and an earth gravitational model. We very briefly review some of these concepts.

In geodetic applications, three different surfaces or earth figures are normally involved: the earth's natural or physical surface, a geometric or mathematical surface called an ellipsoid of revolution, and an equipotential surface called the geoid.

The ellipsoid can be uniquely defined by two parameters which describe its size and shape. Size is conventionally represented by the semimajor axis (a), whereas the shape is given by the

flattening (f). The parameters adopted for the WGS 72 ellipsoid are:

a= semimajor axis = 6378135 m

b= semiminor axis = 6356750 m

f= flattening = $(a-b)/a = 1/298.26$

The geoid coincides with the surface to which oceans would conform over the entire earth (mean sea level surface) if free to adjust to the combined effect of the earth's mass attraction and centrifugal force. As a result of the uneven distribution of the earth's mass, the geoidal surface is irregular and does not coincide with the regular surface of the ellipsoid. Separations between the two surfaces are referred to as geoid heights. For general purposes, the form of the geoid is usually indicated by a contour chart which shows the location of the geoid above or below the ellipsoid selected to approximate the earth. When available, astrogeodetic contour charts are frequently used to obtain geoid height data. However, due to limited coverage of astrogeodetic geoid height data, geoid height information is derived on a worldwide basis from a mathematical representation of the earth's gravitational field.

Vertical positions obtained from TRANSIT will be referenced to the WGS ellipsoid. Baro-altimetry data is usually referenced to mean sea level (MSL). It is therefore important to convert baro-altimetry data from MSL to WGS (or vice versa) which requires knowledge of geoid height data (ranges in value from -100 to +80 meters). Values can be calculated using the WGS-72 earth gravitational model.

Alternatively, the baro-altimeter can be calibrated relative to the WGS ellipsoid by overflying and ranging to the ground stations

2.3.5.2 Use of TRANSIT in FPRS

A TRANSIT satellite receiver can be used to determine the coordinates (latitude, longitude, height above reference ellipsoid) of the ground station antennae. A minimum of two satellite passes, one on either side of the receiver position, are required to obtain a three dimensional position fix. The accuracy of the position fix depends on the number of satellite passes observed during the measuring period. The number of satellite sightings depends on observer latitude (close to continuous at the poles and once each hour or so at the equator)

The single pass position error (RSS) ranges from 12 to 28 meters.⁽⁵⁾ Using observation times of several days, positional accuracies of better than 5m (16 feet) are obtainable. Table 2-4, taken from Reference 6, indicates how the accuracy might improve with the number of passes. This table compares two estimation schemes. The results from the Kalman estimation assume an independent source of information for receiver elevation.

Since, as the table shows, the survey accuracy depends on the number of satellite passes with corresponding surveying time, one might ask: "How accurate should these ground station surveys be?" The answer to this question depends on two factors, the accessibility of the terrain and the method of returning.

If the method of return entails reinstalling several of the ground stations at the original locations (assumed suitably marked), then the geo-reference location accuracy of the stations is not critical. Only the position location relative to the ground stations need be accurate. Thus, the initial ground station survey

TABLE 2-4

POSITION ACCURACY VS NUMBER OF TRANSIT SATELLITE PASSES

PASS	PASS GEOM *	KALMAN EST.			WEIGHTED LEAST-SQUARES		
		σ_{λ} (FT)	σ_{Λ} (FT)	σ_h (FT)	σ_{λ} (FT)	σ_{Λ} (FT)	σ_h (FT)
1	33 NW	48.4	109.3	100	---	---	---
2	52 SW	32.8	39.4	28	37.2	129.6	95.8
5	45 SE	21.4	29.8	19.9	21.9	33.1	19.3
10	67 SW	15.3	19.3	13.8	15.7	23.2	14.2
15	15 NE	12.8	15.2	12.0	13.2	19.3	12.5
20	20 SE	11.0	13.1	10.4	11.4	16.4	10.8
50	39 NW	6.8	8.5	6.5	7.0	10.3	6.6

* Maximum elevation angle and direction of approach

λ = Latitude

Λ = Longitude

h = Elevation

can be performed quickly using several satellite passes.

If the method of return is by some other means (for example, transportation of a TRANSIT receiver), then geo-reference position location is used. The investigation of a radiometric anomaly on terrain that permits easy access and mobility would not require highly accurate position location, since geological ground sampling at different points in the anomalous region could be quickly accomplished. On the other hand, if the anomaly is in mountainous terrain where mobility is limited, it is desirable to return as close to the original flight path points as possible. In this latter situation, accurate geo-referencing of the ground stations is desirable.

TRANSIT user equipment is manufactured by a number of companies; for example, JMR Instruments, Canadian Marconi, Magnavox. Most likely many of the aerial survey companies have TRANSIT user equipment; if not, there is the alternative of having a service company survey ground station sites.

Field equipment is available which permits TRANSIT user equipment to be left unattended while data is recorded on magnetic tape for subsequent computer reduction at a central site. Ground station antenna coordinates may be determined simultaneously with station installation by using a field transportable minicomputer plus TRANSIT receiver.

2.4 FPRS System Operation

2.4.1 Flight Path Guidance of Survey Aircraft

There are four sets of data used to determine and provide flight path guidance corrections to the survey aircraft:

1. Geo-referenced coordinates of ground stations.
2. DME determined range and/or position location of survey aircraft relative to ground stations.
3. Dead reckoner determined position location of survey aircraft.
4. Altimeter data.

The FPRS computer, using DME range data, the position location of the ground stations and baro-altimeter data, computes the survey aircraft position. The FPRS data is then recorded and in addition, sent to the aircraft navigation computer to update the aircraft dead reckoner. This process of updating or recalibrating the aircraft dead reckoning navigation accomplishes two valuable objectives:

1. It allows the information normally displayed on the pilot's existing navigation display to be used to fly the required flight lines, thus saving the cost and complexity of additional computer and display capability.
2. It allows the use of the aircraft dead reckoner as a short term, back-up, position location capability.

The frequency with which the updating process occurs depends upon three considerations:

1. The drift characteristics of the DR.
2. The type of FPRS computer and computer loading.
3. Initial errors, when use as back-up device is required.

In this report we have arbitrarily selected a five second interval as the frequency of DR update.

Thus, every five seconds a DME determined FPRS position location is computed, recorded, and sent to the aircraft navigation computer to update the DR. The result is that the DR determined aircraft track and the FPRS determined aircraft track will coincide to within approximately 100 feet. This correlation can be useful in post-flight analyses. The pilot flies his preplanned flight lines using his DR-displayed data.

(Continued on next page)

2.4.2 Position Location of Survey Aircraft

2.4.2.1 Trilateration

The cartesian coordinates of a point in space can be determined by making three range measurements between that point and three known non-colinear points. Each range measurement describes a sphere about a known point. The three resultant spheres intersect in two points; the use of dead reckoner and/or altitude data removes the ambiguity. Trilateration is the primary position location mode of the FPRS system.

2.4.2.2 Multilateration

In some instances during survey, more than three ground stations will be visible to the FPRS DME. The FPRS computer will automatically search for and accept ranging data from all the ground stations within line-of-sight of the FPRS.

In this case, redundant position location data will be acquired, recorded and used for more accurate position location computations.

2.4.2.3 Two Ground Station Position Location

The FPRS can accurately determine the position of the survey aircraft using range data from only two ground stations. Ranging from the aircraft to each of two ground stations would define a sphere about each ground station. The intersection of the two spheres defines a circle. The addition of the aircraft baro-altitude would further define two points on the circular line of intersection. This two point ambiguity in aircraft position is resolved by using corrected DR data present in the FPRS computer.

2.4.2.4 One Ground Station Plus High Flyer

In terms of computation, this mode of position location is like the two ground station mode except that the coordinates of one station, the high flyer, are not constants. In this mode, the high flyer aircraft position locates itself, either by trilateration or by ranging against two ground stations, once every half second. The high flyer will transmit its position location data to the survey aircraft. The survey aircraft will range both on the one ground station and the high flyer. It will thus compute its position as if in a two ground station mode.

The FPRS computer will collect all available ground station data at all times so that, if the survey aircraft is in the high flyer mode and periodically sees two ground stations, all data from the two ground stations will be recorded and processed.

2.4.2.5 One Ground Station Only

This mode of position location is a degraded performance mode. It is useful when, for short periods of time, only one ground station is available for ranging.

In this mode, a position location is determined once every 5 seconds (1000 ft. of flight line). During the 5 second interval, at least 10 range measurements to the ground station can be made. The DR is used to determine the distance flown between range measurements (the baseline). Using the range measurement and the DR-determined baseline, the FPRS is able to determine the aircraft's position.

The position location errors will depend upon survey aircraft velocity and the time dependent error growth of the survey aircraft

DR. This mode is useful during short intervals of ground station drop out such as might occur when the aircraft is maneuvering, or enters an area of severe multipath environment.

2.4.3 Non-High Flyer Mode of Operation

In the non-high flyer modes, the survey aircraft sequentially ranges to all ground stations within range of the DME. It will range on a maximum of four ground stations. All range data will be acquired and processed every half second of flight. A determination of position location will be available for display to the pilot once every five seconds of flight. All range data, position location data, identity of stations used in ranging, altimeter data, and DR data will be recorded every half second of flight. The FPRS computer will automatically perform the position location computations based upon the best available data. The criteria for the best available data is to be provided for in the computer software. Thus, transitions from four-ground-station-ranging to two-ground-station-ranging occurs automatically and without the necessity for technician or pilot intervention. When position location errors exceed 100 feet for a period of two minutes, a "degraded" mode alert signal will sound/flash to alert the crew. When position location errors exceed 1000 feet for a period of two minutes, a "failure" alert will sound/flash to alert the crew.

Pilot interface with FPRS is required to fly proper flight lines from position location data displayed by the FPRS. Crew interface may be required during periods of "degraded" or "failure" modes of operation. During the survey flight, the FPRS computer will replace ground stations which drop out of DME range with new

ground stations which have entered the aircraft's range and line-of-sight. This is accomplished by testing for available line-of-sight stations (maximum of four) as when the aircraft first entered the survey area.

2.4.4 High Flyer Modes of Operation

The high flyer FPRS functions as a moving reference station and as such has more complex functions. The high flyer FPRS determines its position location by using range data from ground stations, altimeter data and dead reckoner data. Upon command of the survey aircraft FPRS, the high flyer FPRS will transmit all position location data to the survey aircraft. The PLRS DME has this command and data link function already available. The actual sequencing of the high flyer command/data link functions within the half second position location cycle is a matter to be considered in the actual hardware phase of the Flight Path Recovery Program. For example, the high flyer could always be addressed last or the survey aircraft could address the high flyer before ranging upon ground stations. The primary consideration is for the management of the data flow from the high flyer and the timing in which this data is to be processed by the survey aircraft FPRS computer.

2.4.5 Ground Station Operation

The ground station FPRS will, in its normal condition, be in the "receive" mode. Very little power will be needed during this time. When addressed by either a high flyer or survey aircraft FPRS, it will respond by transmitting the appropriate response ranging signal. The station is to operate unattended.

2.5 FPRS Operating Modes for Survey Operations

This section, while it repeats material contained in previous sections, is intended to clearly set out the actual position location and operating modes as they are intended to be used by the survey aircraft.

2.5.1 Survey Aircraft and Ground Stations Only Mode

2.5.1.1 Three Ground Stations in View

This mode is the standard position location mode to be used during a survey. Section 3 presents a discussion of ground station siting and the kinds of geometry which could allow for the use of trilateration. The FPRS will always test for four available ground sites, to be used for trilateration computations. When four are available, it will select the three best stations (best geometry) to compute position location. [Alternately, depending on computer loading, all data will be used in a "weighted least squares sense".]

2.5.1.2 Two Ground Stations in View

When there are only two ground sites available, the survey aircraft FPRS will compute position location from the two ranges,

altimeter data and dead reckoner data available in the FPRS computer. Both the three and two ground station modes should yield position location data with errors not exceeding 100 feet.

2.5.1.3 One Ground Station (Degraded Mode) in View

When only one ground station is available for ranging, the FPRS is in a degraded mode. The accuracy of position location will degrade with time, and will be dependent upon the performance characteristics of the survey aircraft dead reckoner, the time elapsed since the last non-degraded position information was obtained, and the velocity of the aircraft.

2.5.2 Use of Survey Aircraft, High Flyer, and Ground Stations

2.5.2.1 One Ground Station in View

The purpose of the high flyer is to overcome terrain conditions which allow only one ground station at a time to be visible to the low flying survey aircraft. In this mode the survey aircraft, which is always used as an FPRS master, makes use of the high flyer as if it were another ground station. The need for the high flyer is to be determined during the pre-survey planning phase. The flight path of the high flyer is also determined prior to survey.

2.5.2.2 Two Ground Stations in View Intermittently and High Flyer

This mode is discussed to emphasize the fact that the survey aircraft FPRS will accept all available range data from all available sites up to a maximum of four, so as to provide the FPRS computer with the largest possible data base from which to compute position location. We believe the intermittent case will not be unusual because LOS obstructions due to terrain will be a constantly changing process.

In the case where a response from a ground station is received intermittently, the FPRS will process and record all data. If two ground stations and a high flyer are in view, the FPRS computer will compute position on the basis of software established "best data" criteria, which are primarily geometry dependent.

2.5.2.3 No Ground Stations (Degraded Mode) in View

This mode is similar to the one ground station only case. Where there are no ground stations in view, the survey aircraft can range on the high flyer only. Again, the position location accuracy will degrade with time. The rate of degradation will be dependent upon the performance characteristics of the survey aircraft dead reckoner, time elapsed since last non-degraded position location, and the velocity of the aircraft.

2.5.3 Special Modes

2.5.3.1 Extended Range to Ground Stations

The PLRS DME can operate at a range of 100 NM. This can be put to advantage especially by the high flyer. The use of ground stations remote from the survey area can, in some circumstances, result in simpler and more timely ground station installation. Where terrain allows, it may be convenient to place ground stations on roofs of buildings, tops of mountains/hills or other appropriate sites to provide long baseline geometry for position location of the high flyer. In the case of the survey aircraft, similar advantages can accrue when the terrain forms a "bowl" around the survey area. In this instance, placing the ground stations at

high altitude sites and using the upper antenna of the survey aircraft could allow a reduction in the number of survey area ground sites required.

2.5.4 Pre-Survey Planning Phase

2.5.4.1 Requirements for Pre-Survey Planning

Perhaps the most important part of the survey operation is the pre-survey planning phase. It is during this time that the most important decisions with respect to the FPRS are made. In particular, those decisions related to the selection of ground station sites, the use of a high flyer, the number and identity of ground stations to be TRANSIT surveyed, when to perform the TRANSIT survey, the flight path to be flown by the survey aircraft, and the flight path of the high flyer among others are significant. Thus, a pre-survey map study should result in the following:

1. Site selection for ground station installation
2. Survey aircraft flight path
3. High flyer flight path (when required)

Operational considerations should result in the establishment of criteria important to successful FPRS operation:

- * Method and schedule for ground station installation.
- * Procedures and schedules for system test and calibration.
- * Method and schedule for ground station recovery.
- * Schedule for Transit survey of ground station.
- * Post flight debriefing and system check-out procedures.

2.5.4.2 Ground Station Installation, Test and Calibration

Ground station installation will most probably be accomplished in one of the following ways:

1. Surface vehicle and back-packed
2. Helicopter and back-packed

Given that the weight of the PLRS unit is approximately 15 lbs., back-packing should not prove to be a difficult problem. Even in the event that special antenna considerations are required, it is felt that the total weight of a ground station should not exceed 100 lbs. Prior to installation, the PLRS should be subjected to typical vendor recommended test and calibration procedures (e.g. battery test, vendor test equipment tests). Upon installation the PLRS should be tested for ranging response either by the use of a back-packed PLRS or an airborne PLRS. The ground station can be Transit surveyed at this time. If surveyed, the results of the Transit survey are recorded by the installation crew for input to the survey aircraft FPRS computer. If not surveyed, the best dead-reckoned estimate of the latitude, longitude, and elevation of the site is recorded and later corrected when a survey is done.

2.5.4.3 FPRS Test and Calibration Requirements

In addition to whatever test and calibration procedures are followed with respect to the individual system components, there are procedures pertinent to the FPRS which are required. The survey aircraft FPRS is to be provided with testing procedures as follows:

- * Validate reception of Dead Reckoner data output by FPRS computer

- * Validate reception of altimeter data by FPRS computer.
- * Validate FPRS computer position location computation.
- * Test upper and lower antenna.
- * Test warning alerts.
- * Validate ground station input data (position location of ground stations manually input to computer).
- * Validate ground station identity codes for survey area.
- * High flyer FPRS goes through all above tests in addition to data link test. This test can be performed between the survey aircraft and the high flyer while they are on the ground if both are sited at the same airfield. Or, it may be accomplished enroute.

In addition to the above, each component of the FPRS should undergo its usual vendor recommended pre-flight test and calibration procedures.

2.5.4.4 Geo-Referencing Ground Stations, Pre or Post Survey

The manner in which the FPRS operates leaves a choice as to whether a ground station site need be Transit surveyed at the time of installation or at a later time (e.g. at recovery of ground system). This flexibility can be of value. One example is in the case where there is impending unfavorable weather conditions which do not allow for the time necessary to accurately survey all ground sites, but allows for sufficient time to install ground stations rapidly and then survey. Another case would be when the Transit equipment is inoperable. In the case where the Transit survey is deferred to a later time, the survey aircraft FPRS computer will use the best available dead reckoned estimate of the location of ground sites. These estimates are to be corrected in the post-

flight data reduction phase. The new flight path data points can then be generated without loss of position location accuracy.

This capability, to input new ground station position location data, is to be reflected in the design of the post-flight data reduction process to allow for ground station and survey aircraft position location corrections.

2.5.5 Survey Phase

2.5.5.1 Flight Line Guidance

During an actual survey, the FPRS will display the present aircraft position as computed from ranging data, every five seconds. This information is the data the pilot uses to fly his preplanned flight lines. This display can be a simple numerical display of distance along flight line and left/right deviations from programmed flight line; or, the display may be a CRT device which shows the flight line to be flown and the position of the aircraft relative to the flight line. The actual decision is limited only by cost and complexity considerations. Our recommendation is to use the numerical display of present position (simplest case) and determine its degree of usefulness through flight testing.

2.5.5.2 Automatic Survey Mode Selection

Upon entering the survey area, the pilot or crew member will put the FPRS in one of two possible automatic survey modes:

- * Non-high flyer mode
- * High flyer mode

At this point the FPRS will begin to interrogate the ground stations and/or the high flyer, and perform all survey functions under the control of the FPRS computer without the necessity for

crew or pilot intervention.

2.5.5.3 Degraded Modes of Operation

In the event that errors in position location exceed 100 feet, but are less than 1000 feet for a period of two minutes, a "Degraded Mode" alert will light/sound. At this time, pilot or crew should check FPRS display to determine how many ground stations are responding. If two or more stations are responding, the assumption can be made that there is an FPRS component malfunction. If only one station is responding, there is the possibility of ground station malfunction, or severe multipath or line-of-sight obstruction. A discussion of in-flight system test is presented in Section 2.5.5.5.

2.5.5.4 Failure Modes

A failure mode is defined as a mode wherein position location errors greater than 1000 feet have existed for 2 minutes of flight. It is expected that in most cases, a failure mode will be preceded by a degraded mode. In the event of FPRS failure, a failure alert will light/sound.

2.5.5.5 In-Flight System Test Modes

The purpose of in-flight FPRS test modes is twofold.

- * A typical survey flying day is about 10 hours. It is expected that in-flight system testing will be helpful in establishing the validity of data collected over such a relatively long time period.
- * In cases where either degraded performance or failure modes occur, it is important to be able to determine whether the fault lies on board the survey aircraft (in which case it might be necessary to discontinue the survey) or, in the malfunction of a ground station. If the fault lies in a ground station, it would then be possible to continue the survey in an area where other ground stations are available.

To test for the existence of a fault unique to a set of ground stations or, for a general malfunction in the onboard FPRS, the pilot

does the following:

- * Flies to higher altitude in the general area of malfunction; if the system begins to operate, fault is not on board.
- * If system continues to malfunction at higher altitude, pilot acquires new set of stations or returns to an area where system was previously operating, whichever is nearest. If system operates, fault is not on board. If system continues to malfunction, fault is on board FPRS.

Anytime during a flight it is always possible to perform another system test. The pilot overflies a ground station (or known physical feature) visible to him. The FPRS position location of the aircraft at time of overflight should correspond to the known position location of the ground station within the limits of accuracy of the survey. In addition, the measured range to the ground station should correspond with the radar altimeter data at time of overflight.

2.5.6 Post-Survey Phase

2.5.6.1 FPRS Operating Status Validation

At the completion of a survey it is recommended that the survey aircraft overfly at least one ground station a number of times. This overflight data will represent in-flight data with respect to system validation. After landing, FPRS validation should proceed exactly as for pre-flight procedures. All pre-flight and post-flight validation procedures which result in an FPRS computer data output are to be recorded on the flight recorder. All other procedures are to be recorded as part of the aircraft flight log.

2.5.6.2 Ground Station Recovery and Status Test

Ground stations no longer required are recovered. Operating status of ground system at site should be logged. A ranging test should be performed at site and results logged. Ground systems are

returned to base and stored for further use.

2.5.6.3 Ground Station Survey

If ground stations have not been previously TRANSIT surveyed, it should be done at the time of ground station recovery. Posts or markers that are to be placed for possible future use, can be placed at this time.

2.5.6.4 Survey Data Management

It is assumed that there will be a ground based computer which will process and print out the flight recorded data.

The FPRS tape data consists of the following:

- * The identity and position location of all ground stations in the survey area.
- * All range measurements of the ground stations interrogated.
- * Every half second of survey flight will generate a packet of data containing all ranges measured from identified ground stations (high flyer), the dead reckoner data, the baro altimeter data, and all high flyer data linked information.
- * Every five seconds, in addition to the half second data, the FPRS computer will compute the survey aircraft position from the FPRS DME measurements and altimeter data.

The function of the ground based computer regarding post-flight data processing is to compute the aircraft position location for each half second of flight and recompute all five second position location data. Provision should also be made to allow the input of new ground station position location data and the recomputation of aircraft position location using the new ground station data. Print out of any portion of a flight path should be possible by inputting the appropriate latitudes and longitudes.

3.0 SYSTEMS ANALYSIS

3.1 System Design Philosophy

The design philosophy adopted for this study was influenced by several factors. The flight path recovery system should be made operational within the time frame of the NURE Program. Many of the component subsystems which make up a flight path recovery system have been developed and built for military applications - the technology is available and much of the hardware has been developed and tested.

Therefore, in view of the above, we felt that it would be more appropriate to adopt, or modify where necessary, existing and proven subsystem components and properly integrate them into a Flight Path Recovery System (FPRS) to provide the necessary accuracy.

3.2 System Concept

3.2.1 Performance Objectives

We restate from Section 1.3 FPRS performance objectives:

- * Position location and guidance of a survey aircraft within a survey grid of 100 x 100 nautical miles (NM)
- * Recoverable position location accuracy within the survey grid of 100 feet CEP, or less, under continuous flight operation
- * System operation at low survey aircraft altitudes (nominal terrain clearance is 400 feet)
- * System operation in all types of terrain typography (featureless, mountainous, etc.)
- * System output suitable for automatic data processing (ADP)
- * Backup flight path recovery to within 1000 feet CEP

In addition to the above, the system should impose very little, if any, pilot workload during low altitude survey flight.

