CIVIL APPLICATION OF DIFFERENTIAL GPS

John D. Cardall
Richard S. Cnossen
Magnavox Advanced Products and Systems Company
Torrance, California

ABSTRACT

GPS has the potential of satisfying worldwide and local civil navigation requirements for Area Navigation (RNAV), Landings and Takeoffs under minimum ceilings and Advanced Air Traffic Control (ATC) Operations. Use of GPS in a differential mode in local areas is a key to achievement of this potential.

This report describes the GPS system and its status; discusses GPS signal availability for the civil community; defines alternative differential GPS concepts; shows predicted performance enhancement achievable with differential GPS and the operational improvements which are expected.

INTRODUCTION

The need to provide better accuracy for precision landings than available from either the P or C/A Code spurred interest in the concept of differential GPS navigation.(1) Accordingly, the aircraft Guidance and Navigation Branch, NASA, Ames Research Center (ARC) sponsored a study(10) to investigate the utility of differential GPS for Civil applications. Portions of the study results are presented in this paper.

GPS DESCRIPTION AND STATUS

GPS is a satellite based navigation system under development by DoD. It is designed to provide suitably equipped users with worldwide, continuous, highly accurate, 3-D navigation and time. GPS consists of three segments: the space segment, the ground control segment, and the user segment (Figure 1).

In the operational space segment, a constellation of 18 satellites will circle the earth in nominal 10,900 nautical-mile orbits with a period of 12 sidereal hours. The constellation will be configured in several 55° included orbital planes with the objective of providing direct, line-of-sight navigation signals continuously from at least four satellites to any point on or near the surface of the earth. Each satellite transmits its navigation signals on two L-Band (UHF) frequencies.

The signals consist of a Precision (P) Code and a Coarse Acquisition (C/A) Code which are both pseudorandom digital sequences used for ranging. The signals also contain a navigation message which provides satellite position, time, and atmospheric propagation correction data generated by the ground control segment. The two-frequency transmission permits users to correct for frequency sensitive propagation delays and anomalies.

The ground control segment has four monitor stations which are located at Guam, Hawaii, Alaska, and Vandenberg AFB in California. A Master Control Station is also located at Vandenberg. The monitor sites track the satellites via their broadcast signals as they come into view. The Master Control Station collects the tracking data and generates the navigation message for each satellite which is uploaded to each satellite’s memory daily via S-Band telemetry link. In this way, the satellites are able to broadcast an accurate description of their position as a function of time.

The user segment consists of ground-based, marine, airborne, and spaceborne platforms equipped with a GPS receiver/processor capable of tracking four satellite signals either simultaneously or sequentially. Part of the task will be to select which four satellites to track to optimize accuracy as the satellites slowly pass by. Position is computed by making time-of-arrival (TOA) measurements on the P or C/A Code transmitted from discrete satellite positions defined by the navigation message. Each set of four TOA measurements permits determination of the four independent variables of latitude, longitude, elevation, and user clock offset. Velocity is computed by making doppler measurements on the carrier frequency. Each set of four doppler measurements permits determination of the four independent variables of 3-D velocity and user clock drift. Navigation is accomplished via a Kalman filter which propagates a continuous navigation solution based on the TOA and doppler measurements. Use of the filter’s propagation capability permits temporary operation on fewer than four satellites.

Full 3-D Operational capability with 18 satellites is expected by the end of 1987 with 2-D operational capability commencing at the end of ’85. In the meantime, a five to six satellite constellation will be maintained for test and evaluation (see Figure 2).

DIFFERENTIAL GPS CONCEPT

Differential navigation is currently in use with Omega, Loran-C and the TRANSIT satellite system. The differential technique achieves substantial improvements in position accuracy by transmitting corrections from a calibration site to users in the vicinity who apply the corrections to cancel errors common to the locale. In this technique, a receiver located on a surveyed point selected as the reference or calibration site for the locale continuously determines errors present in received navigation signals by comparing computed position with the known coordinates of the calibration site. The difference between computed and known position represents the navigation error which is typically highly correlated for all users in the vicinity of the calibration site. The error generally varies slowly relative to the time required to transmit corrections from the calibration site to nearby users who apply the corrections to improve their position solutions. For Omega, Loran-C and Transit, the technique provides substantially improved positions over distances up to a few hundred miles.

