NAVSTAR GLOBAL POSITIONING SYSTEM (GPS): FUTURE ENHANCED CAPABILITIES

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The Navstar Global Positioning System (GPS), which will be operational in the later part of this decade, will enable a user to determine his position and time with greater accuracy on a worldwide basis than has ever been achieved. This paper reviews and addresses three specific areas of research which are currently being done at The Aerospace Corporation in support of enhancing future capabilities of the Global Positioning System. These areas are 1) navigation using radio interferometric techniques, 2) analyses leading to more accurate orbit prediction of GPS satellites and 3) high precision application of GPS, beyond the current 16-meter spherical error probability (SEP) capability. Results and status of the ongoing activities of the various study areas are presented.

Keywords: Global Positioning System; navigation; interferometry; orbit prediction; clock modeling.

1. INTRODUCTION

Navstar Global Positioning System (GPS) is the most ambitious global navigation system ever attempted. It will be operational in the later part of this decade. The currently envisioned system will consist of 18 satellites suitably placed in orbit such that the user located at any region of the earth will be able to view at least four satellites at any given time. By acquiring and processing the continuously emitted radio signal from the satellites, the user will be able to determine his position and time with accuracy better than what has ever been achieved. The current system concept was the result of research and development over the years by the Department of Defense in the area of navigation technology.

The history and evaluation of the navigation technology program of the Department of Defense has been discussed in detail by Easton (1978). The Navy's Timation program and the Air Force's project 621B were extended to form the Navstar Global Positioning System in the early 70's. In the early years of the GPS, Navigation Technology Satellites (NTS) were launched primarily to provide the required technological understanding of the various subsystem elements of the space vehicle, in particular the onboard clock and frequency standard system. An overview of the Global Positioning System and the system concept have been described by Parkinson (1976). The system capability and specific system configuration are continuously evolving.

The GPS program consists of three phases where the Phase I was oriented towards validating the system concept; the Phase II is directed towards achieving operational evaluation and measuring system capability; by full-scale engineering development; and the Phase III will be the operational phase in which global navigation capability will be available. The basic system elements of the GPS are the space segment, the control segment, and the user segment. There exist several publications describing the characteristics and specific details of these segments, and a GPS special issue of the Journal of the Institute of Navigation (Summer 1978) contains some of these publications. However, a brief account of these segments is given here.

The space segment consists of satellites placed in a 12-hour period orbit. The phasing or placement of satellites is designed such that there exists global coverage for a user. The satellites radiate two spread-spectrum PRN radio signals. The navigation message, which consists of onboard clock and satellite ephemeris information, is modulated onto the PRN sequence. The two navigation signals are transmitted at two frequencies, L_1 (1575 MH_z) and L_2 (1227 MH_z). Both are coherently derived from a highly stable onboard clock. The control segment consists of master control, control monitor stations, and ground antennas. The control segment is responsible for the safekeeping of the satellites. The radiometric data from the satellites are tracked by the ground stations; accurate ephemeris and clock parameters are estimated by extensive data processing. Then predicted information in the form of a navigation message is periodically transmitted uplink to the satellites. The user segment consists of equipment with antenna, receiver, signal processing, and data processing capabilities. The satellite-transmitted radio signal is received by the user system knowing the signal PRN code, correlates the pseudo-range data. The navigation message is then demodulated; and the user state vector consisting of position, velocity, and time is computed.

Currently the system performance of each segment is being continuously evaluated. The continuous assessment of system capabilities has paved the way for further research and development for

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enhancing the total system capabilities. The purpose of this paper is to review and address these specific areas of research which are currently being performed at The Aerospace Corporation. These areas of activities are undertaken with two factors in mind. The first one is to identify state of the art advancements in related fields and to incorporate the development into the GPS program. The second is to fully exploit the inherent GPS concept for wider applications. The three areas of interest here are 1) navigation using radio interferometric techniques, 2) analysis leading to more accurate and durable orbit prediction, and 3) high-precision applications of GPS. The radio interferometry technique can be used to achieve better accuracy; however, modifications are required at the ground systems. Satellite modifications may also be necessary. User system signal processing and data processing capabilities will have to be enhanced to achieve high-precision applications.

2. RADIO INTERFEROMETRIC NAVIGATION

Radio interferometry has been classically used in radio astronomy to study the structure of compact natural radio sources and to locate these extra-galactic radio source positions. The applications of radio interferometry have been recently extended to areas in geodesy, astrometry, time and frequency synchronization, and satellite navigation. Here we shall review some of the research activities in radio interferometry related to our current interest and examine how an interferometric system can be applied to GPS and user navigation.