3.2.2 Characteristics of an Ideal System

Although unobtainable at the present time, an ideal flight path recovery system would have the following characteristics:

- (a) Provide accuracy and repeatability (precision) better than 100 foot CEP or that required to perform all survey operations
- (b) Should either be self-contained on the survey aircraft or require no user installed external aids (e.g. ground transponder beacons)
- (c) Provide an output suitable for automatic data processing (ADP)
- (d) Provide complete coverage in space and time (R, T) over the region to be surveyed
- (e) Should not be sensitive to environmental effects (ionospheric, ground moisture, multipath)
- (f) Should be reliable (have a large Mean Time Between Failure, MTBF)
- (g) Should have low volume, weight, power consumption, cost, and MTTR (Mean Time To Repair)

Table 3-1 summarizes characteristics of several position location systems. If and when GPS becomes fully operational, GPS would come closest to meeting the above characteristics. There has also been FAA/ Coast Guard studies about extending LORAN to CONUS. Thus, if the 100 foot accuracy requirement can be relaxed, LORAN might also be considered. These two developments should be monitored for application to future survey work.

3.2.3 Recommended Approach

The approach that we recommend to meet the above system design objectives is the DME/ Multilateration technique. At the present time this is the only available technique which can give the required accuracy and meet the stated FPRS performance objectives. Line-of-sight (LOS) limitations can be overcome by using, when

TABLE 3-1

NAVIGATION SYSTEMS

	<u>NNSS</u>	<u>VOR/DME</u>	<u>GPS</u>	<u>DME/TRILATERATION</u>
ACCURACY	< 100'	600-1000'	~ 50'	50-100'
COVERAGE (R,T)	NON-CONTINUOUS IN TIME	CONUS; LOS LIMITED	WORLDWIDE	LOCAL (DEFINED BY GROUND STATIONS); LOS LIMITED
SELF-CONTAINED	NO	NO	NO	NO
SUITABLE FOR ADP	YES	YES	YES	YES
AVAILABILITY	IN USE	IN USE	1985-1990	A NUMBER OF DIFFERENT SYSTEMS IN USE
USER-INSTALLED EXTERNAL AIDS	NONE	NONE	NONE	YES
ENVIRONMENTAL SENSITIVITY	MINIMAL	MINIMAL	MINIMAL	MINIMAL

TABLE 3-1 (CONTINUED)

NAVIGATION SYSTEMS

	<u>DR + PHOTOGRAPHY</u>	<u>LORAN</u>	<u>OMEGA</u>
ACCURACY	2-3 NM/HR FROM FIX	500-1500'	1-2 NM
SPACE-TIME COVERAGE	COMPLETE	INCOMPLETE (MAINLY COASTAL COVERAGE)	WORLDWIDE
SELF-CONTAINED	YES	NO	NO
SUITABLE FOR ADP	NO	YES	YES
AVAILABILITY	IN USE	IN USE	IN USE
USER-INSTALLED EXTERNAL AIDS	NONE (EXTERNAL LAND- MARKS USED)	MONITORS AND OWN LORAN D STATIONS FOR COMPLETE COVERAGE	MONITOR FOR DIFFER- ENTIAL OMEGA
ENVIRONMENTAL SENSITIVITY	VISIBLE IDENTIFI- CATION REQUIRED	AFFECTED BY GROUND MOISTURE, PRESSURE FRONTS; SURFACE COMPOSITION	AFFECTED BY IONOSPHERIC DISTURBANCES

necessary, a high flying aircraft as an airborne reference beacon. The high flyer is in LOS view of enough ground stations to accurately position himself by making range measurements to the in-view stations. The survey aircraft (assumed to be in view of at least one ground station) makes range measurements to the high flyer and, as close as possible in time to the range measurements, receives a position report from the high flyer [(XYZ) coordinates of high flyer]. This position reporting operation necessitates a requirement for an air-to-air digital communications link (data link).

We also recommend coupling or integrating the dead reckoner into FPRS via an airborne computer on the survey aircraft. Dead reckoner data is used for flight guidance and position determination in the event of partial system failure or intermittent station drop-out due to LOS blockage or multipath effects.

The total FPRS configuration will therefore consist of (i) a network of ground stations (transponders), (ii) the survey aircraft system and when required (iii) a high flying aircraft. Table 3-2 summarizes the various FPRS positioning modes (see also Section 2.4).

3.3 System Design Considerations

3.3.1 Station Siting

The siting of ground stations will very much depend on the type of terrain. In general, one wants to use the minimum number of stations to obtain coverage over the 100 x 100 NM survey grid consistent with maintaining good geometry. Geometrical dilution of precision (see Section 3.3.1.1) should not degrade position location accuracy below 100 foot CEP or whatever value is suitable for the terrain; if the terrain is easily accessible, the surveyor might

TABLE 3-2FPRS POSITIONING MODES

<u>CONFIGURATION</u>	<u>POSITION DETERMINED BY</u>	<u>COMMENTS</u>
Survey AC plus Ground Stations	* Ranges to 2 ground stations, altitude, dead reckoner data	If one station drops out, system is in degraded mode
	* Ranges to 3 or more ground stations, altitude, dead reckoner data	

Survey AC plus High Flyer plus Ground Stations	* Ranges to 1 or more ground stations, range to high flyer, (XYZ) of high flyer, altitude, dead reckoner data	Least accurate mode- High Flyer's (XYZ) position error propogates into survey AC's position error

want to relax the 100 foot CEP criteria and use fewer stations. If there are places whose positions are already accurately known, ground stations could be placed at these points, eliminating some TRANSIT surveys.

There are essentially three types of terrain topography pertinent to the positioning of a low altitude (400 - 700') survey aircraft using a LOS radio ranging system. We define these terrain types as follows.

Type "A" Terrain is terrain where the survey grid ($\sim 100 \times 100$ NM) is essentially flat but where there are surrounding hills or mountains. With this type of terrain, one would locate ground transponder stations on peaks such that there is LOS to any point in the survey grid. For type "A" terrain a DME with long ranging capability is best since a larger grid size would be possible.

Type "B" Terrain is terrain which is flat over distances much greater than the survey grid. The survey aircraft is horizon limited. At an altitude given as H , the distance to the radio horizon is given as approximately⁽⁸⁾

$$R(\text{NM}) = 1.23 \sqrt{H(\text{ft})}$$

At 400' the distance to the radio horizon is 24.6 NM; at 700' the distance is 32.5 NM. Figure 3-1 is a plot of the above relation.

If the ground beacon is at an elevation H_G , then the above expression becomes

$$R = 1.23 (\sqrt{H} + \sqrt{H_G}).$$

For example, if $H = 400'$ and $H_G = 50'$, then $R = 33.3$ NM.

FIGURE 3-1

DISTANCE TO RADIO HORIZON VERSUS ALTITUDE (4/3 EARTH RADIUS MODEL)

Type "C" Terrain is hilly or mountainous terrain where ground stations are frequently shadowed from the survey aircraft by terrain features. These regions will require the use of a high flying aircraft as an "airborne beacon" and the trade-off will be the cost of installing many ground stations versus the cost of putting up the high flyer. The high flyer would be at an altitude such that he can "see" enough ground stations to accurately position himself and at the same time "be seen" by the low flying survey aircraft when ground station shadowing occurs. At an altitude of 10,000 feet the high flyer's distance-to-horizon is 123 NM; at 15,000 feet it is 150 NM.

3.3.1.1 GDOP

Geometrical dilution of precision (GDOP) must also be considered when siting ground stations. For multilateration systems, an aircraft determines his position by making range measurements to three or more ground beacons (and perhaps an airborne beacon). These range measurements determine spherical surfaces of position, centered on the known positions of the air and/or ground reference beacons. Barometric altitude data defines locally a plane surface of position parallel to Mean Sea Level (MSL).

The intersection of three "range spheres" determines the (XYZ) position; actually two position solutions are obtained, the ambiguity being resolved by other data (e.g., altitude) - see Figure 3-2.

The error ellipsoid associated with the solution depends not only on the errors associated with each surface of position, but on the intersection angle of these surfaces. This is referred to as GDOP - an error magnification effect. Figure 3-3 shows a two

POSITION DETERMINATION: 3 RANGE MEASUREMENTS + ALTITUDE

FIGURE 3-2

GOOD
GEOM.

POOR
GEOM.

AREA OF
UNCERTAINTY

GDOP - GEOMETRICAL DILUTION OF PRECISION

FIGURE 3-3

dimensional example of GDOP - the error is minimum when the lines of position (circles) intersect at 90° . Figure 3-4 shows the error factor as a function of the intersection angle (θ) where the error factor is defined as $\text{CEP}(\theta) / \text{CEP}(90^\circ)$.⁽⁹⁾

Figure 3-5 shows two dimensional CEP contours (solid curves). For a low flying aircraft ($H = 400'$), this two dimensional approximation is reasonable. The values shown represent the CEP due to ranging errors ($1\sigma_r = 3 \text{ m}$) and GDOP. The numbers in parentheses are the RSS of this with the ground station CEP's (assumed to be $50'$). The curves are symmetrical about the X-axis. The dotted circles represent LOS limits. The distance between stations is 25 NM. Along the X-axis, the intersection angle is 0° or 180° and the error factor approaches infinity. The figure illustrates the impact of ground station survey error on position location accuracy as compared to repeatability or precision.

3.3.1.2 Line-of-Sight Coverage

Flat terrain topography will most likely require the greatest number of ground beacons due to horizon limited LOS. At any point in the survey grid, you require a minimum of two stations in view which, together with altitude and dead reckoner data, define position. Even when there are two stations in view, as the aircraft approaches the line connecting the two stations, the GDOP effect magnifies ranging errors. Figures 3-6 and 3-7 show the type of coverage for stations laid out on a square pattern and a rhombus pattern (25 NM LOS is assumed). We see that siting ground stations in a rhombus pattern is better than in a square pattern, since, for the latter, interior regions always have at least three

FIGURE 3-4. CEP MAGNIFICATION VERSUS INTERSECTION ANGLE

CEP CONTOURS FOR
DIFFERENT ERROR FACTORS (EF)

FIGURE 3-5

FIGURE 3-6. LOS COVERAGE - GROUND STATIONS FORM SQUARE PATTERN

FIGURE 3-7. LOS COVERAGE - GROUND STATIONS FORM RHOMBIC PATTERN

stations in view.

There is a cost trade-off that can be made for flat terrain. If the terrain is easily accessible, one could relax position location accuracy, install fewer stations (at least one station in view at all times), and use a high flyer. Figure 3-8 illustrates a possible ground station siting pattern.

$$\text{LOS} = 25 \text{ NM} = 1''$$

LOS COVERAGE - 1 STATION IN VIEW PLUS HIGH FLYER

FIGURE 3-8

3.3.2 Dead Reckoner (DR)

The survey aircraft presently being used to perform NURE surveys carry good quality DR's - inertial navigation systems or precision attitude heading reference and Doppler radar systems (AHRS/Doppler). We have recommended (see Section 2.1.1) that these systems be retained and integrated into the survey aircraft FPRS (i.e., the DR output data is made available to the FPRS computer).

Both DR types have position location errors which increase with time and therefore must be aided in some way (e.g., position location range measurements) to limit the errors. Some of the major differences between the two types are:

- (1) The short-term or instantaneous velocity for a Doppler system is not as accurate as that obtained from an INS.
- (2) Unlike an INS, Doppler radar requires that an external antenna be mounted on the aircraft.
- (3) For an INS, navigation is substantially independent of vehicle maneuvers.
- (4) An INS provides the most accurate means of measuring azimuth and vertical on a moving vehicle.
- (5) A Doppler navigation system does not require preflight alignment or warmup.
- (6) Generally Doppler navigation systems cost less than INS's.

The aided dead reckoner will provide navigation data (this will actually be generated in the FPRS computer) to some type of pilot display which will allow the pilot to follow selected survey flight lines. If all the ground stations are obstructed for a short while, the DR will provide navigation data relative to the last position fix. The increase in position location error will depend on the characteristics of the DR. For example, if all ground stations are obstructed for 10

seconds and the survey aircraft carries a 2 NM/hr DR, the position location error will increase approximately 33' (CEP) over that obtained at the last fix. Thus, disregarding cost, there is preference that the survey aircraft carry an INS which generally is more accurate than a Doppler navigation system. The excellent short term accuracy of an INS is well complemented by intermittent (low frequency) DME fixes.

The high flying aircraft will have line-of-sight to three or more ground stations. The high flyer's DR can be updated more frequently and therefore can be of lower quality (e.g., Doppler/AHRS) and cost less. If the time between the high flyer's position fix and the survey aircraft's range measurement to the high flyer is small enough, errors in the high flyer's DR data will not be significant.

Since the high flyer aircraft may not be used frequently during the survey, it would seem desirable to have the FPRS equipment packaged to afford easy installation and removal from the aircraft.

3.3.3 Data Link

The FPRS requires a digital data-link for communications between the high flyer and the survey aircraft. To estimate the data rates involved for the FPRS application, consider the sequence of operations where the high flyer ranges on four ground stations and reports this data and DR data back to the survey aircraft. The following data is transmitted:

* 4 station ID's	48 bits
* 4 ranges	72 bits
* baro-altitude	13 bits

* latitude	19 bits
* longitude	19 bits
* track angle	12 bits
* ground speed	16 bits
* status	4 bits

203 bits

There will also be some bits required for message protocol and error detection/correction, but, even if this sequence is performed 10 times per second, a data rate capability of approximately 2 kilobits/second would suffice.

3.4 System Performance Analysis

Before discussing error source, we first define what we mean by precision (repeatability) and accuracy in the context of aerial survey operations.

We overfly, many times and at different headings, a physical landmark which has been surveyed and record the FPRS-determined position when we "on-top" the landmark. One measure of accuracy is the mean error (i.e., the difference between the actual surveyed position location and the mean position location determined from FPRS data). See Figure 3-9A.

A measure of the precision or repeatability is given by the standard deviations about the mean latitude and longitude. Another measure would be the CEP relative to the mean, i.e., the radius of a circle centered on the mean position which encloses 50% of the position location points.

The operation of flight path recovery, entails among other things, returning at some later time to a point or points on the originally flown ground track for the purpose of taking ground samples. If the return is accomplished by reinstalling FPRS ground stations in their original locations, then repeatability or precision is the important system performance characteristic. On the other hand, if the return is accomplished by installing FPRS ground stations at other known locations or by transporting a TRANSIT receiver, then both accuracy and precision are important system characteristics.

Flight guidance performance depends not only on FPRS but also on the pilot (or some autopilot system).

With reference to Figure 3-10 the solid lines (A) represent pre-survey planned flight lines with spacing d along which the survey

FIGURE 3-9A. METHOD FOR CHARACTERIZING SYSTEM PERFORMANCE
RELATIVE TO GROUND POINT RECOVERY

FIGURE 3-9B. METHOD FOR CHARACTERIZING SYSTEM PERFORMANCE
RELATIVE TO FLIGHT GUIDANCE

TRACKING PRE-SURVEY FLIGHT LINES

FIGURE 3-10

aircraft is supposed to fly. Line B represents the path flown as determined by FPRS. Along any flight line segment of length 4 miles or greater, the allowed deviation between A and B is not to exceed $0.25 d$ (unless necessitated by terrain, safety, legal restrictions). Data is accumulated and recorded for segments B12, B23, B34, etc. Radio-metric and other data collected along these segments is associated with the ground points located midway along each segment (e.g., ground point C is associated with data collected along segment B34). See Figure 3-10.

For the initial survey, flight guidance along prescribed lines appears not to be that critical. However, there are situations where one would like to fly as close as possible along the same trajectory or ground track. For example, during the survey, a short test line (~ 5 miles) adjoining the base of operation must be flown at the beginning and end of each days production to check repeatability of system performance. This could be accomplished by flying against physical landmarks such as logging roads and/or railroad track.

We can define flight guidance performance in an operational sense. Consider the following experiment (see Figure 3-9B). An FPRS equipped aircraft flies along some physical landmark (e.g., railroad track); as the aircraft "on-tops" certain points A,B,C, etc. (e.g., road crossings) FPRS-determined position is recorded; many flights are made. A cross-track deviation mean ($d_A, d_B, \dots$) can be calculated at each crossing (A,B,...) where the position of the intersection is known. The closeness of these "deviation means" to zero is a measure of flight guidance accuracy, while the variance about the means is a measure of flight guidance precision.

We now examine those error sources which contribute to the accuracy and precision of flight path recovery and flight guidance.

3.4.1 Position Location Error Sources

3.4.1.1 Ranging Error

There are a number of error sources which contribute to the overall ranging error which in general consists of random components and non-random or bias components. The latter can in principal be removed by calibration whereas the random errors can be reduced by averaging many measurements. In a pulse DME system a pulse is transmitted by the interrogator unit which at the same time opens a gate and starts counting clock pulses. The transponder receives the pulse and then there is usually some controlled delay before the transponder transmits the reply pulse (to prevent interference between the transponder's receiver and transmitter unit). The interrogator receives the pulse from the transponder, closes the gate thus stopping the clock count, subtracts any known delay in the transponder to obtain two-way transit time. Multiplying this by the velocity of propagation and dividing by 2 gives the range which must then be corrected for refraction effects. With reference to this operation, the following errors occur.

If the clock frequency drifts, the transit time will be in error by $N \delta T/2$ where N is number of clock pulses and T is the error in clock period. This clock error is a scaling error proportional to range. In addition, a bias error results if the transponder's delay (e.g., determined by a clock) is different from that allowed for by the interrogating unit. Clearly any uncalibrated delays (e.g., changes in receiver or antenna cabling delay after calibration) in the system will cause a bias error (the range measurements will average long or short of true range).

There is the basic clock quantization error - plus or minus one-half the least significant digit; for example, if a 75 MHz clock rate is used for an interrogate-respond ranging system, 1 count corresponds to 2 m and the quantization error is ± 1 m.

With leading edge timing there will be a timing error which depends on signal strength (a large amplitude pulse will appear to arrive earlier than a corresponding small amplitude pulse). This amplitude dependent bias error is clearly range dependent. There are a number of techniques (e.g., automatic gain control) used to reduce this error source.

Reflections of radiated signals from terrain or aircraft structures are added coherently to the direct signals causing distortion of the received signal and a corresponding timing or phase error. These multipath effects depend strongly on geometry and the composition of the reflecting surface. Pulse DME's seem to fare better than CW DME's with regard to their susceptibility to multipath since they allow the receiver to recognize the signal that has arrived by the ~~most~~ direct path.⁽¹⁰⁾ However for pulse DME'S, multipath due to short path differences can distort the leading edge of the pulse and thus introduce timing error. Techniques and design features which reduce multipath are discussed in Section 5.2.1.

Atmospheric conditions can also cause errors in making range measurements. To determine path distance, the transit time must be multiplied by the velocity of light ($v = c/n$) where c is the velocity of light in vacuum ($299792.5 \pm .2$ km/s, NBS 1962 best estimate) and n is the average index of refraction along the path. For radio waves the empirical formula for the index of refraction (n) of the atmosphere is⁽¹¹⁾

$$N = (n-1) 10^6 = 79 P/T - 11 p/T + 3.8 \times 10^5 p/T^2$$

where P = barometric pressure in millibars (1 mm Hg = 1.333 mb)

T = temperature in degrees Kelvin

p = water vapor pressure (mb)

N = refractivity

P and T will be measured at aircraft flight level and used to calculate the index of refraction; however, there may be a difference between this calculated value and the average value over the ray path. In addition, since the index of refraction changes as a function of altitude, the distance along the ray path between two points is greater than the straight line distance between the points. For low elevation angles, this bias error can be significant. Figure 3-11 shows this bias error for an exponential reference atmosphere [$N(h) = 313 \exp(0.04385h)$, h in kilofeet]⁽¹²⁾. Deviations from the assumed atmospheric model result in bias errors.

The basic one sigma timing accuracy for a pulse type DME measurement is given by

$$\sigma_t = T_r / \sqrt{2S/N}$$

where T_r is the rise time of the pulse and S/N is the signal-to-noise ratio. The effect of random errors on precision can be reduced by averaging, so long as the dynamics of the situation don't introduce further errors.

3.4.1.2 Station Survey Errors

Errors in the position location of ground beacons impact on the

FIGURE 3-11. RANGE BIAS VS RANGE

accuracy of survey aircraft position location (see Figures 3-13,14,15). Several trade-offs are possible. If the beacons are re-emplaced at the same locations when the survey returns to ground points under the flight path, then errors in original ground beacon location are not important. If this is not the case, but the terrain is easily accessible, then larger errors in ground beacon location can be tolerated [and initial TRANSIT survey time can be appropriately reduced].

When FPRS is in a high flyer mode, the high flyer is acting like an airborne reference beacon whose position location error is clearly greater than that of a ground reference station. This is then a less accurate position location mode necessitated by LOS restrictions.

3.4.1.3 Altitude Error

The barometric altitude error contributes to the latitude/longitude position error along the survey aircraft ground track. The propagation of altitude error into the final error is treated more generally in Section 3.4.2. From a qualitative point of view, Figure 3-12 illustrates the geometrical dependence of the altitude error contribution to the final error. In Figure 3-12, two range measurements (R_1 , R_2) define a circle centered on a line (Y-axis) connecting the two stations (two ground stations or 1 ground station and the high flyer). In general the plane of the circle is perpendicular to the plane formed by the Y-axis and the vertical (not necessarily the Z-axis unless the X-Y plane is parallel locally to the reference ellipsoid which is usually not the case). The altitude error defines an arc on the circle of position - this arc is projected onto the reference ellipsoid to obtain the contribution of altitude error to latitude/ longitude error. The worst case is when the

POSITIONING MODE
2 RANGE MEASUREMENTS & ALT.
FIGURE 3-12

high flyer is over the ground station (plane of circle is parallel to MSL or reference ellipsoid); then the altitude measurement does not localize position on the circle. The best case is when the plane formed by the survey aircraft and the two stations is nearly parallel to MSL.

Typical accuracies for a barometric altimeter are given in Section 2.1.5.2. Bias error can be removed by overflying a ground station of known elevation and making range measurements. However, the fact remains that the use of barometric pressure to derive elevation necessitates assumptions about the structure of the atmosphere. Errors can occur due to variations in the lapse rate, the height of the tropopause, and sea-level temperature and pressure.

3.4.1.4 Position Report Errors

Any error that occurs in the transmission and receipt of the position report will cause an error in the position location of the survey aircraft. There are a number of coding techniques which can be used to keep this type of error insignificant. Since the data rate is not high, the simplest technique might be redundant transmission. Parity bits and a checksum could also be transmitted. Furthermore, if the high flyer's dead reckoner data is transmitted, this data would serve to check whether one of the more significant bits had been dropped. Any quantization error in encoding the high flyer's data could be made insignificant.

3.4.1.5 Computational Errors

Computational errors arise from the choice of algorithms used to solve the navigation equations and the finite word size of the computer. Detailed computer simulations are required to evaluate the navigation/

position location algorithms. The impact of finite computer precision on solution convergence must also be considered.

(Continued on next page)

3.4.2 Position Location Error Analysis Program

We use the method of least-squares to determine an estimate of aircraft position. This estimate is then used to generate the position error matrix (variance-covariance matrix). A random number generator is used to generate range data (aircraft - to - transponder) and aircraft altitude data from a normal distribution with an appropriate mean and standard deviation. The aircraft position is first determined using this pseudo-data which constitutes the initial guess (x_i^0 below).