Three basic differential GPS concepts are:

- Data Link Type
- Pseudolite Type
- Translator Type

The data link type utilizes a benchmarked GPS set which receives GPS signals, computes its position, and compares its computed position with its known position to determine error corrections. These error corrections are data linked to GPS equipped aircraft in the vicinity and are used to correct the onboard navigation solution. The primary advantage of the data link type relative to the other basic types is that it requires little change to conventional airborne or ground GPS sets. Other advantages are that no new frequency allocation will be required and the technique is suitable for post processing applications. Its primary disadvantage is that it requires a separate data link; this disadvantage disappears if a data link is otherwise available. Figure 3 illustrates this type.

The pseudolite type monitors GPS signals and computes corrections in the same manner as the data link type, but it also generates its own PN code and navigation message which is transmitted at the GPS L_2 frequency along with correction data for the GPS satellites. The PN code and navigation message generated at the calibration site provides another GPS signal source from, in essence, a ground-based or pseudo satellite, hence the term pseudolite. The pseudolite has several advantages: (1) the airborne GPS set can function as the differential data receiver avoiding the necessity for a separate differential data airborne receiver; (2) the pseudolite's navigation signal provides a highly accurate single line of position (LOP) which should reduce UERE errors and/or DOP in its vicinity; (3) the PN transmission provides inherent protection for the correction data; and (4) a side benefit is provided in test programs conducted with the current six satellite GPS constellation because the additional pseudolite signal source permits operation with less than four satellites in view, thus extending available test time. Pseudolites were the basis for inverted range testing during the advanced development phase of the Phase I GPS test program at Yuma, Arizona. Disadvantages of the pseudolite type are: (1) extra cost for the ground equipment for such items as wave form generators, time synchronization equipment and L-band transmitters; (2) added complexity relative to the data link type; (3) possible near/far problems in aircraft reception of the different strength pseudolite and satellite signals depending on pseudolite locaion; (4) the need for two antennas on the aircraft to ensure full time reception; (5) the possible need for a new frequency allocation; and (6) possible problems for non-participating users in the vicinity of the L_2 ground transmission. Figure 4 illustrates this type.

The translator type merely offsets the frequency of GPS signals received by its benchmarked antenna and retransmits them to airborne users on another L-band frequency, L_n. The signals from all available satellites are retransmitted continuously, and the airborne GPS set computes the corrections for its constellation knowing the location of the transponder. No GPS set is required at the ground site and no processing is accomplished or correction data generated at the ground site. Primary advantages of the translator type are minimal complexity and low cost for the ground installation to the point where it becomes practical when one or a few helicopters must serve many landing sites, such as oil rigs. Low power, portable ground stations can also be envisioned. Disadvantages of this type are: (1) two GPS antennas are required on the aircraft; (2) an L-band translator is required on the aircraft to reverse the translation accomplished on the ground; (3) a multi-channel GPS receiver may be required on the aircraft; (4) a new frequency allocation would be required; (5) near-far problems will be encountered in aircraft GPS signal reception; (6) user dynamics may be restricted; and (7) the pilot will be required to enter the coordinates of the ground translator into the airborne system. Figure 5 illustrates this type.

The correction data which would typically be required in the differential mode would include the following:

- Correction data for 3 to 8 satellites
- Correction data quality estimates
- Satellite data and I.D.
- Ground/User coordination data
- Ground equipment status
- Correction data encoding
- Correction data quality estimates

For the data link and pseudolite concepts, two basic types of corrections could be computed and transmitted by the calibration site: (1) X, Y, Z position corrections, or (2) UERE corrections for each satellite. In both cases, the corrections would be based on comparing the GPS solution with the known location of the calibration site's GPS antenna, the difference being the correction to be applied.

The advantage of the X, Y, Z correction is that it can be applied as a simple addition to the airborne set's solution either internal to the GPS set or by an external computer. The disadvantages of the X, Y, Z correction technique are that it requires both sets to track the same satellites and that the resulting airborne solution may be less accurate than a UERE correction introduced into the airborne set's navigation filter.

The advantage of UERE correction is that it can be transmitted for all GPS satellites in view to eliminate the need for the airborne set to track the same satellites as the calibration site. The disadvantages are that (1) more data must be transmitted and (2) update rates may require the use of multi-channel sets at the calibration site. The update rate is a significant parameter for both X, Y, Z and UERE correction methods and requires further study.

A review of the advantages and disadvantages for the three basic differential GPS concepts leads to several conclusions:

- The data link concept requires the least amount of change to standard GPS sets for ground and airborne use in the differential mode. This is accomplished at the expense of a separate data link which may be available anyway as a low cost subsystem in support of next generation ATC operations.