The least-squares method requires that we find that aircraft position, x_i ($i=1,2,3$), which minimizes the expression

$$\sum_j w_j \left(M_j^2 - \sum_{i=1}^3 (x_i - x_i^j)^2 \right)^2 \quad (1)$$

where x_i^j ($i=1,2,3$) is the location of the j -th transponder and M_j is the ranging measurement to the j -th transponder. The w_j 's are weight functions describing measurement uncertainties. We linearize this problem by expanding x_i about some initial guess or estimate x_i^0 .

$$x_i = x_i^0 + \xi_i$$

If we substitute this expression into equation (1) and drop terms of order ξ_i^2 , we obtain

$$\sum_j w_j \left(M_j^2 - \sum_{i=1}^3 (x_i^0 - x_i^j)^2 - 2 \sum_{i=1}^3 (x_i^0 - x_i^j) \xi_i \right)^2 \quad (2)$$

To find the ε_i which minimizes equation (2), we differentiate with respect to ε_i and set the resulting expression equal to zero to obtain

$$\sum_j w_j \tilde{M}_j^2 u_{kj} = 2 \sum_j w_j u_{ij} u_{kj} \varepsilon_i \quad (i, k=1, 2, 3) \quad (3)$$

where

$$\tilde{M}_j^2 \equiv M_j^2 - \sum_i (x_i^o - X_i^j)^2 \quad (3a)$$

and

$$u_{ij} \equiv (x_i^o - X_i^j) \quad (3b)$$

Equation (3) is a set of three simultaneous equations which can be solved for ε_i . Expressing equation (3) in matrix notation, we have

$$\vec{b} = \vec{\bar{m}} \vec{\varepsilon} \quad (4)$$

where we define

$$[\bar{m}]_{ki} \equiv 2 \sum_j w_j u_{kj} u_{ji}$$

and

$$b = \sum_j w_j \tilde{M}_j^2 u_{kj}$$

The aircraft position is therefore

$$\vec{X} = \vec{X}^o + \vec{\varepsilon} = \vec{X}^o + [\bar{m}]^{-1} \vec{b} \quad (5)$$

To compute the variance - covariance matrix, we make use of equation (3). Differentiating both sides of the equation and rearranging terms, we obtain

$$\begin{aligned} & 2 \sum_j w_j M_j u_{kj} \delta M_j - \sum_j w_j \tilde{M}_j^2 \delta X_k^j \\ & + 2 \sum_{i,j} w_j [u_{kj} u_{ij} + u_{kj} \varepsilon_i] \delta X_i^j \\ & + 2 \sum_{i,j} w_j u_{ij} \varepsilon_i \delta X_k^j = \sum_i m_{ki} \delta \varepsilon_i \end{aligned} \quad (6)$$

Defining $\vec{\delta}$ to be the left-hand-side (LHS) of equation (6), we can rewrite this equation as

$$\vec{\delta} = \vec{\bar{m}} \vec{\delta \varepsilon} \quad (6a)$$

The position variance - covariance matrix, $\overline{\overline{ERR}}$, is given by

$$\overline{\overline{ERR}} = (\delta \vec{e})(\delta \vec{e})^T = \overline{\overline{m}}^{-1} \vec{\delta} \vec{\delta}^T (\overline{\overline{m}}^{-1})^T \quad (7)$$

where superscript T means matrix transpose. By inspection of the LHS of equation (6), we see that $\vec{\delta}$ can be written as a product

$$\vec{\delta} = \overline{\overline{G}} \vec{e} \quad (8)$$

where $\vec{e}$ is a N- component vector (N = 4n where n = number of transponders)

$$\vec{e}^T = (\delta M_1, \dots, \delta M_n \mid \delta X_1', \delta X_2', \delta X_3' \mid \dots \mid \delta X_1^n, \delta X_2^n, \delta X_3^n)$$

$\vec{e}$ contains the ranging uncertainties and the transponder position uncertainties. The $\overline{\overline{G}}$ matrix is a (3 x N) matrix. The $\overline{\overline{G}}$ matrix can be simplified by writing

$$\delta_k = \sum_j a_{kj} \delta M_j + \sum_i \overbrace{[\tilde{b}_{ij} \delta_{ik} + c_{ijk}]}^{d_{ijk}} \delta X_i^j$$

where δ_{ik} is the Kronecker delta (= 1 for i = k, 0 otherwise) and

$$\begin{aligned} a_{kj} &\equiv 2 \omega_j u_{kj} M_j \\ \tilde{b}_{ij} &\equiv -\omega_j [\tilde{M}_j^2 - 2 u_{ij} (u_{ij} + \varepsilon_i) - 2 \sum_l u_{il} \varepsilon_l] \\ c_{ijk} &\equiv 2 \omega_j u_{kj} (u_{ij} + \varepsilon_i) (1 - \delta_{ik}) \end{aligned}$$

Therefore

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{bmatrix} = \begin{bmatrix} [a_{11} \dots a_{1m}] \\ [a_{21} \dots a_{2m}] \\ [a_{31} \dots a_{3m}] \end{bmatrix} \begin{bmatrix} [d_{111} d_{211} d_{311}] [d_{121} d_{221} d_{321}] \dots [d_{1m1} d_{2m1} d_{3m1}] \end{bmatrix} \begin{bmatrix} \delta M_1 \\ \vdots \\ \delta M_n \\ \delta X_1' \\ \delta X_2' \\ \delta X_3' \\ \vdots \\ \delta X_1^n \\ \delta X_2^n \\ \delta X_3^n \end{bmatrix}$$

$$\overline{\overline{G}} = \left[\begin{array}{c|c} [a]_{3 \times n} & [d]_{3 \times (3n)} \end{array} \right]$$

If we substitute equation (8) into equation (7), we obtain

$$\overline{\overline{ERR}} = \overline{\overline{m}}^{-1} \overline{\overline{G}} (\vec{e})(\vec{e})^T \overline{\overline{G}}^T (\overline{\overline{m}}^{-1})^T \quad (9)$$

The matrix $\bar{\bar{e}} = \vec{e} \vec{e}^T$ contains all the relevant variances and covariances, that is

$$\bar{\bar{e}} = \begin{bmatrix} \delta M_1^2 & & & & & \\ & \delta M_2^2 & & & & \\ & & \ddots & & & \\ & & & \delta M_m^2 & & \\ & & & & \bar{\bar{VC}}_1 & \\ & & & & & \ddots \\ & & & & & & \bar{\bar{VC}}_m \end{bmatrix}$$

where $\bar{\bar{VC}}_i$ represents the variance - covariance matrix for the i -th transponder. We are assuming that the range measurements are uncorrelated with each other and the transponder location measurements. The latter measurements are also assumed uncorrelated with each other. If this is not the case, the $\bar{\bar{e}}$ matrix would contain additional terms.

Given the error ellipsoid for each beacon $(\sigma_{x'_1}, \sigma_{x'_2}, \sigma_{x'_3})^*$, we can construct the variance - covariance matrix in our reference frame by rotation

$$\bar{\bar{VC}}_i = \bar{\bar{R}} \begin{bmatrix} \sigma_{x'_1}^2 & 0 & 0 \\ 0 & \sigma_{x'_2}^2 & 0 \\ 0 & 0 & \sigma_{x'_3}^2 \end{bmatrix} \bar{\bar{R}}^T$$

We assume no vertical tilt to the error ellipsoid and therefore

$$\bar{\bar{R}} = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

* Note: The primed coordinates are in the ellipsoid body fixed normal axes.

where θ is the rotation angle about the z' -axis which brings the x' -axis parallel to the x -axis.

The weight function (w_j) reflects the measurement uncertainty and is normally taken to be the square of the reciprocal measurement uncertainty. For example, if we repeat a range measurement many times, we can determine a root mean square deviation (σ_j) from the mean range. Therefore, $w_j = (1/\sigma_j)^2$. Using equation (3a), we obtain

$$\delta \tilde{M}_j^2 = 2 M_j \delta M_j + 2 \sum_i u_{ij} \delta \bar{X}_i^j \quad (10)$$

If we are making range measurements to fixed transponders, the second term on the RHS of equation (10) may be dropped. However, if the measurements correspond to: (i) the survey aircraft ranging to an airborne transponder, (ii) the airborne transponder reporting its position to the survey aircraft, and (iii) the airborne transponder determining its position by range measurements to fixed ground stations; the distribution of $\tilde{M}_j^2$ values will reflect not only the ranging uncertainty, but also the transponder position uncertainty as indicated in equation (10). Thus the full expression (10) is used to calculate the weight which corresponds to that measurement.

To calculate the CEP in the horizontal plane, we express the final error matrix $\overline{\overline{\text{ERR}}}$ in normal coordinates parallel to the major and minor error ellipse axes. This can be done by using the relation *

$$\sigma_{x'}^2 = \frac{1}{2} \left\{ \sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2 + \sigma_y^2)^2 - 4\sigma_x\sigma_y(1-\rho^2)} \right\}$$

$$\sigma_{y'}^2 = \frac{1}{2} \left\{ \sigma_x^2 + \sigma_y^2 - \sqrt{(\sigma_x^2 + \sigma_y^2)^2 - 4\sigma_x\sigma_y(1-\rho^2)} \right\}$$

where the x-y projection of the $\overline{\overline{\text{ERR}}}$ matrix is

$$\begin{bmatrix} \sigma_x^2 & \rho\sigma_x\sigma_y \\ \rho\sigma_x\sigma_y & \sigma_y^2 \end{bmatrix}$$

The angle between the x' and x axes is given by

$$\theta = \frac{1}{2} \tan^{-1} \frac{2\rho\sigma_x\sigma_y}{\sigma_x^2 - \sigma_y^2}$$

The CEP is approximately (within 10%)

$$\text{CEP} = 0.589 (\sigma_{x'} + \sigma_{y'})$$

A listing of the computer program which performs the calculations of this section is given in Appendix A.

* W.A. Burt et al., "Mathematical considerations pertaining to the accuracy of position location and navigation systems", Part 1, NTIS # AD629-609, April 1966.

3.4.2.1 Some Program Results

Figure 3-13 shows the CEP-error contours for the situation where the survey aircraft (altitude $Z = 500'$, $\sigma_z = 100'$) ranges to 3 ground stations ($\sigma_r = 10'$). We are assuming that the terrain is "type A"; that is, at 500' altitude, the survey aircraft can see all ground stations. The ground station locations have errors of $\sigma_x = \sigma_y = 35'$, $\sigma_z = 28'$ (vertical error). Only a portion of the contours are shown, the remainder can be constructed from the symmetry of the ground station layout. We see that, for the reasonable uncertainties assumed, CEP errors of less than 100 feet are obtainable over a 100NM x 100NM grid.

Figure 3-14 shows CEP error contours where the survey aircraft ranges to a high flyer as well as three ground stations. The high flyer is located over the origin at $Z = 15,000'$ with $\sigma_z = 100'$ and $\sigma_x = \sigma_y = 30'$ (σ_x and σ_y are determined on basis of range measurements to the three ground stations). All other error values are as before. As one would expect, results are not much different from the first case.

Figure 3-15 illustrates a situation with two ground stations and one high flyer. The numbers are CEP values in the X-Y plane. The high flyer is at 15,000' ($\sigma_x = \sigma_y = 30'$, $\sigma_z = 100'$). Here we have a case where the plane formed by the three stations is tipped considerably from the horizontal. As the survey aircraft gets close to the plane formed by the 3 stations in the vicinity of the extended line through the ground stations (right hand lower corner of figure), the CEP values can get quite large. However, by preplanning the high flyer and survey aircraft orbits, it is possible to keep the geometry favorable with respect to GDOP.

CEP CONTOURS: 3 GROUND STATIONS

FIGURE 3-13

CEP CONTOURS: 3 GROUND STATIONS AND 1 HIGH FLYER
FIGURE 3-14

○ HIGH FLYER: $\sigma_x = \sigma_y = 30'$, $\sigma_z = 100'$, $z = 15000'$

[illegible]

FIGURE 3-15

4.0 FPRS FLIGHT TEST PLAN

4.1 Introduction

4.1.1 Purpose of Flight Test

The purpose of the flight test is to demonstrate the ability of the FPRS design concept to perform the flight path recovery functions of the NURE program and to test and demonstrate specific FPRS performance parameters and operational characteristics.

4.1.2 Flight Test Objectives

The objectives of the flight test are to test and/or demonstrate the following:

- Ranging accuracy of the PLRS DME.

- Operation of ground based transponders.

- Survey operation with survey A/C and 4 ground stations.

- Survey operation with survey A/C and 3 ground stations.

- Survey operation with survey A/C and 2 ground stations.

- Survey operation with survey A/C and 1 ground station.

- Survey operations with survey A/C, high flyer, and 3 ground stations.

- Survey operations with survey A/C, high flyer, and 2 ground stations.

- Maximum useful DME operating range.

- Pre-survey component test and calibration procedures.

- Ground station installation, site survey and recovery.

- Degraded performance and failure modes.

- Recovery of selected points along previously flown flight paths.

- Sensitivity to multipath and other perturbations.

4.1.3 Flight Test Plan Rationale

The flight test plan is guided by two main criteria:

- * Demonstrate flight path recovery to stated requirements.
- * Provide most economical means of accomplishing flight test.

To meet these criteria, the flight test plan to be described embodies the following characteristics:

1. Maximizes use of GFE equipment.
2. Minimizes use of CFE equipment.
3. Minimizes development, consistent with controlled environment of flight test.
4. Minimizes aircraft and ground station installation engineering effort.
5. Minimizes range facility requirements.
6. Demonstrates flight path recovery as required.

4.2 Flight Test System Configuration

The major elements of the flight test configuration consist of:

- * 4 ground stations
- * 1 master controller station
- * 1 helicopter survey aircraft
- * 1 fixed wing high flyer/survey aircraft
- * a range facility
- * 1 transit receiver

Table 4-1 shows these system elements with their associated hardware components.

4.2.1 Helicopter

4.2.1.1 Flight Test Functions

The helicopter has two primary flight test functions:

1. Perform low altitude survey aircraft dynamics.
2. Perform flight path recovery functions and demonstrate system precision.

TABLE 4-1

FLIGHT TEST CONFIGURATION
TABLE OF EQUIPMENT

SYSTEMS COMPONENTS	SURVEY A/C	HIGH FLYER SURVEY	GROUND STATIONS	MASTER STATION	SPARES	QUANTITY	GFE/CFE	RANGE
AIRCRAFT	1 HELO	1 FW				2	GFE	
PLRS/DME	2	1	4	1		8	GFE	
COMPUTER				1	1	2	GFE/CFE	
DEAD RECKONER	1	1				2	GFE	
COMPUTER I. U.				1	1	2	CFE	
ALTIMETERS	1	1				2	GFE	
PLRS/DATA	2	1	4	1		8	GFE	
POWER SUPPLIES AIRCRAFT GROUND STA. VAN	1	1	4	1		2 4 1	GFE GFE GFE/CFE	
TRANSIT RCVR.						1	GFE	1
TRACKING RADAR							GFE	1
VOICE RADIO	1	1		1			GFE	
RECORDER				1		1	CFE	
DISPLAY/ PRINTOUT				1		1	CFE	

The helicopter will fly a series of flight lines of varied spacing as if it were performing an aerial survey. Position location of the helicopter will be determined by multilateration. To accomplish all position modes and for the purposes of the flight test only, the helicopter is equipped with two PLRS transceivers - one whose antenna is positioned on the underside of the helicopter fuselage and one whose antenna is positioned on the top side of the fuselage. The use of two PLRS transceivers avoids incurring the expense of automating antenna switching (up/down) which would be necessary if only one transceiver were used. For purposes of the flight test, the use of two unmodified PLRS transceivers represents the most economical means of accomplishing all of the necessary position location modes. The helicopter position location is determined by two general modes: with high flyer and without high flyer. Position location modes without high flyer take place in the following manner:

1. The master station, by addressing the PLRS transceiver connected to the lower antenna, commands that PLRS to range on any or all of three ground stations.
2. The helicopter's lower PLRS will initiate ranging upon command. When all ranges to selected ground stations are obtained, the PLRS will data link all of the range data obtained from the ground stations to the master station.

The modes which make use of a high flyer will be accomplished in the following manner:

1. The master station will address the helicopter's lower PLRS and command it to range upon pre-selected ground stations. It will perform ranging and data linking as previously described.

2. The master station will then command the high flyer to range upon pre-selected stations, one of which is the helicopter PLRS transceiver connected to the upper helicopter antenna.

3. The high flyer will determine its range to pre-selected ground stations and to the helicopter and relay this data to the master station.

At pre-selected times and/or sites, the helicopter will be asked to hover during position location operation and to relay by voice communication the dead reckoned position location and altimeter data obtained from the helicopter on-board equipment.

This data will be used for purposes of equipment calibration, and to demonstrate the precision of flight path recovery (ability to return to a pre-selected site).

4.2.1.2 Helicopter Flight Test Equipment and Installation

4.2.1.2.1 Equipment

The helicopter will have as existing, installed, on-board equipment the following items of hardware to be used in the flight test (see Figure 4-1).

1. AHRS/Doppler dead reckoner
2. Barometric altimeter
3. Radar altimeter
4. Under fuselage TACAN blade antenna
5. Voice communications radio

4.2.1.2.2 Installation

The following items of hardware are to be installed aboard the helicopter:

1. Two PLRS transceivers - one connected to a bottom-mounted blade antenna and one connected to a top-mounted blade antenna.

HELICOPTER FIXED WING GROUND STATION MASTER STATION

FIGURE 4-1. FLIGHT TEST EQUIPMENT

2. Top mounted blade antenna.
3. Aircraft power/PLRS power supply interface.
4. Necessary rack and cabling.

The installation of the PLRS transceiver in a helicopter has already been accomplished during competitive tests conducted by the Army. Necessary power interfacing and rack and installation engineering has been done.

New engineering will be required to install the upper blade antenna in addition to the necessary antennae cabling.

4.2.2 Fixed Wing Aircraft

4.2.2.1 Flight Test Functions

The fixed wing aircraft has two primary flight test functions:

1. To perform high flyer survey dynamics.
2. To assist range tracking of low altitude survey aircraft.

The high flyer will fly pre-determined orbits around the ground station installation at an altitude of 10,000 feet or greater. It will always be within line of sight of the master/controller station, at least two other ground stations, the range tracking radar, and the helicopter. The range radar will determine the track of the high flyer throughout its flight. The high flyer will, upon command from the master station, determine its range from ground stations and helicopter. The high flyer will then relay all range data to the master station. This mode of high flyer/helicopter operation is unique to the flight test. It has been proposed because it eliminates the time and cost incurred to install computers with their associated software aboard both aircraft and perform system integration. An operational airborne FPRS system would have a computer, integrated with the necessary compo-

nents as described in Section 2.0 of this report, and appropriate software to establish a common navigation grid between the survey aircraft and the high flyer. In the flight test, the use of tracking radar and common surveyed ground stations, serves to establish a common grid. The option to use fully integrated airborne FPRS for flight test remains valid. The flight test described herein would remain the same in every instance except that all aircraft would in addition record all data and the tracking radar would be used to test the FPRS computer derived common navigation grid.

4.2.2.2 Fixed Wing Flight Test Equipment and Installation

4.2.2.2.1 Equipment

The fixed-wing aircraft will have as exisiting, installed, on-board equipment the following items of hardware to be used in the flight test:

1. AHRS/Doppler dead reckoner
2. Barometric altimeter
3. Under fuselage TACAN blade antenna
4. Voice radio

The following items of hardware are to be installed (see Figure 4-1).

1. PLRS DME/data link
2. Aircraft power/PLRS interface
3. Necessary rack and cabling

4.2.2.2.2 Installation

The equipment installation aboard the fixed-wing aircraft is the same as that for the PLRS Army helicopter tests with the exception of cabling length and location in aircraft. No significant installation engineering for the fixed-wing aircraft is anticipated.

4.2.3 Master Station

4.2.3.1 Flight Test Functions

The master station is the facility from which the flight test is directed. It is manned by flight test personnel and will accomplish the following functions:

- * Initiate all ranging operations
- * Initiate data relay commands
- * Receive, process and record all data relayed to the master station by both high flyer and helicopter aircraft
- * Monitor helicopter flight path during each flight
- * Maintain voice contact with flight crews
- * Initiate in-flight equipment calibration tests
- * Receive, process and record calibration data

The following represents an example of a typical sequence of flight test operations initiated and conducted from the master station:

1. Helicopter flies to pre-selected ground station and hovers directly over station at survey altitude. Crew of helicopter notifies master station personnel by voice radio that FPRS equipment is ready for calibration and, at the same time, provides the master station with the helicopter dead reckoned position and altitude.
2. Master station FPRS initiates command to helicopter to perform range measurements on all ground stations.
3. Helicopter FPRS ranges to all stations and relays range data to master station FPRS.
4. Master station FPRS compares range data with that obtained from ground station transit survey data. All data is recorded and displayed

and/or printed out. If status of equipment so warrants, the master station crew commands the helicopter to commence survey flight test.

5. If high flyer aircraft is participating in flight, the high flyer will fly to pre-arranged over-fly site and high flyer crew will notify master station crew that they are ready for in-flight equipment calibration.

6. Master station FPRS will command high flyer to initiate ranging operations on all ground stations.

7. High flyer FPRS will perform ranging operations and relay all range data to the master station FPRS.

8. Master station FPRS will record all range data and compare with range data obtained from transit survey of ground stations. In addition, the high flyer flight crew will relay by voice the aircraft's dead reckoned position and altitude.

9. Master station FPRS will compute position location of both aircraft from relayed range data.

10. Range facility tracking radar will begin tracking high flyer prior to calibration procedure.

11. To conduct flight test survey, helicopter will fly pre-arranged flight lines. Master station will initiate ranging commands to helicopter at pre-selected intervals. Helicopter will perform ranging operations and relay range data to master station.

12. Master station FPRS will record all range data and compute helicopter position location. Master station will be able to call up helicopter position location and/or track for comparison with pre-arranged flight lines. Corrections or modifications to helicopter

flight path can be accomplished by master station crew providing directions to helicopter crew over voice radio.

13. To position locate the high flyer, the master station will follow procedures as for 11 and 12. . The high flyer will range upon all stations and the helicopter.

4.2.3.2 Master Station Equipment and Installation

4.2.3.2.1 Equipment

The master station is to be housed in a mobile van so as to allow for flexibility with respect to the siting of the ground station configuration and to provide the necessary shelter and support facilities for flight test personnel manning the master station. A van suitable for the purposes of the flight test was used in the Army tests of the PLRS.

The following items of equipment and software are to be housed in the van (see Figure 4-1).

- * PLRS/DME
- * Computer/processor
- * Computer software
- * Data recorder
- * Data printout/display
- * FPRS flight test controls
- * Voice radio
- * Component test and system support equipment.
- * Power system

4.2.3.2.2 Installation

No special installation requirements are apparent at this time. Installation requirements will be dictated by the size of the master-station van and the personnel accommodations desired (desk space,

heating, air conditioning, feeding and toilet facilities).

4.2.4 Ground Stations

4.2.4.1 Flight Test Functions

Each ground station has two flight test functions:

1. To mark a TRANSIT surveyed site.
2. To respond to interrogations from the helicopter and high flyer FPRS.

There are four (4) such ground stations to be arrayed about the master station. The array of four ground stations functions as the points of a position location grid reference in which both the helicopter and the high flyer are position located.

4.2.4.2 Ground Station Equipment and Installation

4.2.4.2.1 Equipment

The ground station equipment consists of:

- * A General Dynamics PLRS DME
- * A General Dynamics PLRS power supply
- * A rack or stand to mount the PLRS equipment at the ground station site.

4.2.4.2.2 Installation

No special installation procedure is required. We recommend that installation be as simple as possible. However, we recommend that the PLRS be placed in a simple lightweight container to protect it from the weather, and that it be fixed to the ground to keep the antenna upright.

4.2.4.2.3 Ground Station Siting Geometry

The recommended configuration of the ground stations for the

flight test is shown in Figure 4-2. The ground stations are placed at the corners of a square which is 24.6 n. mi. on a side. Figure 4-2 shows four ground stations A,B,C,D arranged about the master station E placed in the center of the square. The letters contained in areas bounded by the arcs of the circles about each ground station indicate which ground stations are within line-of-sight from the bounded area and from an altitude of 400 feet. The circles about the ground stations all have a radius of 24.6 n. mi.

The helicopter survey aircraft will fly flight lines which are parallel to the side of the square. This will allow for data to be obtained along a flight line such that the effects of GDOP can be evaluated and such that variations in survey modes (number of stations within line-of-sight) can be obtained. The helicopter flight paths will be discussed in more detail in Section 4.3.1, "Helicopter Test Flights".

4.2.5 TRANSIT Receiver

4.2.5.1 TRANSIT Receiver Functions

The TRANSIT receiver has two functions in the flight test:

1. It is used to provide accurate geo-referenced survey of the ground station sites.
2. It is used to determine the geo-referenced coordinates of "markers" dropped by the helicopter or emplaced by ground personnel.

The second function is used to gather data with respect to system precision and to allow for the analyses of position errors.

4.2.5.2 TRANSIT Receiver Equipment and Installation

The TRANSIT receiver used for the flight test will not require additional equipment. It is to be carried in a vehicle with no special installation requirements.

A,B,C,D: GROUND STATIONS

E: MASTER STATION

FIGURE 4-2

GROUND STATION CONFIGURATION
AND
LINE-OF-SIGHT COVERAGE (HELICOPTER AT 400 FT.)

4.2.6 Range/Tracking Facility

4.2.6.1 Flight Test Functions

The range/tracking facility will provide the following for the conduct of the flight test:

1. Land area for ground station configuration and for master station siting as described in Sections 4.2.3 and 4.2.4.
2. A tracking radar to position locate and track the high flyer aircraft. Position location data should be acquired every half second of high flyer flight. All tracking radar data should be recorded.
3. A print out and/or a plot of high flyer flight path is to be provided as soon after a test flight as possible (next day).
4. Range safety and conditions for flight safety are range facility responsibility.

4.2.6.2 Range Facility Equipment and Installation

It is presumed that the range facility will meet all equipment and facilities requirements to perform its test functions. It is also possible however, that the range facility may have additional equipment and facilities for use by the master station such as the van, power generators, CRT display, computer(s), recorders and print out equipment.

One capability that would be useful during the flight test is the provision for communications between flight test personnel manning the master station and the tracking radar. This would permit the master station to confirm the status of high flyer tracking during a test flight.

4.3 FPRS Test Flight

A test flight is defined herein as having three phases. Phase I entails the preparation and ground testing of FPRS components, briefing of the the flight crew, and flight to the test range. Phase II begins when the helicopter is within range of the master station FPRS and/or when the fixed wing aircraft is within range of the range tracking radar and the master station FPRS. The following events take place during Phase II of a flight:

- * All aircraft fly pre-determined flight paths.
- * FPRS in-flight performance is measured and recorded.
- * In-flight calibration of airborne FPRS takes place.
- * When high flyer is in use, range radar tracks high flyer.

Phase II ends and Phase III begins when, after final calibration of airborne FPRS is completed, the master station flight test personnel (director) commands helicopter flight crew to return to base. Phase III encompasses the return of all aircraft to their base. Upon landing, a check of FPRS component operating status is conducted as in Phase I and flight crew records relevant flight history. The test flight descriptions in Section 4.3.1 are confined to the Phase II portion of an FPRS test flight; the activities which take place during the on-range period of any given test flight.

4.3.1 Helicopter FPRS Test Flights

The flight test plan calls for the helicopter to perform the functions of a survey aircraft regarding flight paths flown and aircraft altitudes. Helicopter test flights will vary in flight line spacing and in altitudes at which the flight lines are flown. These

variations may take place within a single test flight or from flight-to-flight.

4.3.1.1 Helicopter FPRS Calibration

The master station will initiate ranging commands shortly before the expected time-of-arrival of the helicopter on range. These ranging commands will occur every 0.5 seconds. The helicopter should be approximately 800 ft. above the ground upon entering the range, (see Figure 4-3).

Voice contact will be established between the helicopter and the master station at which time the flight crew will confirm their readiness to proceed with the test. The helicopter will proceed to a pre-selected ground station and hover 800 feet over the ground station. At this altitude, all ground stations should be within line-of-sight of the lower FPRS* antenna. Thus, ranging data from all stations will be acquired and relayed to the master station by the helicopter lower FPRS. The master station is now able to determine the following:

- * Does helicopter lower FPRS antenna operate?
- * Do ground stations operate?
- * FPRS-computed position location of helicopter.
- * Comparison of FPRS-computed helicopter position to TRANSIT-determined-position of ground station.
- * Accuracy and precision of individual ranging measurements to determine operating status of all FPRS.

Figure 4-4 shows the calibration process. For flights which involve the use of a high flyer, the high flyer will be calibrated as described in Section 4.3.2. Operational status of the helicopter upper FPRS will be tested using the high flyer ranging data.

* NOTE: There are two PLRS units onboard the helicopter, one connected to a bottom-mounted antenna ("lower FPRS") and one connected to a top-mounted antenna ("upper FPRS").

FIGURE 4-3

LINE-OF-SIGHT COVERAGE (HELICOPTER AT 800 FT.)

FIGURE 4-4

CALIBRATION OF DOWNWARD-LOOKING HELICOPTER FLIR

4.3.1.2 Helicopter Test Flight Profile

Helicopter test flights will be flown at two different flight line spacings - two nautical miles and five nautical miles- and at two different altitudes - 400 and 800 feet.

Figure 4-5 shows the general flight path which will be flown at both altitudes and flight line spacings. In this instance, the helicopter enters the range and proceeds to ground station A and hovers. Thus, at position 1, the calibration procedure as described in Section 4.3.1.1 takes place. The helicopter then flies the pre-planned flight line spacing and starts to fly flight lines as shown. It should be noted that the helicopter FPRS will be ranging to all stations and relaying the range data to the master station once every half-second of flight. At position 2, and with the helicopter at 400 feet altitude, the helicopter lower FPRS will be in line-of-sight with ground stations A, B, C, and the master station (See Figure 4-2). Position location computed with respect to baselines AB and AC will be degraded by GDOP to a greater degree than position location computed with respect to BC. The impact of GDOP, with respect to any baseline, will vary along the flight lines with the smallest effect occurring in the region of position 3. At position 3, the lower FPRS will be in line-of-sight to all ground stations and the master station. Position 3 could also be used as a calibration point if the helicopter hovers over the master station which would be sited at position 3 (not shown in Figure 4-5). Position location data in the region of position 3 will be computed with respect to baselines AB, BD, DC, and AC. At position 4, the helicopter will hover over station D and the helicopter FPRS will again be calibrated. The helicopter will proceed to fly the flight lines as shown,

FIGURE 4-5

GENERAL HELICOPTER FLIGHT PROFILE

thus returning to station A, its point of calibration at the beginning of the test flight. The helicopter FPRS will undergo final calibration after which the helicopter will return to base (position 5). The helicopter will fly at a uniform speed of 100 knots. At each calibration point, the helicopter crew will report by voice radio their position location and altitude as read from the dead reckoner and the barometric altimeter.

Flights at 400 feet altitude will produce data such that for each point where position location is computed, at least two independent computations of helicopter position using two different baselines, will be available. The flight shown in Figure 4-5 will take approximately three hours to complete. The helicopter FPRS can be calibrated approximately every 45 minutes of flight.

The same flight lines will be flown at 800 feet above ground. At 800 feet, all stations will be in line-of-sight of the lower FPRS at all times. The 800 foot data will be considered as baseline data for determining FPRS precision and accuracy. All FPRS calibrations will be done 800 feet above ground.

It is possible that the helicopter can not carry sufficient fuel to stay on range to fly all the flight lines in a single flight. This is especially true for the two mile flight line spacing. Helicopter time on range will also be dependent upon the distance between the helicopter home-base and the test range.

Ending a flight at position 3 or 4 of Figure 4-5 poses no problem. It is a simple matter to begin a flight at a calibration point. However, ending a flight at a position other than a calibration point and later returning to that point is a measure of FPRS precision and represents

an operation that could be required in an actual survey. Therefore, it is suggested that this type of precision test be required in some of the flight tests. The return to the starting point will be accomplished in the following manner:

- * At that point on the flight line when it is decided to terminate a flight, the helicopter crew will drop or otherwise emplace an easily visible marker prior to leaving the flight line. The master station will note that a marker has been placed at that position.
- * On some subsequent flight, the master station using present position location data, will attempt to direct the helicopter to the previously marked position. When the master station believes the helicopter to be on the marker, it will notify the helicopter by voice radio to hover, and small position adjustments can be made. The helicopter crew will then be able to visually confirm whether or not they are over the mark. If not over the mark, either visual estimates or actual measurements of the position error can be made.

4.3.2 Fixed-Wing Test Flights

The fixed-wing aircraft will perform the functions of the high flyer and will not be required to fly survey aircraft flight lines. However, if it is desired, the fixed-wing aircraft could fly flight lines and be position located as for the helicopter.

4.3.2.1 Fixed-Wing FPRS Calibration

Figure 4-6 shows a ground station/master station configuration, a range tracking radar and a high flyer aircraft. Phase II of the high flyer flight begins when the high flyer aircraft is in line-of-sight to both the tracking radar and the master station. The high flyer will fly at the minimum altitude which allows it to be detected by both the range tracking radar and the master station during its flight. The minimum acceptable conditions are shown in Figure 4-6. In this case, the high flyer can be tracked by the range radar only when it overflies one ground station. A more useful relationship

FIGURE 4-6
CALIBRATION OF FIXED WING FPRS

between the ground stations, the high flyer, and the tracking radar will result if the high flyer is in the tracking radar beam as it overflies any ground station. To calibrate the high flyer FPRS, the procedure is the same as for the helicopter except that the fixed-wing aircraft cannot hover over the ground station. Instead of hovering, the high flyer will fly over a ground station at least twice. The crew of the high flyer will also report over voice radio the dead reckoned position and the barometric altitude at the time of overflight of the ground station. During the period of overflight and the total time on range, the high flyer will perform FPRS ranging operation to all ground stations every half-second of flight in addition to being tracked by the range radar. The high flyer FPRS will also range upon the helicopter upper FPRS if the helicopter is on range. All high flyer range data for each half-second interval will be relayed to the master station. The high flyer flight path will be an oval (racetrack pattern) approximately 30 nautical miles in its longest dimension. It will be flown so that the following conditions are attainable throughout the flight test:

- * The high flyer is always within line-of-sight of both the Master Station and the range tracking radar.
- * If the helicopter is on range, the high flyer must, in addition to the first conditions, always be within line-of-sight to the helicopter upper FPRS.
- * The high flyer will overfly a ground station at least once for each time it completes a revolution of its flight path.

4.3.3 Extended Range Option

The General Dynamic's PLRS DME is described as having a maximum operating range of approximately 100 nautical miles. There are times when this long range capability can be used to reduce the number of

ground stations required to survey an area. We can characterize three different kinds of terrain that will be encountered during actual survey operations as follows:

- * Type "A": Terrain which is essentially flat, but where there are surrounding hills, mountains or man-made elevations.
- * Type "B": Terrain which is flat and horizon-limited.
- * Type "C": Terrain with topographic features which cause frequent LOS shadowing of survey AC from ground stations.

A flat earth terrain is called for in the ground station configurations shown in Figures 4-2 through 4-6. Thus, flights have been described which will test operations over flat earth terrain.

For a terrain with obstructions, we have called for the use of a high flyer aircraft and ground stations and have described the use of the high flyer.

We now consider type "A" terrain. We recommend that test flights be conducted under the following conditions:

- * Ground stations are to be placed on sites which are at least 3500 feet higher (above sea level) than the surface of the terrain to be surveyed or flown over.
- * At least two ground stations should be placed so that a baseline (the distance between stations) of 50 to 75 nautical miles long is obtained.
- * The Master Station is to be placed on a third elevated site or co-sited with one of the ground stations.
- * The helicopter is to fly flight lines as shown in Figure 4-5. The areas to be surveyed however can be of the order of 50 x 50 nautical miles, and can be as much as 75 to 85 nautical miles distant from the ground station baseline. The helicopter is to fly at an altitude of 400 feet. The helicopter upper FPRS will perform all ranging and data relays.
- * TRANSIT surveyed "markers" are to be placed at various sites in the survey area.
- * Helicopter overflight of the surveyed markers will be used to calibrate and test the accuracy and precision of the extended range performance of the FPRS.

4.4 Flight Test Data Collection and Management

There are two groups of data to be collected from aircraft during Phase II flight.

- * Data collected by the master station.
- * Data collected by the range tracking radar.

4.4.1 Master Station Data Collection and Management

Data collected by the master station from both the helicopter and the high flyer will consist of:

- * All ranging measurements obtained from ground stations following the master station ranging command. A ranging command is emitted every half-second of flight.
- * The aircraft dead reckoned position and altimeter altitude at calibration points.

The master station FPRS computer and controls/display are to provide for the ability to compute and display or point out the position location and track of the helicopter and/or the high flyer. It should be possible to compute and display an aircraft's position and track within 10 seconds from the time the data for that position computation was acquired at the master station. The purpose of this near real time capability as regards aircraft position location and track is to allow flight test personnel at the master station to monitor aircraft flight paths and to validate FPRS calibrations. A cathode ray tube display which will display the position of the ground stations, the pre-planned flight lines to be flown and the flight paths being flown, computed from near real time data, is recommended. Transit surveyed coordinates of the ground stations and the master station will be in the FPRS computer.

All data obtained from aircraft during the Phase II portion of every flight will be recorded.

4.4.2 Range Tracking Radar (RTR) Data Collection and Management

The RTR will begin to acquire data as soon as the high flyer is within RTR range. The data will consist of the position location of the high flyer and the flight path generated during a test flight. RTR data will be considered the baseline data for high flyer position location and track to which master station FPRS data will be compared. All RTR data is to be recorded.

4.4.3 Total Data Per Test Flight

The total data for each test flight will consist of five independent sets of data:

1. Phase I, pre-flight ground test data.
2. Phase II, master station data.
3. Phase II, RTR data.
4. Phase III, post-flight ground test data.
5. Phase III, flight crew report on test flight.

It is recommended that additional flight tests not be flown until a review of the total test flight is conducted.

The flight test plan data collected as described will allow for the data to be analyzed such that all FPRS flight path recovery modes discussed in this report can be evaluated and such that the stated objectives of the flight plan set forth in Section 4.1.2 will be met.

It is noted at this point, that the master station of the flight test plan functions as a stationary FPRS, thus avoiding the costs of a fully integrated airborne FPRS at this point in time. All data collected by the master station during a test flight, in addition to other data described in this report, will be available to the flight crew of a survey aircraft equipped with a fully integrated FPRS. Thus, a survey aircraft equipped with FPRS will function as a master station with regard to ground stations and high flyer.

5.0 SUBSYSTEM CANDIDATE EQUIPMENT CONSIDERED

5.1 Hardware Evaluation Considerations

There is a general class of evaluations to be considered when selecting any of the airborne subsystem components to perform the functions detailed in Section 2.1. These considerations are listed below:

- (a) Performance
- (b) Operational- availability, reliability, maintainability, outside service, expandability;
- (c) Cost- first cost, spares, maintenance, modifications, test equipment, training;
- (d) Physical- size, power, weight, cooling requirements;
- (e) Environmental- operating and storage temperature, vibration and shock, humidity, radio frequency interference, altitude.

Selection considerations pertaining to specific subsystems are given in the following subsections. The equipment manufacturers contacted are listed in Appendix B.

5.2 Distance Measuring Equipment (DME)

5.2.1 Selection Considerations

The overriding performance consideration in selecting a DME(s) is the ranging accuracy as this parameter limits the overall position location accuracy. The one sigma (1σ) timing-noise error, related to the ranging error through velocity of propagation, for a single measurement is given by the expression

$$\sigma_t = T / \sqrt{2S/N} \quad (5-1)$$

where T is the rise time of the pulse and S/N is the signal-to-noise ratio.

Another parameter to be considered is the operating range.

A long operating range means that when operating in the high flyer mode, the higher altitude aircraft can fly a course not severely constrained by his range to the ground stations. When in locations where there are few or no line-of-sight (LOS) obstructions and LOS is not horizon limited, a long operating range provides a larger survey grid size with fewer ground stations. Even when LOS is horizon limited, (e.g., 25 NM), a system which can operate with high precision to 100 NM or greater means a high S/N ratio at lesser distances with a corresponding decrease in timing error. For an omnidirectional antenna, operating range depends basically on radiated power and frequency.

For frequencies above 30 MHz, electromagnetic waves travel almost optically straight paths. For carrier frequencies from 100 MHz to about 3 GHz, the transmission path is highly predictable and is unaffected by time of day or season. Frequencies in this range and higher can be used for the measurement of range to geodetic accuracies. Their short wavelengths also allow the use of smaller antenna structures and ground station equipment is small and portable.

Additional considerations concerning carrier frequency selection are: (a) attenuation and (b) frequency allocation. The transmission loss (in dB) between isotropic antennas in free space is given by the expression (12)

$$L_L = 96.58 + 20 \log D + 20 \log f$$

where f is the carrier frequency in GHz and D is the distance between antennas in statute miles. Figure 5-1 shows the above relation. As can be seen, for a given operating range, more power is required as the operating frequency is increased.

FIGURE 5-1. TRANSMISSION LOSS IN FREE SPACE, ISOTOPIC ANTENNAS

The table below summarizes the operating frequencies of the DME systems surveyed (see Section 5.2).

<u>DME</u>	<u>FREQUENCY IN MHZ (BAND)</u>	<u>COMMENTS</u>
PLRS (GD)	435 (UHF)	Military use
DFCS (IBM)	915 (UHF)	Military use
RMS (GD)	918 (UHF)	Military use
ACMR (Cubic)	1788/1840 (L)	Military use
Del Norte	9480/9325 (X)	Commercial use
Motorola	5450-5600 (C)	Commercial use
TACAN	960-1215 (L)	FAA approval required; Military and civilian use.

Most of the above systems have been used by the military and the use of these frequencies throughout CONUS would require FCC approval and coordination with the appropriate military agency.

The measurement integration time must also be considered with regard to its impact on position location error. The effect of both integration time and sequential range measurements is illustrated in Figure 5-2. A range measurement to ground station 1 (GS1) commences at time t_1 and requires τ seconds. Due to constant aircraft velocity, the range determined at time t for example, is actually the range at $t - \tau/2$ (the distance between point 1 and GS1). Range measurements to other ground stations are likewise "retarded". Thus, if the aircraft position in "real time" (t') is required, it must be extrapolated forward in time (from time mark ($t_3 + \tau/2$)) using dead reckoner data. The aircraft position location (XYZ) solution at time $t + \tau/2$ (determined from range measurements, altitude data, and known ground station locations) is obtained from the following relations:

SEQUENTIAL RANGE MEASUREMENTS
WITH FINITE INTEGRATION TIME

FIGURE 5-2

$$R_1^2 = (X_{t_1+\tau/2} - X_{GS1})^2 + \dots$$

$$R_2^2 = (X_{t_2+\tau/2} - X_{GS2})^2 + \dots$$

$$R_3^2 = (X_{t_3+\tau/2} - X_{GS3})^2 + \dots$$

where $X_{t_2+\tau/2} = X_{t_3+\tau/2} + V_x(t_2-t_3) + a_x(t_2-t_3)^2/2 + \dots$

with V_x and a_x the aircraft's X velocity and X acceleration respectively. A similar relation holds for $X_{t_1+\tau/2}$.

If the integration time τ is too long and ignored in the position location computation, an error results. If it is compensated for using DR data, more computer computation is required. The same tradeoff applies to the time between range measurements.

The degradation of a DME system by multipath reflection must be considered when evaluating potential DME candidates. All DME systems, both pulse and CW, are subject to some degree of multipath degradation which depends on many factors, for example, geometry (e.g., low altitude), surface type and shape (water, mountainous, flat and sandy), antenna patterns, polarization of radiated energy. Figure 5-3 illustrates multipath situations. Propagation path #1 is the direct path. Path #2 represents an indirect path over which a pulse could travel from the ground transponder to the aircraft DME antenna and arrive later than the pulse along the direct path. Path #3 shows a situation where the interrogation pulse reflects from an obstacle and returns to the DME antenna before (or after) the pulse along path #1.

There are a number of design techniques or features which

MULTIPATH INTERFERENCE

FIGURE 5-3

help reduce multipath degradation of the signals:

- (a) Use of a wide bandwidth (ΔB) permits fast rise time pulses which, along with leading edge timing, reduces timing errors due to multipath interference. In addition, large ΔB improves the basic timing accuracy (eq. 5-1). For a FM/CW DME system a high modulation index (~ 10) reduces phase measurement multipath errors.
- (b) The ground station antenna pattern should have decreasing gain below the horizon to reduce multipath interference like that illustrated in Figure 5-3 (Path #2). It is also best to transmit vertically polarized radiation whenever possible.
- (c) Knowledge of the expected range allows the DME receiver to be desensitized or turned off until the pulse return is expected, thus preventing multipath situations as illustrated in Figure 5-3 (Path #3).
- (d) Track smoothing using dead reckoner data prevents erroneous range data from being heavily weighted in the position location calculation.
- (e) Transmitting more power than is required (on the basis of desired signal-to-noise and operating range) provides some margin for channel fading (destructive interference).
- (f) The use of spread spectrum techniques provides some immunity to multipath interference.

There are a number of other considerations which are self-evident, for example: the ground units must be easily transportable and not require too much power; the ground units must operate in and withstand temperature and moisture conditions appropriate to the survey regions;

the interrogating unit must withstand the vibrations and shock environment associated with survey and high flying aircraft.

5.2.2 DME Subsystems

In this section we review a number of candidate DME systems which were evaluated for use in FPRS. Some of these systems were more than just DME systems (e.g., PLRS, DFCS, RMS/SCORE); however, our interest was mainly focused on the DME function and, where it existed, the communications or data link function.

(Continued on next page)

5.2.2.1 Position Location & Reporting System (PLRS)

General Description

The Position Location and Reporting System (PLRS) is being developed for Army and Marine use. Two competitive versions of PLRS's were originally built. General Dynamics (GD) built a code division multiple access system and Hughes built a time division multiple access system. Hughes won the competition, essentially on the basis of their communication security features, and is presently developing the engineering model. Either version would be suitable for FPRS. We have elected to describe the GD version as it is less complex (no time synchronization is required).