- The pseudolite concept may, depending on the location of the pseudolite, provide the best accuracy because of improved geometry (i.e., lower PDOP) and would be of benefit during limited satellite availability. Also, this concept eliminates the need for a separate airborne data link receiver. However, these benefits are achieved at the expense of added complexity, risk, and cost for both ground and airborne GPS equipment. Also, these benefits may be of questionable value during the operational GPS era since (a) the accuracy improvement will not be substantial, (b) satellite availability will not be limited, and (c) a separate, low cost data link to support next generation ATC operations may be available at no cost to the data link concept.

- The translator concept would provide the lowest cost ground installation at the expense of considerable complexity in the airborne GPS system and at some technical risk. This concept would be cost effective where, for example, a few helicopters serve a large number of off shore oil rigs.

DIFFERENTIAL GPS NAVIGATION PERFORMANCE

GPS system errors have been well documented and fall within specified limits as indicated in Figure 6. These errors are allocated to their appropriate bias or random category and their combined effect on position accuracy estimated in Table 1 for a P Code receiver. The

Root-Mean-Square, RMS, value for the bias and random errors provides an estimate of a 1σ User Equivalent Range Error, UERE, to a satellite. Use of a filter, such as the Kalman filter used in GPS sets, substantially reduces the contribution of random errors to total error, particularly in steady or benign states. For purposes of illustration, the random error contribution to UERE is reduced by a factor of four in Table 1. This is a high level of filtering for sequencing sets which is considered attainable with a navigation filter optimized for the low dynamics approach and landing environment.

Multiplying UERE by an appropriate Dilution of Precision (DOP) factor based on space segment geometry provides an estimate of the spatial, horizontal, or vertical position error which will result from the combined effects of ranging errors and system geometry. PDOP is the spatial (3-D) position DOP factor; HDOP is the horizontal (2-D) position DOP factor; and VDOP is the vertical (single axis) DOP factor. The statistical distribution of DOP factors is generally highly non-gaussian and varies with geographic location. For a discussion of the distribution of DOP value and its use in computing position error statistics see Reference 6.

Based on Reference 6 data, a single axis VDOP value of 2.5 multiplied by a 1σ UERE is used in this report to provide a conservative estimate of the 1σ vertical axis position error. It is also considered roughly representative of 1σ crosstrack, and along track errors. For example, the 1σ single axis error for the Field Test P-Code case shown in Table 1 is estimated as follows:

$$\begin{aligned} 1\sigma \text{ single axis error} &= \text{VDOP} \sqrt{\text{Bias}^2 + \text{Filtered Random}^2} \\ &= 2.5 \times 3.7 \text{ meters} \\ &\sim 9 \text{ meters.} \end{aligned}$$

Similar calculations using field test errors are summarized in Tables 2 and 3 for conventional and differential use of P Code and C/A Code. As shown in Table 2, the 1σ ionospheric error for the C/A Code in the conventional mode is assumed equal to the specification amount allocated to the bias category (i.e., 4 meters) since the accurate ionospheric correction applied in field tests by the two frequency P Code receivers is not available to single frequency C/A Code sets. Also, a 7.5 meter receiver noise is assumed in both modes for C/A Code code tracking sets based on in-house experience with the Magnavox Z-Set. As indicated in Table 3, all bias errors are assumed cancelled in the differential mode. This is based on the premise that GPS geometry is essentially constant over large areas so that nearby users will experience and be able to cancel common errors. It is consistent with our experience in the TRANSIT satellite system. For differential GPS calculations, an additional random error equal to the filtered random error is included as shown as an estimate of the residual error at the calibration site.

DIFFERENTIAL PERFORMANCE VS PRESENT FAA STANDARDS

Table 4 summarizes the results of the performance calculations, 2σ values are shown to facilitate comparison with FAA navigation system accuracy standards shown in Table 5.(4)

A comparison of predicted differential GPS performance in Table 4 with current FAA navigation system accuracies listed in Table 5, indicates that differential P-Code sets should satisfy Category I requirements and meet horizontal navigation accuracy requirements for Category II and III operations but not vertical requirements. However, differential GPS vertical accuracy is very close to the stringent FAA vertical accuracy requirements for Category II and III operations, and a review of these requirements relative to differential GPS characteristics seems warranted. It is expected that differential C/A Code performance could approach the performance of differential P-Code for civil applications, if receiver noise effects were reduced. This could be accomplished by tracking loop optimization doppler aiding, navigation filters and satellite sequencing rates for applications with relatively low platform dynamics.

CONCLUSIONS

Conventional use of C/A Code signals will accommodate all RNAV/IFR enroute, terminal area and non-precision approach and landing requirements on a full time basis but will not accommodate RNAV/IFR Category I precision approach and landing conditions under current FAA regulations.