The PLRS system was essentially a tactical version and out-growth of GD's RMS system. PLRS provides three functions: (1) a ranging function, (2) a reporting or communications function, and (3) a relay function. The system is made up of two different types of units, a master unit (MU) and user unit (UU). The master unit (MU) controls a network of several hundred users units (UU) and provides for a central display of their locations. The UU is designed for manpack operation, while functionally identical units are employed in aircraft, helicopters, and ground vehicles. Each user unit contains all of the equipment necessary to allow it to be located by the master unit and to send and receive digital messages.

The whole system is controlled by the MU which consists of real time data processing and display equipment, data recording equipment for post-test analysis, and RF equipment to link to UU's. The UU's - seventeen of which were built during the System Validation phase - provide the MU with measurements necessary for position

computation, relay data and commands among units in the system, and send or receive digital data.

Characteristics

1. Range/Accuracy

A ranging accuracy of 3m (10') out to a range of 100 NM is claimed. Range determination is based on round trip transit time of a single interrogate-respond pulse sequence. The 3m accuracy at 100 NM was based on a few tests which were performed over water.

2. Peak RF Power/ Input Power

Both the ground unit and airborne unit transmit 100 watts peak RF power and require 12 watts of input power. Ground units are battery operated. Aircraft units have an interface to adapt to aircraft power.

3. Frequency/ Bandwidth

Center frequency is 435 MHz with bandwidth (ΔB) equal to 8 MHz.

4. RF Modulation

GD's version of PLRS uses a signaling wave form of the spread spectrum type. A surface acoustic wave device (polychromatic delay line,PCDL) is used to achieve spread spectrum capability. Specifically, each time a UU or MU sends a pulse train, the data pulses are fed onto the PCDL which rings at a center frequency of 60MHz. The output signal resembles band limited (8MHz @ 3dB) gaussian noise centered at 60 MHz. This signal is then upconverted to 435 MHz. The advantage of a spread spectrum signal format over a non-spread spectrum signal format is the former's greater immunity to both

multipath and external interference. At the receiver the spread spectrum signal is fed back through the conjugate PCDL to recompress the pulse (stretched to 13 μ s) and recover the data pulse train.

5. Antenna

UU (ground) - omnidirectional dipole

UU (air) - top and bottom antennas (omni)

MU (ground) - essentially hemispherical; 7dB gain

6. Access/ Addressing

Each unit is identified by a unique 12 bit address or code.

7. Range Data Output

The range register holds 18 data bits which are transmitted serially.

8. Weight and Size

Ground unit (GU): 7.3 kg (16 lbs.) not including battery ($\sim$ 6 lbs.)

31 x 10.2 x 19.9 cm³ (electronics only)

Airborne unit (AU) : Same as for GU

9. Temperature Range

For the 17 units built for the System Validation Phase, the temperature specifications were relaxed to 0° - 50° C. For operation at temperatures less than 0° C, a heater blanket would be required for these particular units.

Data Transmission Capability

PLRS provides a two-way communications capability, but the master unit (MU) controls and schedules all activities. Four types of messages may be transmitted through the PLRS network: user data

output messages; user data input messages; network control messages; and measurement report messages (TOA data, altitude, etc.)

The UU contains an I/O device. Controls include two 10 position switches, allowing the operator to request any of 100 precoded messages by number. If the user wants to transmit data to the MU, he sets switch (00-99), loads data, and depresses transmit request button. The MU receives the user request, and requests that data be transmitted.

There is provision on the UU for a special data mode. In this mode, data would be automatically read in from some external device for transmission to the MU. For the FPRS application, this mode would be implemented.

1. Burst Transmission Rate: 150 KBPS

2. Data Modulation:

Four-ary pulse pair modulation (2 bits/pulse pair). Pair spacings are 10, 11, 12 and 13 μ s.

3. Information Rate:

The information rate is lower than the transmission rate and depends on transmitter/receiver distance, mode type (ranging, relaying, reporting) and overhead bits (preamble, address, mode, parity bits, etc.)

4. Error Control:

The data format (unique number of pulses) is checked through the network. If any error is detected, an error message is sent back to the master unit. Parity is checked at the destination. If the parity check fails, an error message to retransmit is sent.

Availability/Status

The seventeen User Units built by General Dynamics for the System Validation Phase of the PLRS program are presently in storage. With appropriate arrangements, these units could be used by ERDA/BFEC for testing FPRS.

Evaluation

PLRS can be used for FPRS. PLRS provides both a DME function and a communications function, thus simplifying system design and reducing system cost. The units provide sufficient accuracy and range to satisfy FPRS goals and have also been developed for a rugged environment. The use of spread spectrum reduces the effects of multipath or external interference.

The essential modification to PLRS would be the much simplified software for controlling a small number of User Units. A heater blanket would be required for operation outside the temperature range 0° to 50° C. Use of the special data mode in the UU's would entail building the necessary interface to automatically input or output data.

Information Source(s)

Telephone conversation with N. Lawhead, General Dynamics

Trip Report

"PLRS - A New Spread Spectrum Position Location Reporting System", J.A. Kivett, article in Position Location and Navigation Symposium(PLANS), San Diego, California, 1976

5.2.2.2 Drone Formation Control System (DFCS)

General Description

DFCS provides simultaneous location, navigation, guidance, control and telemetry functions for up to six remotely piloted vehicles (RPV or drone) plus precision location and navigation for four additional vehicles. This system was developed and built by IBM's Federal Systems Division for use at the White Sands Missile Range as a range instrumentation system.

DFCS consists of a drone control center with its interrogation station, several surveyed ground interrogation stations, and airborne systems onboard the drones. The system uses the trilateration technique (3 range measurements) to locate drones.

Characteristics

1. Range Accuracy

The range of DFCS is presently limited to 60 NM as a result of propagation time and the requirement for a 10 drone capacity (with each drone being interrogated 10 times per second). Accuracy claims within the region of coverage are as follows:

- * 23 feet (10') in absolute position and 19 feet (10') in relative position in the x-y plane
- * 9 ns timing accuracy (~ 2.7 m)

2. Peak RF Power/Input Power

Peak RF transmitted power for the drone system is 150 watts and 250 watts for the ground system. Input power for the ground unit is 45 watts.

3. Frequency/Bandwidth

The system operates at a carrier frequency of 915 MHz (L-band). If necessary, this frequency could be easily changed over a range of ± 42 MHz. The signal bandwidth (3 dB) is 10 MHz.

4. RF Modulation

The modulation is pulsed BPSK (Bi-Phase Shift Keying, $0^\circ/180^\circ$).

5. Antenna

A vertical and horizontal dipole antenna on the drone tail and another antenna on the underside of the nose provide almost spherical coverage. The ground antennas provide coverage which is omnidirectional in azimuth and $\text{CSC}^2 \theta$ in elevation.

6. Access/Addressing

Addressing is accomplished by an 8 bit address in the transmitted message.

7. Range Data Output

Range data is available as 16 bit parallel data which is transmitted serially.

8. Integration Time/Range Update

Range is determined by a single RF pulse transit time measurement; a number of measurements may be averaged or smoothed in the computer if so desired. Each drone is interrogated at a rate of 10 times per second. DFCS allows 100 ms for the entire sequence of 6 control and 4 track drones.

9. Weight and Size

Ground Station: 9.1 kg (20 lbs.), not including power source or antenna; tripod antenna weighs about 60 lbs.

61 x 38.1 x 38.1 cm

Airborne Package
(2 units)

22 kg (48 lbs.)

50.8 x 25.4 x 19 cm

30.5 x 30.5 x 7.6 cm

10. Temperature Range

Both ground and air units: -30° to +55°C.

Data Transmission Capability

DFCS incorporates the DME and data transmission functions into a common data link. A number of features were designed into the link to combat multipath interference.

1. Burst Transmission Rate

The burst data rate is 500 KBPS.

2. Data Modulation

The signal waveform was designed to combat the effects of multipath interference, as well as meet data and ranging requirements. The synchronizing preamble consists of three unique pulses: 12.7 μ s, 3.1 μ s, and 3.1 μ s in length. Spread spectrum is achieved by bi-phase coding each pulse at a 10 MHz rate (minimum time between phase reversals is 10 ns) to give processing gains (time-bandwidth product) of 21 dB and 15 dB respectively. This is called pseudo-noise or PN coding.

The received sync signal is amplitude limited and processed by a

SAW (surface acoustic wave) device. The time that the processed sync signal crosses a fixed threshold defines time-of-arrival for ranging purposes and establishes time for subsequent detection of the 4-ary (2 bits) pulse position modulated data.

The 3.1 μ s pulses in the sync preamble are separately coded (called A & B) - codes selected have low cross correlation. When received and processed, these pulses are used to establish signal acceptance level criteria as a safeguard against multipath interference.

Data is then transmitted (2 bits/4 μ s) by alternating the two BPSK (Bi-Phase Shift Keying) PN codes (A & B) in a 4-ary pulse position modulation technique. This pulse code alternation also provides a degree of immunity to multipath interference.

3. Information Rate

The transmitter was designed for a 15% duty factor so the average rate must be less than 75 KBPS.

4. Error Control

There is one parity bit for eight data bits. Two bytes are interleaved so each symbol consists of one bit from each of two bytes (byte = 8 data bits + 1 parity bit). Erasure correction permits one of nine symbols to be recaptured if not received. If multiple errors occur, a validation bit indicates an error condition and the message would be repeated.

Availability/Status

DFCS is installed at White Sands Missile Range (WSMR) and has undergone a number of tests. The equipment at WSMR includes a

command center, 6 ground stations and 10 airborne units, plus associated test equipment. This equipment was built for this specific range instrumentation application. Even if the WSMR equipment can be used to test FPRS, additional units would have to be built for ERDA survey work.

Evaluation

DFCS can be used for FPRS. DFCS provides both a DME function and a communications function, thus simplifying system design and reducing system cost. Sufficient accuracy for flight path recovery has been demonstrated. However, DFCS has not been used at 100 NM ranges and some redesign (either antenna system or RF amplifier) would be required to achieve this longer range. A number of features (including spread spectrum) have been designed into DFCS to combat multipath or external interference.

Information Source(s)

"DFCS Data Link Tests at White Sands Missile Range", IBM Report # 76-505-005, Federal Systems Division, Owego, N.Y., March 1976

"Precision Location, Navigation and Guidance Using DME Techniques", J.T. Raney and K.D. Rehm, article in Reference 13

Telephone conversations with J.T. Raney and K.D. Rehm, IBM

Trip Report

5.2.2.3 Range Measurement System (RMS)

General Description

The RMS (Range Measurement System) is essentially a multiple object multilateration (range only) tracking system, originally developed for the U.S. Army Combat Developments Experimental Command (CDEC) by General Dynamics (Electronics Division). The original system has undergone several modifications, the most recent of which is the addition of a pod which incorporates an INS to provide, in addition to other parameters, the attitude of the tracked object. This latest version is referred to as RMS/SCORE (SCORE: Simulated Combat Operation Range Equipment).

This family of systems is intended to serve a number of purposes:

- Tracking aircraft, ground vehicles and personnel to evaluate tactical exercises
- Evaluation of air-to-ground missiles
- Electronic warfare joint testing
- Aircraft fly-offs for close air support missions

The system consists of fixed ground stations (A-stations), transponders (B-stations) carried by platforms and/or personnel being tracked, relay stations (D-stations), and a master station (C-station) which controls the station network.

Characteristics

1. Range/Accuracy

Ranging accuracy is ± 3 m (1σ) and precision is ± 2 m (1σ).

Maximum transmission ranges are as follows.

C to D or A: 9 km (4.8 NM)

A to B: 64 km (34 NM)

At the time of this survey the RMS-2 system was undergoing a number of tests to assess its accuracy and to evaluate the effect of increased transmitter power. Prototype add-on high power RF amplifiers, which would bring the peak RF power from the present 12 watts to a minimum of 80 watts, were being tested. This would increase the range by a factor of approximately 2.6.

2. Peak RF Power/Input Power

	Peak Xmt Power (Min.)	Duty Cycle (Max.) %	Input Power
Micro-B unit	12	1	10.5W (+22 to +31 VDC)
A-station	5	8.5	40W (+22 to +31 VDC)
D-station	1.5	30	"
C-station	1.5	30	Not applicable

The duty cycle for any message is defined as the ratio of the transmitter "on" time to the time between starts of messages.

3. Frequency/Bandwidth

The operating frequency is 918 MHz with a bandwidth of 15 MHz.

4. RF Modulation

For range pulses the RF carrier is pulsed. For command and message pulses there are four subcarrier channels.

5. Antenna

Several antenna designs have been used in the A and B units. Two types of antenna assemblies are used with the A station; a low-angle omnidirectional dipole array used primarily for interro-

gation of transponder units installed in ground vehicles, and a high-angle shaped-beam dipole array used primarily for interrogation of airborne transponder units. For the aircraft units a TACAN blade antenna is used which gives close to omnidirectional coverage.

6. Access/Addressing

The A,B and D-stations have their own unique addresses: A stations - 7 bits, B stations -10 bits, D stations - 3 bits. Under computer control the C stations instruct appropriate A-stations to interrogate appropriate B transponders. Range data is returned to the C station.

7. Range Data Output

The range counter in the new A-stations is 17 bits (15 bits in the older units).

8. Interrogation Time/Range Update

The A-station computes the range by measuring the time required for a single, fast rise-time pulse to traverse from it to the B-station and return.

9. Weight and Size

A and D-stations (electronic assembly): 31.8 kg (70 lbs)

55.9 x 43.2 x 35.6 cm

[Note: new A-stations weigh about 13.6 kg.]

Micro B-stations:

1.4 kg (3 lbs)

3.5 x 11.5 x 20.5 cm

10. Temperature Range

The operating temperature range is -20°C to $+55^{\circ}\text{C}$. These units have been used at lower temperatures, but were enclosed in heater blankets.

Data Transmission Capability

The communications netting is under control of the C-station which receives parallel output commands from a computer and converts them to serial form for output to the field units. The commands, either ranging or digital communications, are coded with the D, A and B-station addresses which determine the path a particular command will take. A ranging command instructs a specified A-station to obtain a range on a specified B-unit. Communication commands are transferred via an A-station to the specified B-unit. The B-unit response travels the same path back to the C-station, where it is converted to parallel form and input to the computer.

1. Burst Transmission Rate

The maximum transmission rate is 200 KBPS and 100 KBPS per channel in accordance with the duty cycles previously given.

2. Data Modulation

Four subcarrier frequencies, each referred to as a channel, are used for communication purposes. Two channels are used to link station types (e.g. C to A) with data bits being alternated between channels. The four channels are used to prevent interference. Through the use of selective narrowband filters, the upper and lower sidebands of each channel are used to transmit digital

pulses on each channel as logic "1's" and "0's".

3. Information Rate

The rate at which the system can execute a series of commands is a function of the type of command (mode) as well as the distance between stations.

There are three communication modes: short communication (SCOM), extended communication A-to-B (EAB), and extended communication B-to-A (EBA).

SCOM: specified A-station is requested to transmit a 4-bit message to the specified B unit, and retrieve a 13-bit message from the B-unit in return.

EAB: specified A-station is requested to transmit a 42-bit message to the specified B-unit. The only return to this message is a single "validity" bit, indicating the B unit received the message.

EBA: specified A-station is requested to obtain a 42-bit message from the specified B-unit.

4. Error Control

The number of bits in the message are counted and the presence of either the upper or lower sideband is checked. The user can add parity bits to the data as a further check for errors.

Status/Availability

The RMS family of systems has undergone testing and been used at a number of facilities. There are RMS derivatives at Yuma Proving Ground, the joint range at Hill AFB and Dugway Proving

Ground, and Point Mugu. RMS has been used at CDEC's field experimentation laboratory at Hunter Liggett Military Reservation (California) over the last seven years.

There is the possibility that presently installed RMS equipment could be used to test FPRS, but additional units would have to be built for NURE survey work.

Evaluation

RMS provides both ranging and communication functions. Tests of RMS with the new high power RF amplifiers would have to be evaluated with regard to accuracy and operating range. RMS may be more susceptible to multipath interference than either DFCS or PLRS, both of which have spread-spectrum capability.

Information Source(s)

"SCORE (Simulated Combat Operations Range Equipment), a position location system for modern military weapons testing, training, and tactics evaluation", Report No. R-76-061, May 1976, General Dynamics, Electronics Division, San Diego, California.

"RMS/SCORE", Technical Description, Report No. RMS 2-DCS-72-1, July 1976, General Dynamics, Electronics Division, San Diego, California.

R. Gehrke, "Development of the RMS-2 System of ODDR&E (T&E)", pg. 68 in Reference 13

P.F. Hughes, "History and Development of the SCORE Pod", pg. 77 in Reference 13

Telephone conversations with J. Garcia, GD Electronics Division

Trip Report

5.2.2.4 Cubic

Cubic Corporation has several DME systems which meet the necessary range and accuracy FPRS requirements. In addition, these systems provide data link capability. Range is determined by continuous-wave (CW), multiple-tone-modulation, phase comparison measurement techniques. Some DME systems also provide range-rate based on the round trip Doppler frequency shift of the carrier signal transmitted between the interrogator and transponder; however, range-rate measurements are not required for the FPRS application. The following describes the operation and characteristics of a specific DME, the RT-1091, 1092/ URQ=22 with minor exception, which is representative of the CW class of DME's.

The operation is as follows:

- (a) The interrogator transmits the RF carrier and data link subcarrier containing the particular transponder unique binary code to the transponder
- (b) The transponder receiver phase locks to the transmitted carrier received from the interrogator, decodes the binary code, and checks for the unique transponder binary code.
- (c) Upon verification of the proper binary code, the transponder transmits the transponder carrier to the interrogator receiver. The transponder carrier is offset in frequency and phase coherent with the interrogator transmitted carrier.
- (d) The interrogator turns off the data link subcarrier and provides the range tone modulation to the interrogator carrier.
- (e) The transponder demodulates the range tones on the interrogator carrier and remodulates the tones coherently on the offset transponder carrier.
- (f) The interrogator receives the transponder carrier and demodulates the range tones to formulate the range data.
- (g) Range-rate data is derived from the information on the transponder carrier as received by the interrogator.

Characteristics

1. Range/Accuracy

The ranging error is 3 feet, 10' out to a range of 198.6 statute miles with a range resolution of 1 foot.

2. Peak RF Power/Input Power

Interrogator: 3 watts minimum output;
Power consumption $\leq$ 80 watts
($\leq$ 120 watts with blower)

Transponder: 3 watts minimum output;
Power consumption $\leq$ 50 watts
peak during normal operations
($\leq$ 6 watts in standby mode)

3. Frequency/Bandwidth

Interrogator: $f = 1630$ MHz

Transponder: $f = 1564.9$ MHz

4. RF Modulation

Phase modulation is used with the modulation index for the range tones as follows: FINE > 10 , INTERMEDIATE > 2 , COARSE > 2 , and VERY COARSE > 1 .

5. Antenna

Interrogator: elevation - $23^\circ \pm 2^\circ$, monopole pattern
azimuth - omnidirectional
peak gain - 3 dbi at $21^\circ \pm 5^\circ$ above 7'
diam. ground plane
polar. - vertical

Transponder: elevation - $32^\circ \pm 2^\circ$, monopole pattern
azimuth - omnidirectional
peak gain - 3 dbi at $27^\circ \pm 5^\circ$ above
horizon
polar. - vertical

6. Access/Addressing

Addressing is accomplished by the interrogator, uniquely addressing over the subcarrier data link, one of 255 possible transponder units.

7. Range Data Output

The interrogator provides the following data outputs:

Range - four 11-bit binary words
 Range rate - two 20-bit binary words
 Data quality - one 7-bit binary word

8. Integration Time/ Range Update

Since this unit provides range-rate to an accuracy of 0.05 ft/sec, a long averaging time (~ 1 second) must be used. Twenty range measurements per second is typical for those units which do not provide range-rate.

9. Weight and Size

Interrogator: < 30 lbs
 < 8" x 8" x 13" (not including antenna, vibration isolators, cooling air plenum)

Transponder: < 42 lbs
 < 14" x 10" x 16" (not including antenna)

Transponder Antenna & Groundplane:
 < 35 lbs
 < 4.1' x 2.1' x 1' (when folded)

10. Temperature Range

Interrogator: MIL-E-5400 (Class 1)

Transponder: MIL-E-4158
 Non-operating -62°C to +71°C

Data Transmission Capability

This system provides a two-way voice grade communications data link with a data rate of 2500 bits/second. The interrogator sub-carrier frequency is 205 KHz with a 6 KHz bandwidth. Bit error rate is less than 10^{-4} at LOS ranges of less than 50 miles. Other DME's, such as that used for the Aircraft Combat Maneuvering Range (ACMR), provide data rates of about 40 KBPS.

Availability

Although proven designs exist, units would have to be built, and delivery would take about one year.

Evaluation

The above described or similar units could provide both the FPRS DME and data link functions.

Information Sources

Brochures

Telephone conversations with D. Krenz, H. Kohnen, D. Rizzardi

"Performance/ Design and Test Requirements Specification for the Range/Range Rate Interrogator", Cubic document # SP/549-1, September 1975

"Performance/ Design and Test Requirements Specification for the Range/Range Rate Transponder", Cubic document # SP/549-2, September 1975

5.2.2.5 Del Norte Trisponder

General Description

The "TRISPONDER" consists of the following:

- * Distance measuring unit (DMU),
- * Master transmitter/receiver (MT/R) plus omni antenna,
- * Two remote T/R's (RT/R) and directional antennas.

The DMU provides signals to the MT/R for transmission to RT/R's. Signals from the RT/R's are in turn received by the MT/R and returned to the DMU to determine distance. Two separate displays show distance directly in units of meters or feet.

The DMU can be replaced by a multichannel DMU which permits ranges to 8 RT/R's (as opposed to the former 2) to be obtained within a 1-second update period. Any two ranges can be displayed, while all eight are made available at the BCD output for external use.

Characteristics

1. Range/Accuracy

Range resolution is 0.5 meter. An accuracy of $\pm 3m$ is claimed out to a range of 80 km(43NM). No statistics for the $\pm 3m$ is given. There is approximately a 10 to 12 db signal strength margin remaining in the RF link at 50 NM; at 100NM, this RF margin would drop by 6 db. Thus higher RF power would be required to maintain suitable margin at distances greater than 50 NM. This in turn would necessitate repackaging to accommodate an uprated power supply.

2. Peak RF Power/Input Power

The MT/R and RT/R's are identical except for transmit and

receive frequencies. Peak RF power is 1 KW. Input power requirements are as follows.

DMU: 23-32 VDC, 2A

MT/R or RT/R: 23-32 VDC; 0.7A (Xmt), 0.4A (stand by)

3. Frequency/Bandwidth

MT/R: Xmt. frequency 9480 MHz (X band)

Rcv. frequency 9325 MHz

RT/R: Opposite that of MT/R

4. RF Modulation

Amplitude modulation of the magnetron

5. Antenna

The airborne antenna (MT/R) is omnidirectional with 30° elevation ($\pm 15^\circ$ about plane perpendicular to antenna). The ground units (RT/R) have sectorized antennas (87° x 5° elevation, 180° x 5° elevation). Antenna gains are 16 dB and 15 dB respectively.

6. Access/Addressing

Del Norte's TRISPONDER systems use the pulse repetition interval (PRI) to identify the proper remote stations. The MT/R under control of the DMU generates a series of pulses. Each RT/R, having its own particular PRI, will receive the interrogations from the MT/R and, through its detector circuits, test the incoming signal to determine if it is the proper code. If the incoming pulses from the MT/R line up with the particular PRI to which each remote is set, the RT/R will transmit a series of pulses of the same PRI back to the MT/R. The master will then begin to detect the incoming signals from the

remote. If the return pulses meet the PRI test, the master instructs the DMU to perform distance calculations and output the valid information.

A similar system ("MULTITRACKER") can accommodate 30 addressable stations.

7. Range Data Output

BCD parallel or serial ASCII (optional) output is available and both are TTL compatible.

8. Integration Time/ Range Update

Ten (10) or one hundred (100), referred to as "10 sum" and "100 sum", are averaged to reduce random errors. For the "10 sum", 50 pulses are transmitted with the first 10 returns (not necessarily sequential) which meet certain conditions used for the average. For the "100 average", 200 pulses are transmitted. Ranges to the eight RT/R's can be obtained within a 1-second update interval and are available for display and external use.

9. Weight and Size

DMU:	11 kg (25 lbs)
	40 x 30 x 22 cm ³
MT/R, RT/R:	7 kg (15 lbs)
	36 x 16 x 27 cm ³

10. Temperature Range

DMU:	0° to 67°C.
MT/R, RT/R:	-30° to 70°C.

Data Transmission Capability

None

Availability/Status

The TRISPONDER System is commercially available with several hundred having been built over the past eight years.

Evaluation

The Del Norte system has several shortcomings regarding its use in FPRS.

It does not support the data link required for the high flyer mode. This means that a separate digital communications system would have to be installed.

Although the range (80 km) is great enough for terrains where line-of-sight is horizon limited, there are terrain topographies where greater range would mean fewer ground installations. In the high flyer mode increased range is desirable. The required high power magnetron to obtain this greater range would entail some redesign and repackaging.

The antenna patterns are restrictive, especially for use in the high flyer mode where air-to-air ranging is required.

And finally, a range update interval of 1-second is marginal.

Information Sources

Telephone conversations with J. Stegall and H. Mitchel.

Del Norte Brochures

Del Norte Report, "Results of Tests at Casa Grande, Arizona, for Bureau of Land Management, July 1976"

5.2.2.6 Motorola Mini-Ranger III

General Characteristics

The basic "Mini-Ranger III" positioning system consists of a range console, receiver/transmitter unit, and two reference stations with 13-dB antennas. The system operates in the C-band and determines range by measuring the time required for a pulse of RF energy to travel from the receiver/transmitter unit to a reference station and return. The time is converted to range by assuming the speed of light is a constant (the value used is that in a standard atmosphere, $P = 1013 \text{ mb}$, $T = 20^\circ\text{C.}$, $RH = 50\%$) and using a counter with a precise crystal clock to measure the time in range units.

Characteristics

1. Range/Accuracy

The standard unit has a range of 37 km (20 NM) with a probable error of 3 m. Reference stations normally operate with 13 dB sector antennas. The range can be doubled to 74 km (40 NM) by replacing the 13 dB antennas with higher gain 19 dB sector antennas. The probable error remains the same. A second option is available to further increase the range to 185 km (100 NM). This entails replacing the standard omnidirectional antenna on the platform (to be located) with a rotating antenna and using the 19 dB sector antennas in the reference stations.

2. Peak RF Power/Input Power

Peak RF power transmitted from the R/T unit and the reference

stations is 400-600 watts. Pulse repetition frequency for interrogating is 875 PPS. Input power required is about 13 watts (24-30 VDC). The range console use 115/230 VAC @ 50-400 Hz or optionally 24-30 VDC.

3. Frequency/Bandwidth

The system operates in the C-Band. R/T unit transmits at 5480 MHz and receives at 5570 MHz. The rise time of the pulse is typically 0.1 μ s.

4. RF Modulation

The magnetron output is amplitude modulated with a pulse width of 0.5 μ s.

5. Antenna

Reference Station: 13 dB sectored (75° x 15° elev.)

19 dB sectored (80° x 5°) - optional

Mobile R/T: 6 dB (omni, 360° x 25°)

18 dB antenna rotating @ 30RPM, (8° x 30°)- optional

6. Access/Addressing

Reference station addressing is based on pulse position (pulse pair spacing) coding. The standard system has 2 addressable stations, but 4 or 16 stations are optionally available.

7. Range Data Output

Range data output is BCD parallel and TTL compatible. Any two ranges can be displayed, while all are available for external use.

8. Integration Time/Range Update

The standard unit averages 5 pulses to obtain range. As an

option, the number of pulses for averaging (i.e., 10,20,40,75) may be switch selected. Range-update time can be selected from 1 to 10 seconds.

9. Weight and Size

Range Console: 14.5 kg (AC power)
12.7 kg (DC power)

43 x 45.7 x 14 cm

Receiver/Transmitter Unit: 2.3 kg (5 lb) with brackets
15.8x23.5x16.5 cm

Refernce Stations: 2.3 kg (5 lbs) less antenna
14x26x16.5 cm

10. Temperature Range

Range Console: 0° to 50°C

Receiver/Transmitter Unit: -40° to 60°C

Reference Stations: -54° to 71°C

Data Transmission Capability

None

Availability/Status

The units are commercially available. They have been used on a variety of aircraft (twin engine light fixed wing aircraft, FH 1100 and "Chinook" helicopters, and F-86 fighter jet). The units have been mostly used in the areas of offshore work.

Evaluation

With the exception of the increased range, obtained by use of a rotating antenna on the mobile platform, the short comings

called out for the Del Norte system apply to the Motorola system. At long range and in a high flyer mode, the high flyer would carry a rotating antenna and the survey aircraft would carry, in addition to its bottom mounted antenna, one or more top mounted sectorized antennas to avoid restrictive geometry configurations. Thus the system would need some redesign with reference to antenna configuration.

Information Sources

- * Telephone conversation with C. Lavance, Motorola
- * Brochures

5.2.2.7 TACAN

TACAN (military TACTical Air Navigation System) or the civilian VOR/DME was considered as a potential candidate for a flight path recovery system for the following reasons.

- (a) Work had been done under the sponsorship of the FAA on precision DME for the Microwave Landing System.
- (b) Work on precision L-band DME's had also been sponsored by the military for the MRALS (Marine Remote Approach Landing System).
- (c) There is an existing network of some 750 DME ground stations currently in service in the United States and adjacent areas.
- (d) There are accuracy claims of 100' (CEP) or better achieved by using only existing VOR/DME ground stations and slightly modified airborne DME units. These results have essentially been obtained by ranging to many ground beacons, thus overdetermining position, and using the redundant data to remove bias error (typically 400') in the ground stations

In addition, since VOR/DME or TACAN are onboard most aircraft for safety of flight purposes, these DME's were also considered for system backup purposes.

General Description

TACAN is a bearing and distance measuring system, used by the military, operating in the 960 to 1215 MHz band.

When used for distance measurement, an airborne interrogator

transmits a pair of pulses on one of 126 frequencies spaced 1 MHz apart in the frequency band 1025 - 1150 MHz. An airborne or surface-based beacon receiver receives this interrogation which, after a fixed delay, triggers a beacon transponder, transmitting a reply at a frequency displaced 63 MHz from the interrogation frequency. Surface based beacons respond with a pair of pulses in the 962-1213 MHz band while airborne beacons respond with a single pulse in the 1025-1150 MHz band.

The interrogator receiver measures the total round trip time, subtracts the fixed delay, and then determines the distance to the beacon. The beacon antenna normally rotates and provides a bearing reference signal from which the interrogator aircraft can determine its bearing relative to the beacon. In an FPRS application, only the ranging mode would be used.

In the NORMAL mode of operation, the interrogator antenna is fixed, and the beacon antenna rotates. In the INVERSE mode, the interrogator antenna rotates and the beacon antenna is fixed.

In the T/R (Transmit/Receive) mode, an airborne interrogator transmits to a surface-based beacon. In the A/A (Air/Air) mode, the airborne interrogator transmits to an airborne beacon. In the RECEIVE mode, the aircraft does not transmit but obtains its bearing to a surface-based beacon. In the BEACON mode (BCN), the aircraft acts as a beacon for other aircraft.

In the T/R mode, the surface-based beacon can respond to 100 aircraft interrogating simultaneously, whereas in the A/A mode, the airborne beacon can only respond to 5 aircraft interrogating

simultaneously. The limitations result from the fact that the beacon transmitter's duty cycle limits the maximum number of interrogations per second which can be handled.

Characteristics

The following summarizes the major technical characteristics of TACAN.

TACAN CHARACTERISTICS

Operational Range	300NM
Max. Time to Search, Track & Display Distance	1 sec.
Range Accuracy	
Digital	$\pm .05\text{NM}$ (0-50NM); $\pm .1\text{NM}$ (50-300NM)
Analog	$\pm .1\text{NM}$ (0-50NM); $\pm .15\text{NM}$ (50-300NM)
Bearing Accuracy	
	.5° - 2°
Traffic Capacity	
T/R Mode	100 aircraft
A/A Mode	5 aircraft

The following summarizes the leading characteristics of a precision L-band DME ground transponder (PR/T - 413 built by Hoffman Electronics) which can be used with airborne TACAN or DME.

1. Range/Accuracy ± 60 ft. (10') to 3NM
 ± 150 ft. (15') to 40NM
2. Peak RF Power/Input Power

For the ground transponder, peak power output is 100

watts. Input power is 21 watts.

3. Frequency/Bandwidth

The ground transponder receives at 1025-1045 MHz and transmits at 1088-1108 MHz (or any 20 consecutive TACAN channels). The TACAN bandwidth is 500 KHz.

4. Access/Addressing

The access method is based on frequency. This ground transponder presently has 20 channels but can be expanded to the full 252 TACAN channels.

5. Weight and Size

4.8 kg (10.5 lbs) without case

11.3 kg (25 lbs) with case

25.4x35.6x10.1 cm without case

Data Transmission Capability

Although a data transmission capability for TACAN has been discussed for many years and is even written into the TACAN specifications, it has never been implemented.

Status/Availability

At the present time there are no commercially available TACAN systems with 50 to 100 foot (1 σ) ranging accuracies out to 100NM. At the time of this survey, Hoffman Electronics had one precision ground unit which was being used for demonstration and test purposes.

A number of commercially available DMEs and TACANs have been modified to permit the units to switch frequency channels under computer control, thus permitting multilateration to the VORTAC or VOR/DME ground stations within range.

Evaluation

TACAN-like systems are not suited to accurate low altitude

flight path recovery. There are several reasons for this.

First, there is no data communications capability. To implement such a capability would require additional development. Without this, a separate communications link would be required for the high flyer mode.

Secondly, the precision TACAN or DME development work has been mainly focused on the short distances associated with landing approaches. There has been minimal, if any, testing at longer ranges and only air-to-ground ranging has been considered.

Finally, the distribution of existing ground stations is such that at the low altitude of the survey aircraft very few, if any, installations would be in line-of-sight. There is the possibility of using two high flyers both performing multilateration to many ground stations; however, this would be costly.

Information Sources

Brochures (Hoffman, Collins, King Radio)

Telephone Conversations - G. Thuor and S. Doddington (ITT)

E. Murphy (FAA)

E. Micozzi (Hoffman Electronics)

"Military Specification - Navigational Set, TACAN AN/ARN-84"
MIL-N-81207 (AS) 13 May 1971

"Military Standard - Standard Tactical Air Navigation (TACAN)
Signal" MIL-STD-291B 13 Dec 1967

5.3 Dead Reckoner

5.3.1 Selection Considerations

In addition to those considerations listed in Section 5.1, one must also consider the fact that the survey companies presently performing NURE surveys have made capital investment in expensive dead reckoning equipment - either an inertial navigation system (INS) or a Doppler radar system used with a precision attitude heading reference device.

With reference to FPRS, several questions can be asked:

- * Is there any advantage over a Doppler navigation system in using an INS for the DR subsystem or vice versa?
- * What type of DR should be selected for the high flying aircraft?
- * What is the status of new DR system developments? Should they be considered for integration into FPRS?

The first two questions are addressed in Section 3.3.2. This section addresses the last question and briefly reviews the characteristics of presently available systems.

5.3.2 Inertial Navigation System (INS)

5.3.2.1 Gimballed Systems

An INS consists of essentially three subsystems: (1) inertial measurement unit (IMU) containing accelerometers and gyroscopes, (2) computer unit, and (3) control and display unit. In a gimballed system, the IMU contains a stabilized platform on which the accelerometers and gyroscopes are mounted. In a strapdown system, the accelerometers and gyroscopes are mounted directly to the case. The principles of operation and the error sources of these devices are well understood and discussed in a number of references. (10, 14)

Very briefly a gimballed INS works as follows:

- * The inertial platform which is gimbal mounted to the case is

stabilized in three axes by the three gyroscopes mounted on the platform

- * The inertially stabilized platform maintains a specified orientation for the accelerometers.
- * The INS computer performs double integration of the vehicle acceleration sensed by the accelerometers and computes vehicle position and direction of travel.
- * The platform isolates the accelerometers from transient aircraft maneuvers so that the system can determine aircraft velocity and position in terms of the selected coordinate reference frame.
- * If a North-East-Local Vertical reference frame is used, the inertial platform is driven so two axes point North and East and the third axis is vertical. This implementation is called a North-slaved local vertical inertial navigation system.
- * A coordinate reference frame mechanized by the orientation of the accelerometers is used as the reference for measuring the magnitude and direction of aircraft acceleration.
- * The display unit generally provides such information as present position, true heading, ground track, ground speed, and range to destination.

The overall position location error of an INS consists of contributions from many error sources, the principal source being the drift rate of the gyroscopes which maintain the inertial platform in a level position. Examples of other error sources include accelerometer measurement uncertainty, gravity deflections of the vertical, gyrotorquer errors, and the geodetic earth model used. The impact of these error sources is such that the INS error behavior displays a time increasing characteristic. System position error performance is usually characterized in terms of a given number of NM/hr. In contrast to this long-term time increasing error, the short term stability of the position and velocity information available from an INS is excellent.

There are several manufacturers of commercially available inertial navigation systems: Litton, Delco (GM) and Collins Radio.

Cost for such systems is approximately \$100,000. The leading characteristics typical of these gimballed INS's are listed in column 1 of Table 5-1. The data given is that quoted by the manufacturer.

5.3.2.2 New Developments

5.3.2.2.1 Electrostatically Supported Gyroscopes (ESG) (15)

The ESG is being developed under military sponsorship by several companies - Autonetics Group at Rockwell International and Honeywell. The ESG is part of a program, underway since the mid 1960's, to develop a low cost, medium accuracy strapdown inertial navigation system. The Autonetic's system is called Micro-Navigator (MICRON), the design goals of which are as follows:

Acquisition Price:	\$35,000 presently inflated to \$60,000 (targeted for 500th production unit)
10 Year Life Cycle Cost:	\$70,000, presently inflated to \$120,000
MTBF:	2000 hours
Accuracy:	1NM/hr. CEP rate

MICRON has as its attitude sensing device a small 1-cm diameter spherical rotor which provides two axes of attitude reference. The spinning rotor is electrostatically suspended within a spherical cavity formed by two envelope hemispheres. Each hemisphere has four capacitor plates plated on the hemispherical cavity surface. The rotor is electrostatically suspended by placing the proper electrical charge on each of the eight capacitor plates. The suspension electronics are mechanized to control the electrical charge on each plate to servo the rotor to the center of the cavity. The gyroscope is evacuated to approximately 10^{-8} torr.

The spinning rotor is not torqued. Thus, the rotor spin axis remains fixed (except for gyro drift rates) in inertial space and no

TABLE 5-1

INS LEADING CHARACTERISTICS

<u>PARAMETER</u>	<u>INS TYPE</u>		
	<u>GIMBALLED</u>	<u>CONVENTIONAL STRAPDOWN</u>	<u>LINS STRAPDOWN (2)</u>
CEP RATE (NM/hr	1	1-2	1
VELOCITY ACCURACY (ft/sec) (1 σ /axis)	1.2, increases 0.6 ft/sec/hr	---	5.5
ATTITUDE ACCURACY (arc mins rms)	12 - 60 (1)	0.3-0.6	2.5
TRUE HEADING ACCURACY (arc mins rms)	24	---	3 arc mins rms and .02 $^{\circ}$ /hr (1 σ)

NOTES:

LINS = Laser Inertial Navigation System

(1) These accuracies can be improved by about a factor of 6 by using dual speed resolvers.

(2) Goal numbers

attempt is made to torque the rotor at vehicular rates as would be required on conventional gyros used in a strapdown configuration. Therefore all errors associated with gyro torquing are eliminated.

Whole angle attitude readout is obtained by purposely creating a mass unbalance in the rotor - the center of mass and center of geometry are displaced perpendicular to the spin axis. Thus, as the hemispherical cavity which contains the capacitor plates rotates with the airframe, the gap between the spinning rotor and the eight capacitor plates vary. This is the basis for the gyro pick-off scheme mechanized in this ESG. The whole angle attitude readout capability of this system offers computational load advantages over other strapdown systems that are based on incremental readout gyros. When an incremental readout gyro is used in a strapdown system, the computer must continually compute the new whole angle by adding each of the sensed angle increments to the previously computed whole angle attitude.

The MICRON system has undergone laboratory tests, van tests, environmental tests and flight tests on a number of different aircraft. In all tests the accuracy goal of 1 NM/hr CEP rate was exceeded. Presently, preproduction units are undergoing qualification and verification tests. Production is scheduled to start mid 1978 with first delivery at the end of 1979.

High accuracy systems using ESG's are also possible. Autonetics, by making software/ calibration modifications and using standard MICRON hardware, is striving for performance goals of 0.1 NM/hr CEP rate and 1 ft/sec rms velocity error per channel. Honeywell has used ESG's in a gimballed configuration and has demonstrated similar results.

5.3.2.2.2 Laser Inertial Navigation System (LINS) (15,16,17)

The development of strapped down laser gyros (also called ring laser gyros - RLG) has been pursued by several companies since the

middle 1960's. There are military sponsored programs at Honeywell and United Technology. Laser gyros are presently in the advanced development stage with considerable emphasis being placed on producibility aspects for cost reduction and on reliability assurance. The interest in these systems is based on their promise of:

- * Low production cost and low cost of maintenance,
- * High reliability (goal is 2500 hrs MTBF),
- * Fast reaction time (< 5 mins.),
- * Infrequent calibration (stability up to 1 year),
- * Insensitive to high-g environments,
- * Performance equivalent to conventional systems (1NM/hr).

Performance goals for a ring laser inertial navigation system are given in Table 5-1.

The laser gyro has no spinning mass. It consists, in part, of a ring-like optical cavity within which two laser beams propagate - one clockwise and one counterclockwise. It detects and measures angular rates by measuring the frequency difference between these two contra-rotating laser beams when rotation occurs around an axis perpendicular to the plane of the beam paths. The frequency difference is measured by optical means, resulting in a digital output. The pulse rate of the digital output is proportional to the input angular rate, while the cumulative pulse count is a measure of the input angle.

Laser gyro navigation systems have undergone a number of tests to demonstrate the potential and feasibility of meeting the established goals. The Honeywell LINS was flight tested in a C-141 aircraft at Holloman Air Force Base. System performance was 0.7 NM/hr CEP rate for 12 test flights. The final report on the Holloman AFB tests lists CEP rate of 0.89 NM/hr for the first 4 hours of 11 flights analyzed.

However, this analysis disregarded a significant number of data points in the longer flights.

At the present time, the Advanced Development Program (managed by Naval Air Systems Command) is scheduled for completion by the end of 1978. The data provided by this program will form the foundation for proceeding into the engineering and preproduction development program.

5.3.2.2.3 Gimbal INS versus Strapdown INS

The main impetus for the development of strapdown INS's is the elimination of gimbal associated hardware and platform stabilization electronics which should result in cost savings and reliability enhancement. In a strapdown configuration, the gyros and accelerometers are essentially bolted to the vehicle body. The computer calculates vehicle orientation from the outputs of the body-mounted gyros and resolves the accelerometer outputs into local level coordinates, (i.e., north, east and up), in which they are processed as if they came from a platform.

The strapdown configuration places additional computational load on the navigation computer. Each velocity increment must be transformed into the computational coordinate frame. This transformation of each velocity increment is not required on a gimballed system since the accelerometer sensing axes can remain essentially fixed with respect to the computational coordinate frame. A comparison of a completely coded and operating navigation program for a strapdown INS with a program for a gimballed INS shows that the gimballed INS uses one third the real time computer capacity and 30% less memory storage than the strapdown INS. (18) However, present high speed airborne minicomputers and microcomputers can easily handle this increased computational load.

Another constraint is that the gyros and accelerometers must be designed to perform their navigation sensing functions while undergoing whatever angular maneuvers and rates the vehicle performs. Either "wide-angle" gyros (e.g., MICRON's ESG) must be used or larger torquers of high accuracy must be used to torque the gyro so that it can follow vehicle motion.

Strapdown INS using rotating wheel gyros give radial position error CEP rates of 1-2 NM/hr (e.g., Teledyne Systems). These INS's are not "off-the-shelf" items and, in limited production, cost between \$100,000 to \$130,000.

5.3.3 Doppler/ Attitude Heading Reference System (AHRS)

A Doppler/AHRS consists of the following components: Doppler radar, heading and attitude reference, navigation computer, control/display unit, data converters (e.g., synchro-to-digital, digital-to-analog).

A Doppler radar measures velocity with respect to the earth of the vehicle in which the radar is carried. The radar transmitter radiates electromagnetic energy in several beam directions towards the earth's surface. The difference between the frequency of a return beam and the frequency of the transmitted beam is proportional to the velocity component along the beam, of the aircraft's velocity with respect to the earth. Most systems operate with three or four beams and thus are potentially capable of measuring the aircraft's ground velocity vector (3 dimensions). Because the Doppler radar beams have finite width, the return is composed of energy reflected from a group of random scatterers on the ground and, instead of a single Doppler frequency, the return contains a spectrum of Doppler frequencies. The process of determining ground speed consists of averaging over a time interval

to find the center frequency of the spectrum. Because of this averaging process, the Doppler measured instantaneous velocity is not highly accurate; however, the long term average is very accurate.

Since the Doppler radar measures aircraft velocity with respect to the Doppler radar frame coordinates, a heading and vertical reference are required to determine the rotation of the antenna frame coordinates relative to the earth navigation coordinate system (e.g., North-East-UP). Some Doppler radar systems have their antenna continuously stabilized to the local horizon.

Doppler navigation system accuracy degrades at a nominal rate of 1/2 NM/hr along track and 2% of the distance traveled across track. Some of the leading performance characteristics of several Doppler radar systems as quoted by manufacturers are given in Table 5-2. Costs, including a precision gyro-compass, can range from about \$60,000 to \$150,000. The performance characteristics for the Sperry C-12 precision gyro-compass are quoted as 0.25° rms in the magnetic slaved mode and, in the free gyro mode as 0.25°/hr rms (random) and 0.5°/hr rms (latitude corrected).

5.3.4 Evaluation

The newer DR's offer considerable future promise with regard to acquisition cost, cost of ownership and accuracy. However, in accordance with our design philosophy of using existing and proven hardware, we recommend that the dead reckoner subsystem for FPRS be either the gimbaled INS or the Doppler/AHRS.

Experience with newer strapdown systems is very limited. The rotating wheel gyro strapdown INS's are only in limited production. Their present cost equals or exceeds that of a conventional gimbaled INS, while the performance is about the same.