Conventional use of the P-Code will not materially enhance civil enroute or non-precision approach and landing operations relative to conventional use of the C/A Code; nor will it provide precision approach and landing capabilities. Thus, widespread early conventional use of the higher cost P-Code sets by the general aviation community does not seem likely or warranted, particularly since P-Code availability could lag C/A code availability considerably.

Calculations performed in this study indicate that single channel P code receivers have the potential in the differential mode to provide navigation accuracies on the order of 2.5 meters, 2σ, in each axis. This type of navigation performance would qualify for Category I approaches and landings per current FAA specifications and warrants consideration for Category II and III operations.

Study results also indicate that single channel C/A Code receivers as presently designed would provide navigation accuracies in the differential mode on the order of 10 meters, 2σ, in each axis. This type of navigation accuracy would not qualify for Category I approaches and landings under current FAA navigation standards. However, differential C/A Code performance sufficient for Category I and, perhaps Category II and III operations is projected for C/A Code sets optimized for the approach and landing environment, particularly if FAA navigation standards can be broadened for selected applications, such as helicopter service. In this vein, a review is recommended of FAA navigation accuracy requirements relative to both GPS characteristics and aircraft with slow speed landing capability, such as helicopters and VTOL aircraft.

REFERENCES

1. Howell, W.E. et. al., "Civil Aviation Applications of Navstar/GPS through Differential Techniques," NASA, Langley Research Center, Hampton, Virginia. Paper presented at 1980 National Telecommunications Conference, Houston, Texas, December 1980.

2. Cnossen, R. and Cardall, John D., "Civil Helicopter Applications of the NAVSTAR Global Position System", Magnavox, Torrance, California. Paper presented at the Advanced Rotocraft Technology Workshop, NASA, Ames Research Center, Moffett Field, California, December 1980.

3. Gilbert, Glen A., "Fourth Generation Air Traffic Control", Glen A. Gilbert & Associates, Inc., Washington, D.C. Paper presented at the Aviation/Space Writers Association 42nd Annual News Conference, Toronto, Canada, May 1980.

4. U.S. Department of Defense and Department of Transportation, "Federal Radionavigation Plan", Washington, D.C., July 1980.

5. NAVSTAR/GPS Joint Program Office, "DSARC II Briefing", Air Force Space Division, El Segundo, California. Briefing presented to Defense System Acquisition Review Council for GPS, Washington, D.C., June 1979.

6. Jorgensen, P.S., "NAVSTAR/Global Positioning System 18 - Satellite Constellations," Journal of the Institute of Navigation, Vol. 27, No. 2, Summer 1980.

7. Teasley, Stewart P. et. al., "Differential GPS Navigation", Texas Instruments Incorporated, Dallas, Texas. Paper presented IEEE 80 Position, Location, and Navigation Symposium, Atlantic City, New Jersey, December 1980.

8. Cnossen, R., "Low Cost GPS Navigation Receiver for General Aviation", Magnavox, Torrance, California. Paper presented at the 32nd Annual Helicopter Association of America Meeting and Industry Showcase, Las Vegas, Nevada, February 1980.

9. Euler, W.C. and Jacobson, L.J., “A Perspective on Civil Use of GPS”, Magnavox, Torrance, California. Paper presented at the Institute of Navigation 36th Annual Meeting, Monterey, California, June 1980.

10. Cardall, John, D. and Cnossen, Richard S., “Civil Application of Differential GPS Using a Single Channel Sequential Receiver”, NASA, Ames Research Center, Moffett Field, California, May 1981.

Table 1. Calculated la Single Axis P-Code Accuracy

	Spec			Field Test		
	1σ Error (Meters)			1σ Error (Meters)		
Error Source	Bias	Random	Total	Bias	Random	Total
Ephemeris Data	3.7	0	3.7	3.5	0	3.5
Satellite Clock	2.6	0.7	2.7	1.5	0.7	1.7
Ionosphere	4.0	0	4.0	1.5	0	1.0
Troposphere	0	3.0	3.0	0	0.5	0.5
Multipath	0	2.8	2.8	0	1.0	1.0
Receiver	0	1.5	1.5	0	1.5	1.5
UERE (RMS)	6.0	4.2	7.5	3.7	2.0	4.2
Filtered UERE (RMS)	6.0	1.1	6.1	3.7	0.5	3.7
1σ Single Axis Error (DOP = 2.5)			~15			~ 9

Table 2. Calculated la Single Axis Accuracy, Conventional P-Code and C/A-Code

	Conventional P-Code			Conventional C/A Code		
	1σ Error (Meters)			1σ Error (Meters)		
Error Source	Bias	Random	Total	Bias	Random	Total
Ephemeris Data	3.5	0	3.5	3.5	0	3.5
Satellite Clock	1.5	0.7	1.7	1.5	0.7	1.7
Ionosphere	1.0	0	1.0	4.0	0	4.0
Troposphere	0	0.5	0.5	0	0.5	0.5
Multipath	0	1.0	1.0	0	1.0	1.0
Receiver	0	1.5	1.5	0	7.5	7.5
UERE (RMS)	3.7	2.0	4.2	5.5	7.6	9.4
Filtered UERE (RMS)	3.7	0.5	3.7	5.5	1.9	5.7
1σ Single Axis Error (VDOP = 2.5)			~9			~ 14

Table 3. Calculated la Single Axis Accuracy, Differential P-Code and C/A-Code

Error Source	Differential P-Code			Differential C/A Code		
	1σ Error (Meters)			1σ Error (Meters)		
	Bias	Random	Total	Bias	Random	Total
Ephemeris Data	0	0	0	0	0	0
Satellite Clock	0	0.7	0.7	0	0.7	0.7
Ionosphere	0	0	0	0	0	0
Troposphere	0	0.5	0.5	0	0.5	0.5
Multipath	0	1.0	1.0	0	1.0	1.0
Receiver	0	1.5	1.5	0	7.5	7.5
Calibration Site Residual	0	0.5	0.5	0	1.9	1.9
UERE (RMS)	0	2.1	2.1	0	7.9	7.9
Filtered UERE (RMS)	0	0.5	0.5	0	2.0	2.0
1σ Single Axis Error (VDOP = 2.5)			~1.3			~ 5.0

Table 4. Calculated GPS Performance Summary

GPS Signal	2σ Single Axis Error (Meters), DOP = 2.5	
	Conventional Mode	Differential Mode
P Code	18	2.6
C/A Code	28	10

Table 5. FAA Navigation System Accuracy Standards (4)

Operational Phase		Minimum Altitude (ft)	Accuracy (2 drms)	
			Lateral	Elevation
Enroute/Terminal		500	4 NM	500 M
Approach and Landing	Non-Precison	250	2 NM	100 M
	Precision Category I	100	±9.1 M*	±3 M*
	Precision Category II	50	±4.6 M*	±1.4 M*
	Precision Category III	0	±4.1 M*	±0.5 M*