TABLE 5-2
DOPPLER RADAR CHARACTERISTICS

PARAMETER	DOPPLER RADAR		
	MARCONI CMA-712	SINGER SKK-1000	TELEDYNE RYAN APN-200,213
SPEED RANGE (KNOTS)	100-999	70-1000	50-1000
VELOCITY ACCURACY (10')	.14%	.17%	.13% $\pm$.1 KNOT
DRIFT ANGLE* RANGE	$\pm 20^\circ$	0 to $\pm 40^\circ$	0 to $\pm 45^\circ$
DRIFT ANGLE ACCURACY (10')	.2%	.17%	Not quoted
ALTITUDE RANGE (FT)	40-50,000	50-50,000	3-70,000
TIME CONSTANT (SEC)	Not quoted	Not quoted	0.2

* Angle between aircraft center line and groundspeed vector

INS's incorporating ESG's are not yet in production. Calibration requirements, rapid temperature stabilization (due to poor thermal conduction across the near vacuum in the gyro) and protection against bottoming the spinning ball (orderly shutdown with power loss) are areas of concern.

Laser gyro INS's are still in the developmental stage and important questions of producibility and cost have not yet been answered.

5.4 Computer

5.4.1 Selection Considerations

In selecting a FPRS computer both hardware and software must be considered. Hardware impacts on all 5 general considerations listed in the introduction to this section (5.1). The availability of existing software (assemblers, editors, loaders, general arithmetic and utility subroutines, high level language compilers, operating systems, etc.) and its maintenance by the vendor can have a significant impact on the cost of developing application software. The availability of user developed software can also help in lowering software development costs.

The computer types considered could be classified as follows:

- (a) commercial or laboratory
- (b) same as type (a), but "ruggedized"
- (c) a fully militarized version of type (a)
- (d) militarized, but no commercial version

Generally, the costs increase from type (a) to (d). Types (c) and (d) are most appropriate for an airborne environment.

We now discuss the computer features most desirable for the FPRS airborne computer subsystem.

Memory size was estimated (Section 2.1.4.1) to be sixteen thousand 16 to 18 bit words. However, it has been our experience that an end-user usually requires additional tasks of the software. Therefore, memory should be expandable (preferably as modules) within the same main chassis frame. One should, however, plan for minimum memory to reduce costs. With regard to memory type, most avionic software, once developed, rarely needs changing. Therefore, magnetic core, read-only-memory (ROM), or a combination of both is desirable, offering the advantages of noise and transient immunity plus eliminating a program loading device. Read/Write semiconductor memory, while faster and generally cheaper than magnetic core memory, is subject to erasure in case of power failure and thus requires battery backup. It is also more susceptible to noise, making parity checking and error correcting circuitry an important consideration.

The most popular word size for minicomputers is 16 bit. This word size is sufficient for the data manipulation tasks, control tasks and about 80% of the computational tasks (e.g., solution of navigation equations, filtering and estimation) involved in FPRS. For subroutines requiring high numerical precision, double precision arithmetic should be available.

Floating point capability is another very desirable inclusion for the FPRS computer. Floating point capability, implemented in hardware or software, eliminates the time consuming and error prone scaling tasks required of the programmer without such a capability. Thus, software costs are reduced. Floating point can be implemented in a number of ways:

- (a) Hardware

- (b) Firmware (via a microprogrammable control storage type minicomputer)
- (c) Subroutines
- (d) Interpreter software package

The execution speed decreases from type (a) to type (d). Type (d) is not only slow, but requires considerable core storage (e.g., two thousand 16 bit words). The trade-off is hardware cost versus software development cost, core storage and execution speed. We would recommend the FPRS computer have either type (a) or (b) above.

Multiple general purpose and index registers are desirable features for the FPRS computer. In most applications, the efficiency (speed x size) of programs is related directly to the number of registers. This results from the fact that register-to-register operations are almost always faster than those involving core locations (although there is not much difference for semiconductor memory). Also, if there are only a few registers, intermediate results must often be stored temporarily in core to free a register, thereby increasing execution time and core storage overhead.

Multiple index registers are useful. They permit the generation of relocatable code (thereby reducing software development cost). In addition, if ROM is being used, pure code is necessary (i.e., instructions are not altered except indirectly through index registers). Pure code allows re-entrant subroutines (e.g., subroutine may call itself) which have an obvious advantage when the program involves several interrupt levels, avoids errors which arise through instruction modification and avoids overly complex program structures.

The FPRS computer must interface with a number of subsystems (e.g., PLRS, Doppler/AHRS or INS, display, control input, magnetic

tape); therefore, the input/output control and interrupt structure are important considerations with regard to computer selection. One of the most critical parameters for this real time application is the interrupt latency time (the time it takes to sense an interrupt, such as "data ready for transfer to computer", and transfer control to the processing subroutine). Hardware stack capability and automatic vectoring to the appropriate subroutine are desirable features which expedite and simplify the handling of interrupts. The number of interrupt levels is also an important parameter for computer selection when the computer has to service a number of external devices. Both DMA (direct memory access) and programmed I/O channels are desirable features.

The instruction set is another consideration which can impact on execution speed and storage requirements. A computer which has both short and long instruction formats (e.g., 16 and 32 bits) is desirable when considering core storage requirements.

There are many other features, in addition to those mentioned which characterize a computer. There are two other important considerations for FPRS. These are that the computer operate reliably in an airborne environment and that it be a proven computer system.

Sections 2.1.4.2 and 5.4.2 summarize the characteristics of some of the computers considered for FPRS.

5.4.2 Computer Performance Characteristics

In the course of this study we surveyed both military and commercial computers as candidates for the FPRS computer. Manufacturers contacted included Bendix, Control Data, Data General, Delco, Digital Equipment, Honeywell, IBM, Interdata, Hughes, Litton, Norden, ROLM, Singer, Sperry Flight Systems, Texas Instrument,

and Varian.

Within the large class of airborne military computers many are special purpose and lack extensive hardware and software support. It is only recently that the military has attempted to standardize to a general purpose modular airborne computer suitable for many different applications.

Table 5-3 summarizes the characteristics of several of the computer systems examined. For additional discussion see Section 2.1.4.

TABLE 5-3

SUMMARY OF COMPUTER CHARACTERISTICSNORDEN PDP-11/34 MDELCO M362F

WORD LENGTH (BITS)	16 (+ 2 PARITY)	16 + PARITY
FIXED POINT OPERAND LENGTH (BITS)	16	
INSTRUCTION LENGTH (BITS)	16, 32, 48	16, 32
NUMBER BASIC INSTRUCTIONS	400	86 (M362F-1); 94 (M362F-2)
STORAGE TYPE	CORE; MOS	CORE, ROM, RAM
CYCLE TIME (μ sec)	0.9	1 - 2
ACCESS TIME (μ sec)	0.45	
MEMORY CAPACITY	32K MAX, 16K or 32K MODULES	65K MAX (16K CORE MODULES)
STORAGE PROTECTION	128K WITH EXP. CHASSIS YES	4K ROM 2K RAM MODULES YES
PARITY CHECKING/ ERROR PROTECTION	PARITY CHECK	PARITY CHECK
NUMBER OF ACCUMULATORS/ INDEX REGISTERS	6/6	16 GENERAL PURPOSE
NUMBER OF DIRECTLY ADDRESSABLE WORDS	32K	
NUMBER OF ADDRESSING MODES	8	4
HARDWARE STACK CAPABILITY	YES	YES
CONTROL STORAGE		512 WORDS; GROWTH TO 2K
ADD TIME (μ sec)	1.9	2.4 (CORE MEM)
HARDWARE MULTIPLY/DIVIDE	OPTIONAL	YES
FLOATING POINT	OPTIONAL	YES (24 BIT PRECISION SINGLE POINT; 48 BIT. PREC. DOUBLE)

TABLE 5-3 (CONTINUED)

NORDEN PDP-11/34 M

DELCO M362F

HARDWARE BYTE MANIPULATION	YES	YES
REAL TIME CLOCK	YES	YES
DIRECT MEMORY ACCESS CHANNEL (TRANSFER RATE, WORDS/SEC)	YES (2.5 M)	YES
I/O CHANNELS (TRANSFER RATE, WORDS/SEC)	SEE NOTE [1]	SEE NOTE [1]
NUMBER EXTERNAL INTERRUPT LEVELS - MIN (MAX)	4	MULTIPLE PRIORITY LEVELS
SIZE	1/2 ATR, 1 ATR	1/2 ATR; 1 ATR
WEIGHT (LBS)	28 (1/2 ATR); 50 (1 ATR)	
ENVIRONMENTAL	MIL-E-5400, 16400, 4158	MIL-E-5400; E-16400, STD-704, 461
POWER (WATTS)	240 MAX (1/2 ATR) 410 MAX (1 ATR)	
ADDITIONAL COMMENTS	[1] SINGLE 16 BIT BI- DIRECTIONAL BUS, ASYNCHRONOUS; AUTOMATIC VECTURING TO OWN SERVICE ROUTINE	[1] 16 BIT BIDIRECTIONAL BUS FOR USE FOR DMA & PROGRAMMED I/O

TABLE 5-3 (CONTINUED)SUMMARY OF COMPUTER CHARACTERISTICS

	<u>TEXAS INSTRUMENTS (980B)</u>	<u>INTERDATA 8/16</u>
WORD LENGTH (BITS)	16 (+6 CHECK BITS)	16
FIXED POINT OPERAND LENGTH (BITS)	8, 16	8, 16, 32
INSTRUCTION LENGTH (BITS)	16,32,48	16, 32
NUMBER BASIC INSTRUCTIONS	98	108
STORAGE TYPE	SEMICONDUCTOR (MOS)	CORE
CYCLE TIME (μ sec)	0.75	0.75
ACCESS TIME (μ sec)		0.275
MEMORY CAPACITY	64K	65K MAX
STORAGE PROTECTION	STANDARD	NO
PARITY CHECKING/ ERROR CORRECTION	NO/STANDARD	OPTIONAL PARITY
NUMBER OF ACCUMULATORS/ INDEX REGISTERS	8 HARDWARE REGISTERS	16 GENERAL/ 15
NUMBER OF DIRECTLY ADDRESSABLE WORDS	64K	65K
NUMBER OF ADDRESSING MODES	5	3
HARDWARE STACK CAPABILITY		
CONTROL STORAGE	ROM; 256 x 16 BITS	ROM
ADD TIME (μ sec)	3.6	0.75
HARDWARE MULTIPLY/DIVIDE	OPTIONAL	OPTIONAL
FLOATING POINT	NO	OPTIONAL

TABLE 5-3 (CONTINUED)

TEXAS INSTRUMENTS (980B)

INTERDATA 8/16

HARDWARE BYTE MANIPULATION	NO	YES
REAL TIME CLOCK	OPTIONAL	OPTIONAL
DIRECT MEMORY ACCESS CHANNEL (TRANSFER RATE, WORDS/SEC)	YES (1.3M)	4 (2.66 M)
I/O CHANNELS (TRANSFER RATE, WORDS/SEC)	SEE NOTE [1]	SEE NOTE [1]
NUMBER EXTERNAL INTERRUPT LEVELS - MIN (MAX)	3 (2048)	1 (255)
SIZE		14 x 19 x 19 IN.
WEIGHT (LBS)		70
ENVIRONMENTAL	MIL. SPEC. AVAILABLE	0 - 50°C : [2]
POWER (WATTS)		6A, 115 VAC
ADDITIONAL COMMENTS	[1] 4 DATA BUS PORTS	[1] UP TO 4 SELECTOR CHANNELS FOR DMA; 1 MULTI- PLEXED I/O CHANNEL; I/O LOOP RATE 66 KBYTES/SEC; INTERRUPT RESPONSE TIME: 8.25 μ SEC [2] 90% RH; VIB: 0-55 ~ @ 1.25G

TABLE 5-3 (CONTINUED)

SUMMARY OF COMPUTER CHARACTERISTICS

	<u>IBM AP-1 (CP-1075 AYK)</u>	<u>SPERRY 1819B</u>
WORD LENGTH (BITS)	32	18
FIXED POINT OPERAND LENGTH (BITS)		
INSTRUCTION LENGTH (BITS)		18
NUMBER BASIC INSTRUCTIONS	83	104
STORAGE TYPE		CORE/ ROM
CYCLE TIME (μ sec)	1.0	1.2
ACCESS TIME (μ sec)	0.45	0.42
MEMORY CAPACITY	8K MIN/ 24K MAX	16K MIN/ 65K MAX
STORAGE PROTECTION		
PARITY CHECKING/ ERROR CORRECTION		
NUMBER OF ACCUMULATORS/ INDEX REGISTERS	16 GENERAL PURPOSE	2/ 8
NUMBER OF DIRECTLY ADDRESSABLE WORDS		4K
NUMBER OF ADDRESSING MODES		2
HARDWARE STACK CAPABILITY		
CONTROL STORAGE		ROM 512 x 52 BIT
ADD TIME (μ sec)	2.0	1.6 (REG. - REG.)
HARDWARE MULTIPLY/DIVIDE	YES	YES
FLOATING POINT	NO	NO

TABLE 5-3 (CONTINUED)

	<u>IBM AP-1 (CP-1075 AYK)</u>	<u>SPERRY 1819B</u>
HARDWARE BYTE MANIPULATION		NO
REAL TIME CLOCK		YES
DIRECT MEMORY ACCESS CHANNEL (TRANSFER RATE, WORDS/SEC)		YES (833 KHz)
I/O CHANNELS (TRANSFER RATE, WORDS/SEC)		8 (417 KHz) [2]
NUMBER EXTERNAL INTERRUPT LEVELS- MIN (MAX)	SEE NOTE [1]	8
SIZE	7.6 x 12.7 x 15.6 IN.	1/2 ATR (4.9 x 7.6 x 19.5 IN.)
WEIGHT (LBS)	36	25
ENVIRONMENTAL	MIL. SPEC.	MIL-E-5400, CLASS 2
POWER (WATTS)	200	150
ADDITIONAL COMMENTS	[1] 16 INTERRUPTS WITH 9 PRIORITY LEVELS; 8 DISCRETE OUTPUTS; 4 DISCRETE INPUTS; 4 16 BIT SERIAL MULTIPLEXING	[1] SMALL QUANTITY PRO- DUCTION - 12 UNITS DELIVERED AS OF 10/8/76 [2] 8 INDEPENDENT FULLY BUFFERED I/O CHANNELS

5.5 Data Link

There are two alternatives for selecting equipment to perform the data link function:

- * Select a DME which also has digital communications capability.
- * Select a digital communication system separate from the DME.

We are recommending the first alternative for a number of reasons:

- * No separate radio, modem and antenna need be used, thus reducing cost.
- * Spare equipment is reduced.
- * Frequency allocation is only required for the DME/Data Link system.
- * Only one antenna (DME) is required, simplifying installation problems.

In addition, it appears that there are no non-military, "off-the-shelf" (in production) systems for air-to-air digital communications. The manufacturers contacted are listed in appendix B.

Of the DME's considered, four provide digital communications capability: PLRS, DFCS, RMS, and Cubic. The characteristics of these systems are described in Section 5.2.2. Table 5-4 summarizes the data link characteristics of DFCS, PLRS and RMS. We recommend General Dynamics' PLRS mainly due to its GFE availability.

TABLE 5-4. DATA LINK CHARACTERISTICS

	<u>DFCS</u>	<u>PLRS</u>	<u>RMS</u>
Range	60 NM (1)	100 NM	34 NM (2)
Frequency	915 MHz	420 - 450 MHz	918 MHz
RF modulation	Pulsed BPSK; Spread Spectrum	Spread Spectrum	AM/ 4 subcarrier frequencies
Data modulation	4-ary, PPM, 2 bits/ pulse pair	4-ary, PPM, 2 bits/ pulse pair	Upper & Lower side bands used for "1" and "0"
Trans. rate (burst)	500 KBPS	150 KBPS	200 KBPS
RF margin	5 dB		10 dB
Error correction	One error/ byte recoverable, otherwise repeat	Parity check @ des- tination, check # of pulses, retrans- mit on error	Check # bits, and only upper or lower sideband present, can insert parity bits
Bandwidth	10 MHz	30 MHz	15 MHz
RF peak power	150W (AU)/250W (GU)	100 W	12 W

NOTES:

1. The operating range of this system was based on considerations other than power (i.e., number of drones, update rates, etc.)
2. A high power amplifier (80W) will increase operating range to approximately 85 nm.

6.0 Summary Conclusions and Recommendations

6.1 Summary Conclusions

A system for accomplishing flight path recovery has been presented. A key component of the system is the DME. This report calls for the use of the General Dynamics' PLRS. Section 5.0 of this report describes other DME devices, some of which would perform as well as the PLRS for the purpose of flight path recovery. The PLRS was selected primarily because there are a relatively large number of Genral Dynamics' PLRS's that might be available as GFE for use in an FPRS flight test. The FPRS system presented collects flight path recovery data in digital form and automates the process of collecting, analyzing and printing out data. This is a positive feature of the system. The system requires the installation and recovery of ground stations in the area to be surveyed and requires that the ground and air elements of the system be in line-of-sight. This represents a negative feature of the system. The use of ground stations and the line-of-sight constraints imposed on the system are consequences of the accuracy requirements for flight path recovery and the physics applicable to the design of a flight path recovery system. A near ideal solution to flight path recovery would be a satellite system such as the Global Positioning System (GPS) which would eliminate, for the most part, the need for ground stations in the survey area and provide maximum line-of-sight at the same time. However, to our knowledge, the kind of performance required for flight path recovery will not be available from the GPS in the near future. The system configuration presented in this report represents, in our judgement, the best use of available technology to accomplish flight path recovery at the present time.

6.2 Recommendations

At the present time NURE surveys are conducted by survey companies under contract to BFEC/DOE. It is not required nor is it expected at the present time, that each company supply aircraft which use the same type, quality and manufacturer of dead reckoner navigation equipment. However, the use of the same kind and quality of dead reckoner equipment would result in greater economy and uniformity of data as regards the cost and performance of the FPRS as the FPRS airborne computer software must contain and model the error characteristics of the aircraft dead reckoner. Thus, instead of having to model the error characteristics and thus provide different software for each of the different dead reckoners contained in contractor furnished aircraft, it would be better to require a single software for all FPRS. It is recommended therefore, that consideration be given to the possibility of supplying the FPRS as GFE to contractors. The FPRS could be supplied in a pod equipped for interfacing with the aircraft power and the radiation measuring equipment.

Supplying the airborne FPRS as GFE in a suitably packaged form would result in advantages to BFEC/DOE in the conduct of any type of aerial survey where accurate position location is required. The greater flexibility which would result from podding the airborne FPRS would allow BFEC/DOE to establish a relatively inexpensive test range. The flight test plan configuration is one example of such a range. This range could be used to test contractor equipment used for determining aircraft position location. Podding would also allow for use of the FPRS in other applications of aerial survey, thus extending its usefulness, its lifetime, and improving its cost/benefit ratio.

It is recommended that BFEC/DoE initiate efforts to acquire, on a permanent basis, the total inventory of General Dynamics' PLRS hardware presently controlled by DoD. If BFEC/DoE could acquire the DoD PLRS hardware on a permanent basis, the concept of podding the FPRS and supplying the FPRS pods to survey contractors as GFE, would represent a most reasonable approach to realizing the FPRS performance characteristics with a minimum of development cost and time.

It is recommended that BFEC/DoE initiate efforts to arrange for the use of General Dynamics' PLRS hardware for the conduct of an FPRS flight test as described and configured in Section 4.0 of this report.

The flight test will demonstrate the two primary FPRS performance characteristics which, to our knowledge, are not available from any other flight path recovery system presently in operation:

1. Positional error of 100 feet (CEP)
2. Automated acquisition of digital flight path recovery data

We believe that the flight test demonstration will provide incentive, both within the DoE and within the community of aerial survey contractors, to make more effective use of the FPRS capabilities and technology.

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APPENDIX A

POSITION LOCATION ERROR ANALYSIS

PROGRAM LISTING

A-2

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C COMPUTE CEP
C PLANE - NOT SPHERICAL - GEOMETRY
  REAL*8 B,PM,PMO,PIVOT,STDET,ALGDET,B12,B23
  REAL*8 BB,A,B0,B1,C,COP,CORR,CORT,E00,E01,ERR
  DIMENSION XX(3,10),EXX(3,10),TH(10),X(3,100),DX(3,10),RMO(10),XR(1
100),NPAR(5),R(3,10),RM(10),DXX(3,10),ERM(10),PMO(4,4),IPVOT(4),PIV
2OT(4),INDEX(4,2),XD(3)
  DIMENSION U(3,10),B(4),PM(4,4),P(4),E0(3,3),E(41,41),COR(41,41)
  DIMENSION BB(10),B0(3,10),B1(3,10,4),C(3,10,3),A(4,10)
  DIMENSION CORR(4,41),CORT(41,4),E00(4,4),PMT(4,4),ERR(4,4),E01(4,4
1)
  DIMENSION SIG(3,100),CEP(100)
  DIMENSION XM(3,10),Y(3,100),YN(3),PN(4)
  DIMENSION Y1(3,100)
  DIMENSION FRANGL(100)
  DIMENSION NXM(10)
1  FORMAT(3F10.4,5I5)
2  FORMAT(1I5)
22  FORMAT(2I5)
3  FORMAT(7F10.4,1I5)
4  FORMAT(3F10.4)
5  FORMAT(3F10.4)
6  FORMAT(4F10.4)
66  FORMAT(4D15.4)
7  FORMAT(1I5,3F10.4)
77  FORMAT(1I5,8F10.4)
8  FORMAT(1I15)
9  FORMAT(10F10.4)
99  FORMAT(10D12.4)
  PT=3.141592654
C CLEAR TEMPORARY ERROR MATRIX E0
  DO 50 I=1,3
  DO 50 J=1,3
50  E0(I,J)=0.
C INPUT NAVIGATION PARAMETERS
  READ 8,KSTART
  JLAST=0
  READ 1,ALT,U1,FAM,N1,N2,N3,NIT,NTEST
C
C ALT IS DISTANCE OF DUMMY ALTITUDE BEACON BELOW REFERENCE PLANE
C N1,N2,N3 ARE RANGE MEASUREMENTS USED FOR INITIALIZATION OF LINEAR LEAST
C SQUARES POSITION DETERMINATION
C
80  READ 2,NMTNUS
C READ BEACON COORDINATES
C NXM=0 =GROUND STATION OR ALTIMETER, NXM=1=HIGH FLYER
  READ 3,(XM(1,I),XM(2,I),XM(3,I),EXX(1,I),EXX(2,I),EXX(3,I),TH(I),N
1XM(I),I=1,NMTNUS)
  N=NMTNUS+1
  DO 85 I=1,3
  EXX(I,N)=1.E-6
85  XM(I,N)=0.
  TH(N)=0.
  XM(3,N)=ALT
  NXM(N)=0
  DO 101 I=1,N
  DO 101 J=1,3
  IF(J.EQ.3)GO TO 101
  XM(J,I)=XM(J,I)+6080.
101  XX(J,I)=XM(J,I)

```