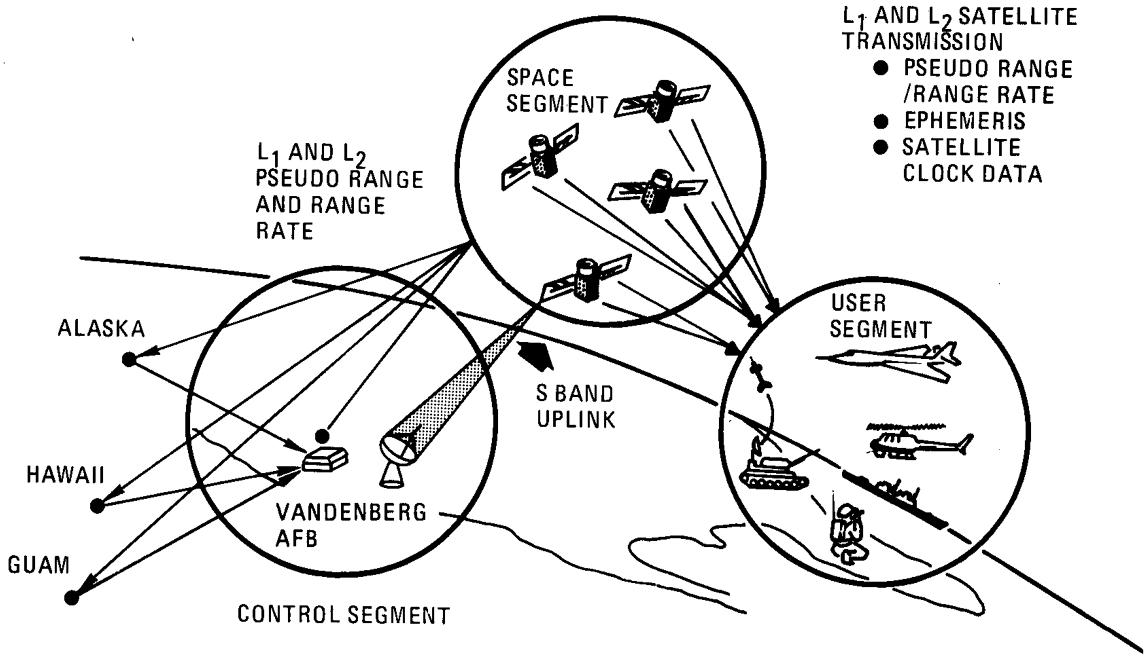

Figure 1. NAVSTAR GPS Segments

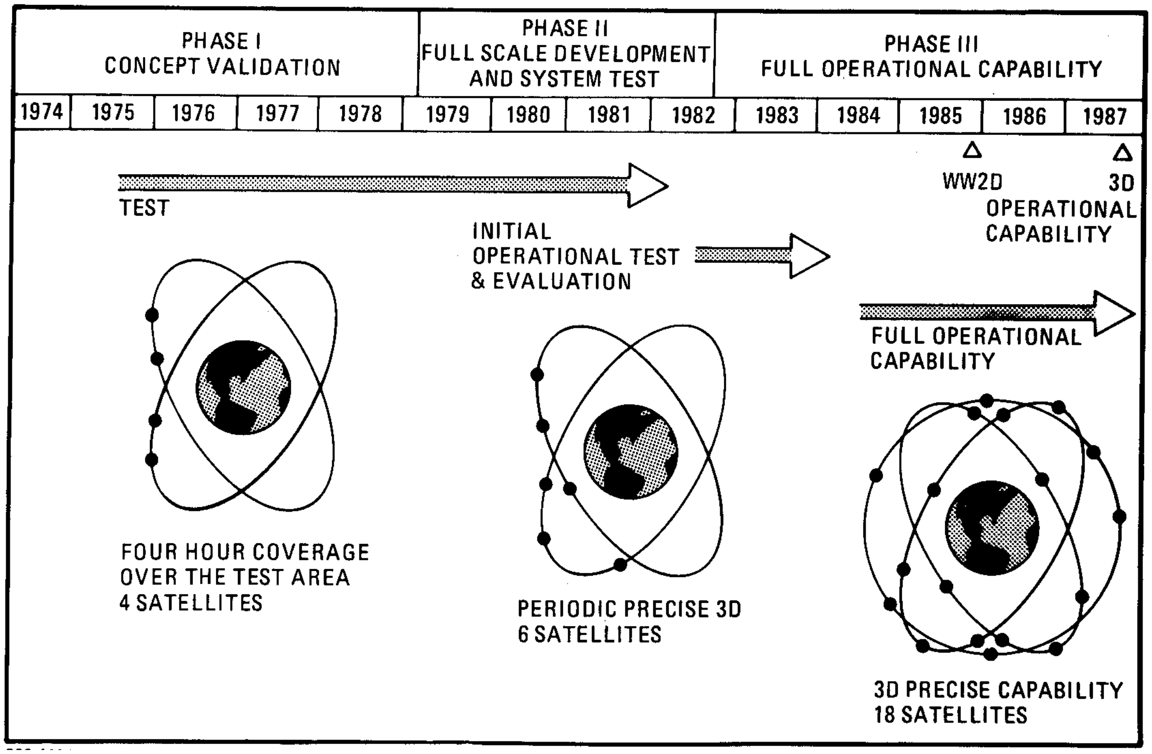

Figure 2. Schedules and Orbital Configurations

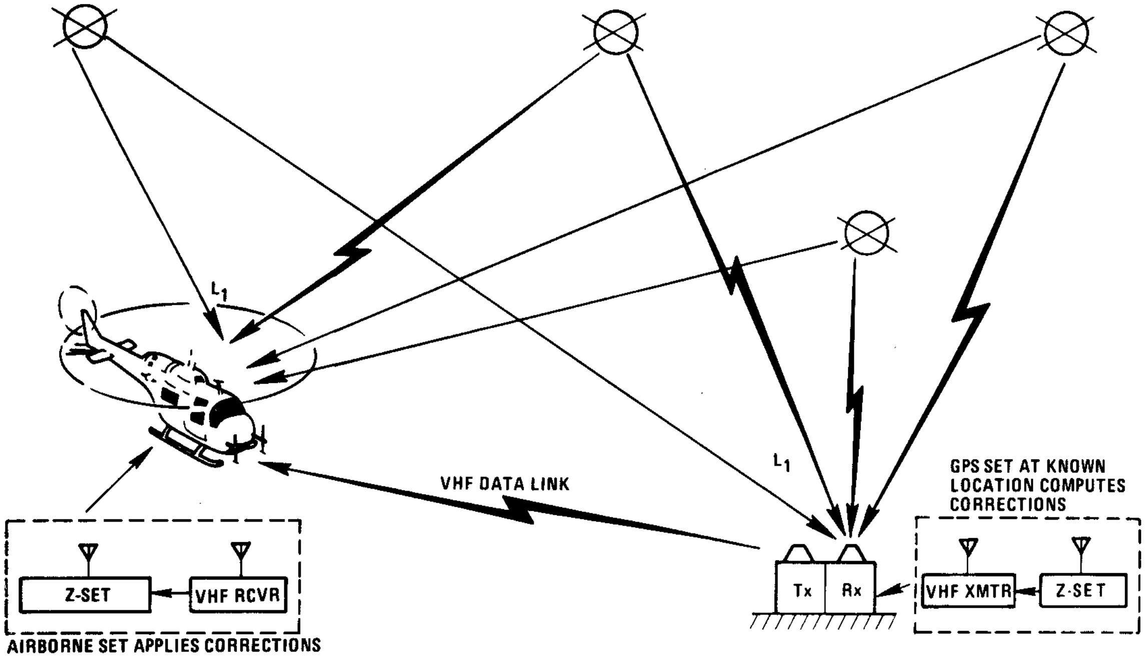

Figure 3. Differential GPS - Data Link Type

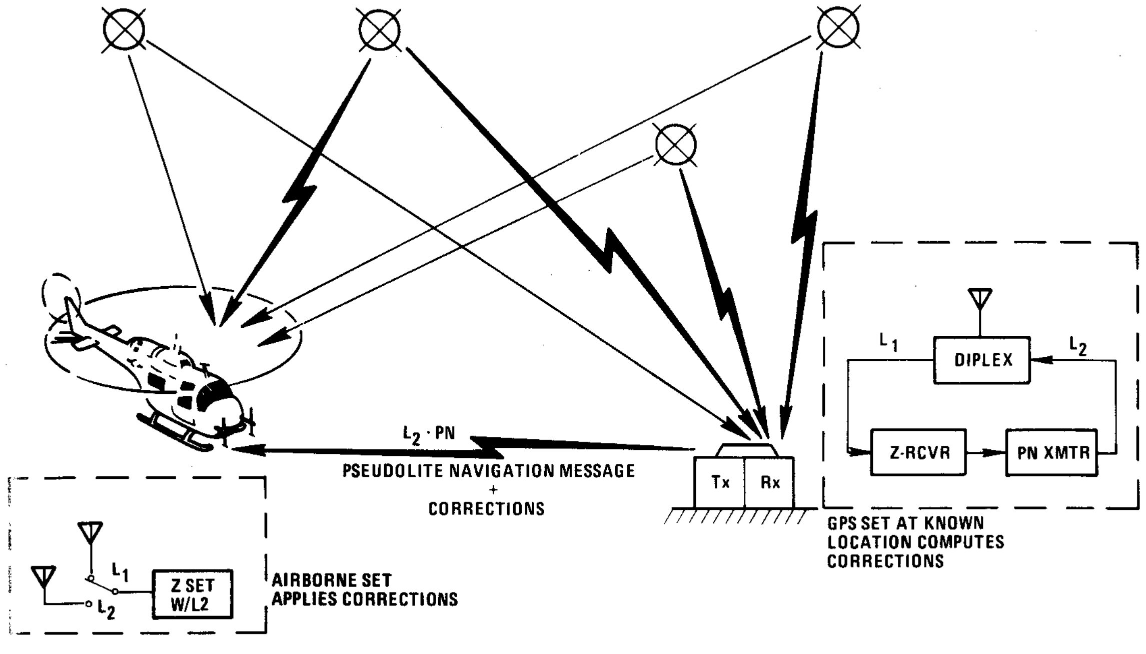

Figure 4. Differential GPS - Pseudolite Type

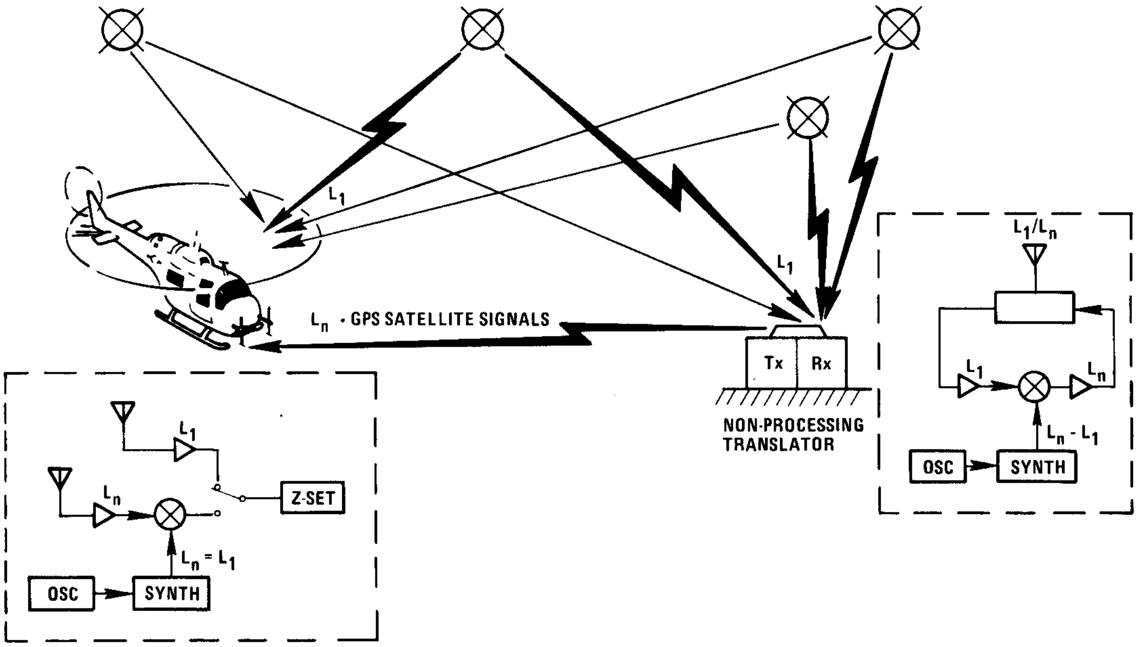