```

C
: READ AIRCRAFT LOCATION
:
: GENERATE WEDGE MESH
  READ 4,Y(1,1),Y(2,1),Y(3,1)
  READ 11,WEDGE,GRID,NANG,NGRID
11  FORMAT(2F10.4,2I5)
  FNANG=FLOAT(NANG)
  DELANG=WEDGE*PI/180./(FNANG-1.)
  DO 1015 K=1,NANG
  SUMANG=(K-1)*DELANG
  DO 1015 J=1,NGRID
  R=J*GRID
  IT=(K-1)*NGRID+J+1
  Y(1,IT)=R*COS(SUMANG)+Y(1,1)
  Y(2,IT)=R*SIN(SUMANG)+Y(2,1)
1015 Y(3,IT)=Y(3,1)
  NP=NANG*NGRID+1
C
C
C
C
  DO 102 IT=1,NP
  DO 102 J=1,3
  IF(J.EQ.3)GO TO 102
  Y(J,IT)=Y(J,IT)*EORD.
102  X(J,IT)=Y(J,IT)
  ITEST=1
C
C  GENERATE BEACON LOCATIONS USING RANDOM NUMBER GENERATOR TO ASSIGN POSITIONS
C  WITHIN ONE STANDARD DEVIATION OF ASSIGNED MESH POINTS
C
C  RANDN(XP,N,MEAN,SIGMA) IS A RANDOM NUMBER GENERATOR WHICH PRODUCES A NORMAL
C  DISTRIBUTION OF N POINTS ABOUT A MEAN VALUE OF MEAN, AND HAVING A STANDARD
C  DEVIATION OF SIGMA. RANDN USES TWO DUMMY DATA FIELDS-NRAN AND NRAND.
C  RANDN REQUIRES A STARTING INTEGER AS INPUT- KSTART.
C
C
125  DO 200 IT=1,N
  DO 150 J=1,3
  NRAN(J)=NPAND(J,LAST,KSTART)
  XR(1)=NRAN(J)
  CALL RANDN(XR,100,0.,FXX(J,1))
150  R(J,IT)=XR(1)
C  ROTATE TO LAB SYSTEM
  THETA=TH(I)*PI/180.
  DXX(1,IT)=R(1,IT)*COS(THETA)-R(2,IT)*SIN(THETA)
  DXX(2,IT)=R(1,IT)*SIN(THETA)+R(2,IT)*COS(THETA)
200  DXX(3,IT)=R(3,IT)
C
C  BEACON LOCATIONS NOW FIXED
C
C  BEGIN LOOP OVER AIRCRAFT LOCATIONS
  DO 1000 IT=1,NP
  ANORM=1.
  IF(ITEST.GT.1)ANORM=0.
  DO 225 I=1,2
225  XX(I,N)=XM(I,N)+X(I,IT)*ANORM

```

```

C   GENERATE RANGE MEASUREMENTS RM
      DO 300 I=1,N
        RM2=0.
        DO 250 J=1,3
          DX(J,I)=XX(J,I)-X(J,IL)+DXX(J,I)
250    RM2=RM2+DX(J,I)**2
        RM(I)=SQRT(RM2)
        ERM(I)=111
        IF(I.EQ.N) ERM(I)=EAM
        IF(NXM(I).NE.1) GO TO 270
        THETA=TH(I)*PI/180.
        PROX=EXX(1,I)**2*COS(THETA)**2+EXX(2,I)**2*SIN(THETA)**2
        PROY=EXX(1,I)**2*SIN(THETA)**2+EXX(2,I)**2*COS(THETA)**2
        PROXY=(EXX(1,I)**2-FXX(2,I)**2)*SIN(THETA)*COS(THETA)
        PROT=PROX*DX(1,I)**2+PROY*DX(2,I)**2+2.*PROXY*DX(1,I)*DX(2,I)
        PROT=PROT+EXX(3,I)**2*DX(3,I)**2
        ERMPRO=SQRT(111**2+PROT/RM(I)**2)
        ERM(I)=ERMPRO
270    CONTINUE
C   ERM IS RANGING UNCERTAINTY
C
C   USE RANDOM NUMBER GENERATOR TO PRODUCE A RANGE MEASUREMENT WITHIN ONE
C   STANDARD DEVIATION OF THE ACTUAL BEACON-MESHPPOINT SEPARATION
C
      NRAN(4)=NRAND(JLAST,KSTART)
      XR(1)=NRAN(4)
      CALL RANDN(XR,100,0.,ERM(I))
300    RM(I)=RM(I)+XR(1)
301    AM=ALT+RM(N)
C
C   COMPUTE ZERO ORDER POSITION ESTIMATES FROM BEACONS N1,N2,N3
C
302    A1=RM(N1)**2-(AM-DX(3,N1))**2
      A2=RM(N2)**2-(AM-DX(3,N2))**2
      A3=RM(N3)**2-(AM-DX(3,N3))**2
      R12=A1-A2-((XY(1,N1)+DXX(1,N1))**2-(XX(1,N2)+DXX(1,N2))**2)-((XY(2
1,N1)+DXX(2,N1))**2-(XX(2,N2)+DXX(2,N2))**2)
      R12=-R12/2.
      R23=A2-A3-((XY(1,N2)+DXX(1,N2))**2-(XX(1,N3)+DXX(1,N3))**2)-((XY(2
1,N2)+DXX(2,N2))**2-(XX(2,N3)+DXX(2,N3))**2)
      R23=-R23/2.
      PM0(1,1)=(XX(1,N1)+DXX(1,N1))-(XX(1,N2)+DXX(1,N2))
      PM0(1,2)=(XX(2,N1)+DXX(2,N1))-(XX(2,N2)+DXX(2,N2))
      PM0(2,1)=(XX(1,N2)+DXX(1,N2))-(XX(1,N3)+DXX(1,N3))
      PM0(2,2)=(XX(2,N2)+DXX(2,N2))-(XX(2,N3)+DXX(2,N3))
C
C   INVERT(X,NMAX,N,KDUM,MDUM,XDUM,YDUM,ZDUM) IS A MATRIX INVERSION ROUTINE
C   REQUIRING DUMMY STORAGE LOCATIONS KDUM--ZDUM, WHICH INVERTS THE N*N ARRAY
C   DESIGNATED AS X WHICH HAS A MAXIMUM ORDER OF NMAX.
C   ELEMENTS OF THE INVERSE ARE PLACED IN THE ORIGINAL ARRAY
C
      CALL INVERT(PM0,4,2,IPVOT,INDEX,PIVOT,SIDET,ALGOET)
      X0(1)=PM0(1,1)*R12+PM0(1,2)*R23
      X0(2)=PM0(2,1)*R12+PM0(2,2)*R23
      X0(3)=AM
      Y0(1)=Y0(1)/6080.

```

```

      Y0(2)=X0(2)/6080.
      Y0(3)=X0(3)
C      PRINT 5,(Y0(T),T=1,3)
C      BEGIN COMPLETE POSITION DETERMINATION
      IT=0
C      FORM U VECTORS
399  DO 400 T=1,N
      RM0(I)=RM(I)**2
      DO 400 J=1,3
      U(J,T)=X0(J)-(XX(J,T)+DXX(J,I))
400  RM0(I)=RM0(I)-U(J,J)**2
C      CONSTRUCT R VECTORS
      DO 450 T=1,3
      R(I)=0.
      DO 450 J=1,N
450  R(I)=R(I)+RM0(J)*U(I,J)/ERM(J)**2/RM(J)**2
C      CONSTRUCT POSITION MATRIX PM
      DO 500 T=1,3
      DO 500 J=1,3
500  PM(I,J)=0.
      DO 510 T=1,3
      DO 510 J=1,3
      DO 510 K=1,N
510  PM(I,J)=PM(I,J)+2.*U(I,K)*U(J,K)/ERM(K)**2/RM(K)**2
      CALL INVERT(PM,4,3,IPVOT,INDEX,PIVOT,SIGET,ALGDET)
      DO 550 T=1,3
550  P(I)=0.
      DO 560 T=1,3
      DO 560 J=1,3
560  P(I)=P(I)+PM(T,J)*R(J)
      DO 561 T=1,3
      IF(I.GT.2)GO TO 561
      P0(I)=P(I)/6080.
561  P0(I)=P(I)
C      PRINT 6,(P0(T),T=1,3)
      DO 570 T=1,3
570  X0(I)=X0(I)+P(I)
      IT=IT+1
      IF(IT.LT.NIT)GO TO 399
      Y0(1)=X0(1)/6080.
      Y0(2)=X0(2)/6080.
      Y0(3)=X0(3)

C
C      POSITION DETERMINATION COMPLETE
C
C      DO 590 T=1,3
C 590 PRINT 66,(PM(T,J),J=1,3)
C      PRINT 5,(Y0(T),T=1,3)
C
C      BEGIN ERROR MATRIX DETERMINATION
      IF(NP.EQ.1.AND.ITEST.LE.NTEST)GO TO 1000
      MAX=3*N+N
      DO 600 I=1,MAX
      DO 600 J=1,MAX
      COR(I,J)=0.
600  E(I,J)=0.
      DO 610 T=1,N
610  E(I,I)=ERM(I)**2

```

```

      DO 620 I=1,N
      T1=TH(I)*PI/180.
      EQ(1,1)=EXX(1,I)**2*COS(T1)**2+EXX(2,I)**2*SIN(T1)**2
      EQ(2,2)=EXX(1,I)**2*SIN(T1)**2+EXX(2,I)**2*COS(T1)**2
      EQ(1,2)=(EXX(1,I)**2-EXX(2,I)**2)*SIN(T1)*COS(T1)
      EQ(2,1)=EQ(1,2)
      EQ(3,3)=EXX(3,I)**2
      DO 620 J=1,3
      DO 620 K=1,3
      NCOVAR=N+(I-1)*3+J
      NVAR=N+(I-1)*3+K
620   E(NCOVAR,NVAR)=EQ(J,K)
C     FUNDAMENTAL ERROR MATRIX COMPLETE
C
C     DO 630 T=1,MAX
C 630   PRINT 99,(E(T,J),J=1,MAX)
C
      DO 700 J=1,N
      RR(J)=0.
      DO 699 IT=1,3
699   RR(J)=RR(J)+P(IT)*U(IT,J)*2./ERM(J)**2/RM(J)**2
      DO 700 K=1,3
      A(K,J)=2.*U(K,J)*RM(J)/ERM(J)**2/RM(J)**2
      B0(K,J)=RR(J)-(RMO(J)-2.*U(K,J)*(U(K,J)+P(K)))/ERM(J)**2/RM(J)**2
      DO 700 I=1,3
      KDEL=0
      IF(I.EQ.K)KDEL=1
      B1(I,J,K)=B0(K,J)*KDEL
      C(I,J,K)=2.*U(K,J)*(U(I,J)+P(I))*(1-KDEL)/ERM(J)**2/RM(J)**2
700   B1(I,J,K)=B1(I,J,K)+C(I,J,K)
      DO 760 I=1,3
      DO 760 J=1,N
760   COR(I,J)=A(I,J)
      DO 800 T=1,3
      NN=N+1
      NM=MAX
      DO 800 J=NN,NM
      JJ=(J-N-1)/3+1
      II=J-N-3*(JJ-1)
800   COR(I,J)=B1(T,JJ,II)
C     DO 810 I=1,3
C 810   PRINT 99,(COR(T,J),J=1,MAX)
      DO 850 I=1,3
      DO 850 J=1,MAX
      CORR(I,J)=0.
      DO 850 JJ=1,MAX
850   CORR(I,J)=CORR(I,J)+COR(T,JJ)*E(JJ,J)
C     TRANSPOSE COR MATRIX (3 X MAX)
      DO 860 I=1,3
      DO 860 J=1,MAX
860   CORT(J,I)=CORR(I,J)
C     COMPUTE PRIMITIVE ERROR MATRIX EDD (CORR X CORT)
      DO 870 I=1,3
      DO 870 J=1,3
      EDD(I,J)=0.
      DO 870 KK=1,MAX
870   EDD(I,J)=EDD(I,J)+CORR(I,KK)*CORT(KK,J)
C     TRANSPOSE POSITION MATRIX PM TO PMT

```

```

      DO 887 I=1,3
      DO 887 J=1,3
887   PMT(I,J)=PM(J,I)
C     COMPUTE FINAL ERROR MATRIX
      DO 897 I=1,3
      DO 897 J=1,3
      E01(I,J)=0.
      DO 897 KK=1,3
897   E01(I,J)=E01(I,J)+E00(I,KK)*PMT(KK,J)
      DO 907 I=1,3
      DO 907 J=1,3
      E00(I,J)=0.
C     ERR IS POSITION VARIANCE COVARIANCE MATRIX
      DO 909 KK=1,3
899   E00(I,J)=E00(I,J)+PM(I,KK)*E01(KK,J)
C     DO 919 I=1,3
C 910 PRINT 66,(ERR(I,J),J=1,3)
      DO 957 K=1,3
957   V1(K,IL)=V0(K)
      RH1=E00(1,1)
      RH2=E00(2,2)
      RH=SQRT(RH1)*SQRT(RH2)
      RH0=E00(1,2)/RH
      SUM=E00(1,1)+E00(2,2)
      SIG(2,IL)=0.5*(SUM-SQRT(SUM**2-4.*(1.-RH0**2)*RH**2))
      SIG(1,IL)=0.5*(SUM+SQRT(SUM**2-4.*(1.-RH0**2)*RH**2))
      SIG(1,IL)=SQRT(SIG(1,IL))
      SIG(2,IL)=SQRT(SIG(2,IL))
      SIG(3,IL)=SQRT(E00(3,3))
      TAN2TH=2.*E00(1,2)/(E00(1,1)-E00(2,2))
      EPANGL(IL)=0.5*ATAN(TAN2TH)*180./PI
      NCEP=2
      RATIO=SIG(1,IL)/SIG(2,IL)
      IF((SIG(1,IL)-SIG(2,IL)).GT.1.E-5)NCEP=1
      IF(NCEP.EQ.1)RATIO=1./RATIO
      CEP(IL)=0.589*(1.+RATIO)*SIG(NCEP,IL)
1000  CONTINUE
      ITEST=ITEST+1
      IF(NP.EQ.1.AND.ITEST.LE.NTEST)GO TO 125
C
C
      PRINT 77,(I,V1(1,I),V1(2,I),V1(3,I),SIG(1,I),SIG(2,I),SIG(3,I),CEP
1(I),EPANGL(I),I=1,NP)
C
1001  CONTINUE
      GO TO 80
      STOP
      END

```


APPENDIX B

VENDOR CONTACTS

1. DISTANCE MEASURING EQUIPMENT (DME)

ITT, Avionics Division
Nutley, New Jersey 07110
Tel. (201) 284-0123 (G. Thuor, Ext. 3101)

King Radio
Olathe, Kansas 66061
Tel. (913) 782-0400 (C. Christie)

Collins Avionics Division
Rockwell International
Cedar Rapids, Iowa 52406
Tel (214) 690-5000 (Bill Evans)

IBM, Federal Systems Division
Owego, New York
Tel. (607) 687-2121 (J. Raney)

Cubic Corporation
9233 Balboa Avenue
San Diego, California 92123
Tel. (714) 277-6780 (Hugh Kohnen)

General Dynamics (Electronics Division)
San Diego, California
Tel. (714) 279-7301 (Neal Lawhead, Ext. 3078)

Del Norte Technology
1100 Pamela Drive
Euless, Texas 76039
Tel. (817) 267-3541 (James Stegall)

Hoffman
4323 Arden Drive
El Monte, California 91734
Tel. (213) 442-0123 (E. Micozzi)

Montek Division, E-Systems Inc.
Salt Lake City, Utah 84101
Tel. (801) 973-4300 (F. Ausseresses)

Mototola, Government Electronics Division
Scottsdale, Arizona 85252
Tel. (602) 949-3428 (Cecil Lavance)

2. DEAD RECKONERS

Litton Aero Products Division
21050 Burbank Boulevard
Woodland Hills, California 91364
Tel. (213) 887-2731 (R. Miller)

Rockwell International (Autonetics Group)
3370 Miraloma Avenue
Anaheim, California 92803
Tel. (714) 632-8111 (J. Schwarz, Ext. 1463)

Sperry Flight Systems
Phoenix, Arizona
Tel. (602) 942-2311 (J.R. Jarrett)
Also computers, radio alt.

Honeywell
Government & Aeronautical Products Division
St. Petersburg, Florida
Tel. (813) 531-4611 (John Bailey, Ext. 3541)
Also alt. (R.Coxon, (813) 378-5313)

Singer Co., Kearfott Division
1150 McBride Avenue
Little Falls, New Jersey 07424
Tel. (201) 256-4000 (Donald Hough, Ext. 5319)
Also computers (Dick Wieland, Ext. 2432)
DME (George Henf, Ext. 3198)

Teledyne Ryan
2701 Harbor Drive
San Diego, California 92112
Tel. (714) 291-7311 (Victor Andreone)

Canadian Marconi Co., Avionics Division
2442 Trenton Avenue
Montreal, Quebec, Canada H3P1Y9
Tel. (514) 341-7630 (W.A. Lovett, Ext. 222)

Teledyne Systems
19601 Nordhoff Street
Northridge, California 91324
Tel. (213) 886-2211 (Drew Frohlich, Ext. 2195)

Delco Electronics Division, General Motors Corporation
Goleta, California 93017
Tel. (805) 961-5044 (T. Dziennik)
Also computers (Jack Toney)

3. COMPUTERS

Norden
Norwalk, Connecticut 06856
Tel. (203) 838-4471 (W. McCoy)

SysTech Incorporated

3. COMPUTERS (cont.)

Interdata
2 Crescent Place
Oceanport, New Jersey 07757
Tel. (201) 229-4040 (J. Cohen)

ROLM
18922 Forge Drive
Cupertino, California
Tel. (201) 367-6100 (D. Smaldone- Regional Rep.)

Hughes, Data Systems Division
Culver City, California 92030
Tel. (213) 670-1515 (D. Manos, Ext. 1396)

IBM, Federal Systems Division
Owego, New York 13827
Tel. (607) 687-2121 (R.D. Flanagan)

Data General
Southboro, Massachusetts 01772
Tel. (617) 485-9100; (212) 557-1136 (P. Currier)

Texas Instruments
Austin, Texas
Tel. (512) 258-5121 (C. Jack, Ext. 2539)

Honeywell, Aerospace Division
St. Petersburg, Florida 33733
Tel. (813) 531-4611 (W.R. Moore)

Control Data
Minneapolis, Minnesota 55440
Tel. (612) 853-5370 (J.I. Bloomfield)

Digital Equipment Corporation
Maynard, Massachusetts 01754
Tel. (617) 897-5111 (Dick Amann)

4. DATA COMMUNICATIONS, RADIOS, MODEMS

Rockwell International
Collins Government Telecommunication Division
Newport Beach, California 92663
Tel. (714) 833-4600 (W. Coleman)
(319) 395-1000 (J. Kramer)

Harris Electronics
Melbourne, Florida 32901
Tel. (305) 727-4000 (C. Currey, Ext. 6677)

4. DATA COMMUNICATIONS, RADIOS, MODEMS (cont.)

Magnavox, Government & Industrial Electronics
Torrance, California 90503
Tel. (213) 328-0770 (S.B. Fishbein)
also TRANSIT Satellite Receivers (J. Moyer)

Electronic Communications Inc.
Division of E-Systems
St. Petersburg, Florida
Tel. (813) 381-2000 (H. Wilkes)

Motorola, Government Electronics Div., Communications Operations
Scottsdale, Arizona 85252
Tel. (602) 949-3142

Digital Communications Corporation
Gaithersburg, Maryland
Tel. (301) 948-0850 (Prisekin)

E-Systems, Garland Division
Dallas, Texas
Tel. (214) 272-0515 (R. Gilbert)

5. TRANSIT RECEIVERS

JMR Instruments, Inc.
20621 Plummer Street
Chatsworth, California 91311
Tel. (213) 882-2800 (P. Rogers)

Canadian Marconi Company
2442 Trenton Avenue
Montreal, Quebec, Canada H3P1Y9
Tel. (514) 341-7630 (D.V. Bassett)

6. OTHERS

Aeronautical Radio, Inc.
2551 Riva Road
Annapolis, Maryland 21401
Tel. (301) 224-4000
Ref: ARINC Characteristics

Analytical Technology Laboratories
Gaithersburg, Maryland 20760
Tel. (301) 869-6790 (A.R. Dennis)
Ref: Survey Service

6. OTHERS (cont.)

Sperry Gyroscope
Great Neck, New York
Tel. (516) 574-1415 (W. Leeseman)
Ref: LORAN-D

Bendix Flight Systems Division
Teterboro, New Jersey 07608
Tel. (201) 288-2000 (H.F. Wood)
Ref: Air Data Computers, GP Computers

EDO-Aire
Fairfield, New Jersey 07006
Tel. (201) 228-1880 (J. Knott)
Ref: DME, LORAN-D

Teledyne Energy Systems
110 West Timonium Road
Timonium, Maryland 21093
Tel. (301) 252-8220 (Paul Bessert)
Ref: Thermoelectric Generators

SUPPLEMENT
to
FLIGHT PATH RECOVERY SYSTEM (FPRS)
DESIGN STUDY

Prepared for
Bendix Field Engineering Corporation
and
Department of Energy

Subcontract No. 76-023-5
Project No. 50-76-5122

Submitted by
SysTech Incorporated
370 Seventh Avenue
New York, N.Y. 10001

September 18, 1978

SysTech Incorporated

SUPPLEMENT - FLIGHT TEST COST ESTIMATES

Cost estimates presented in this supplement are for support engineering and the CFE items listed in Table 4-1 of the associated report. A labor cost of \$250/man-day is used.

S.1 Cost Estimate for Airborne Elements of Flight Test PlanS.1.1 Helicopter Associated Tasks and Costs

- * Installation of lower PLRS to include rack mounting and necessary power and antenna cabling.
- * Installation of upper PLRS to include rack mounting, necessary power and antenna cabling, installation design and installation of upper PLRS blade antenna.

Estimated man-days: 50

Estimated cost (including materials) = \$15,000

S.1.2 Fixed Wing Aircraft Associated Tasks and Costs

- * Installation of PLRS to include rack mounting and necessary power and antenna cabling

Estimated man-days: 20

Estimated cost (including materials) = \$5,000

S.2 Cost Estimate for Ground Elements of Flight Test PlanS.2.1 Ground Associated Tasks and Costs

- * Design and build simple stand to mount and shelter ground station PLRS.

Estimated cost: Under \$1,000

S.2.2 Master Station Associated Tasks and Costs

Although the following items could possibly be supplied GFE, they have been listed as CFE and thus included in the master station cost estimate.

- * Computer/Processor
- * Display
- * Recorder

- * Printer
- * Antenna
- * Software
- * Van installation design
- * Van installation

Hardware cost estimates were based, in most instances, on cost data provided by vendors during discussions regarding their equipment and do not represent firm quotes. Experience dictates that the cost to purchase would be somewhat higher than the estimate provided by vendors. The following items of hardware are to be procured:

- * Computer/Processor plus peripherals
- * CRT display
- * Recorder
- * Printer
- * Software
- * Antenna (PLRS)

Procurement Cost Estimate: \$150,000 to \$200,000

- * Van Installation Design
- * Van Installation

Cost Estimate: \$25,000

S.3 Support Engineering During Flight Tests

Contractor furnished personnel will be required to support the PLRS equipment, the master station integrated system and to operate the master station. Flight crews and logistics in support of the aircraft are not included in this estimate. The cost of engineering support personnel is very much dependent upon the period of time over which the

flight test extends and the eventual number of flights flown. However, a reasonable estimate for support engineering based upon past experience would not exceed \$50,000.

S.4 Total Cost Estimate

The total cost estimate for the flight test is given here as \$245,000 to \$295,000.

This estimate could be substantially reduced if the computer, computer software, display(s), and van installation used in the Army/Marine Corps PLRS test program could be obtained for use in the flight test.