Figure 5. Differential GPS - Translator Type

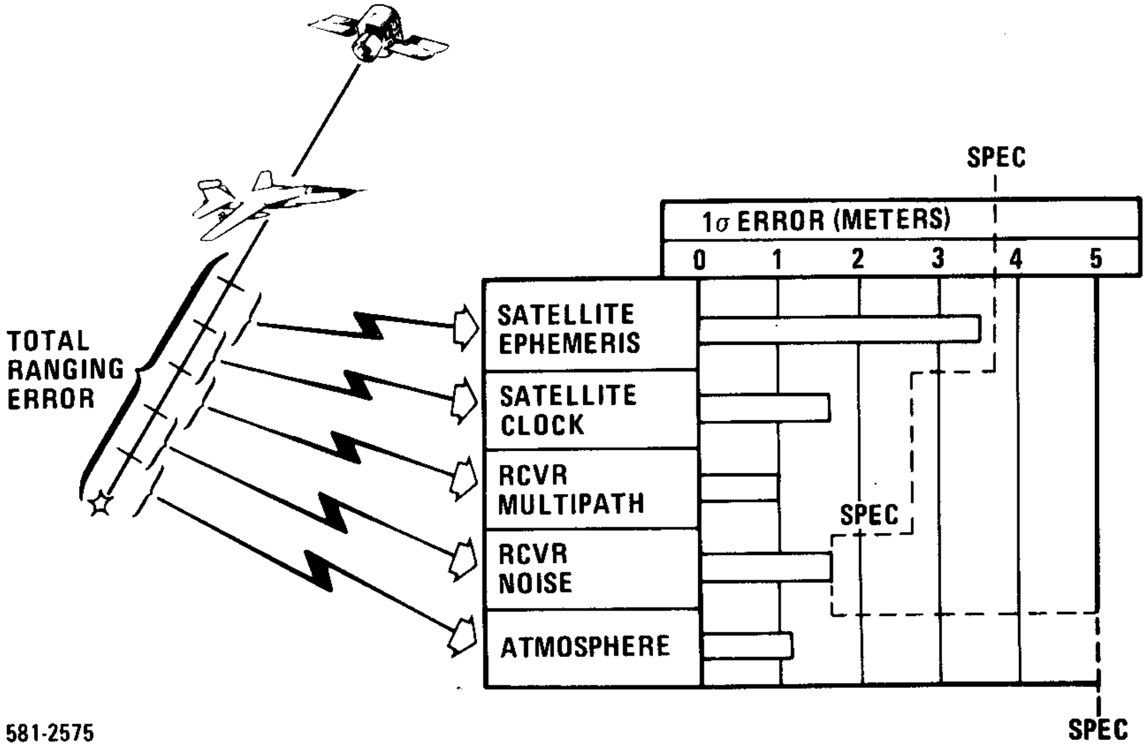

Figure 6. GPS System Error Budget Allocation - 1σ Field Test Results vs. Specification