Figure 1 illustrates the underlying first principles of radio interferometry. Two ground antennas separated by some distance receive radio signals from a distant source. The delay between the arrival times of the radio signal at the two stations can be measured by cross-correlating the two signals and time shifting one of the signals to achieve peak correlation. Here the signal is

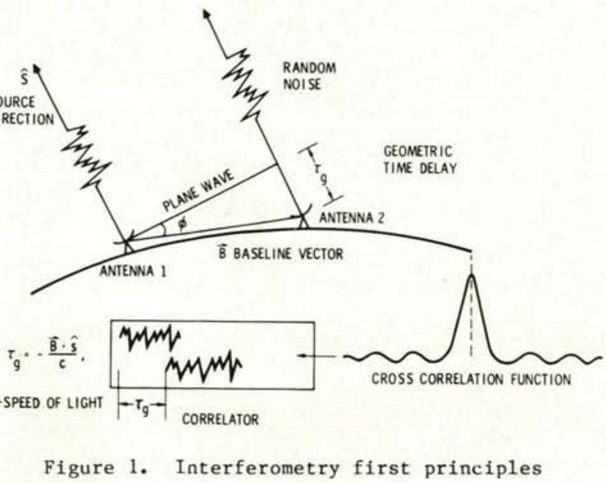

Figure 1. Interferometry first principles

assumed to be white noise, and since the radio source is distant, a plane wave assumption can be made. Observing the geometric time delay; the baseline distance; the distance between the ground antennas; and the orientation of this baseline with respect to the source can be determined. The observed geometric time delay is also equivalent to the measured range difference from the source to the ground antennas. When the interferometric technique is applied to radio signals generated from a nearby satellite, the curvature of the wavefront must also be taken into account. Figure 2 shows how the curvature correction can be applied to the measurement.

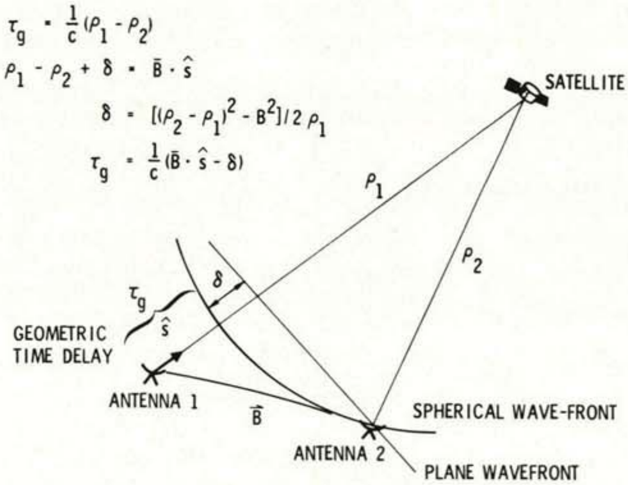

Figure 2. Interferometric measurement assuming spherical wavefront

There exists a large volume of publications related to the application of radio interferometry to geodesy, earth physics, and satellite navigation. Radio interferometry using Quasar (extra-galactic radio sources) signals has been utilized in earth physics applications by precise determination of geodetic control points achieving better accuracy for UT1 and polar motion (Ong and MacDoran, 1979; Neill et al., 1979). Very long baseline interferometry has been proposed to achieve accurate navigation of interplanetary probes using Quasar and spacecraft radio signals (Melbourne and Curkendall, 1977; Curkendall, 1978 and Brown et al., 1980). It has also been suggested that the radio signals radiated by the GPS satellites can be used instead of the extra-galactic radio sources for the earth physics applications (MacDoran, 1979; and Councilman and Shapiro, 1979).

Tables 1 and 2 represent some of the specific interferometric applications which have been demonstrated as well as those which are in progress. These have been updated from a presentation by Fanselow (1978). The results shown in Table 1 clearly illustrate the utility of the interferometric technique for geodetic applications.

Let us now examine how this advanced radiometric technology can be made useful to the GPS functions. As we discussed earlier, there are two primary functions of GPS. The control segment, by processing radiometric measurements, generates the navigation message which provides the predicted state of the orbit parameters of the satellites and clock model parameters. The user system by processing the psuedo-range measurements obtained from the satellites in combination with the acquired navigation message self

Table 1. Interferometry: Specific Applications (Achieved)

Program	Institutions (Sponsors)	Results
Haystack/Ovro/Fairbanks Triangle	MIT/HO/GSFC (DOD-ARPA)	1-3 m vector closure of baseline for a 4000 km baseline (1977)
Quasar Patrol	GSFC/MIT/HO/JPL (NASA, NSF)	20 cm repeatability of cross country baseline (1977)
DSN VLBI Development	JPL (NASA)	A) 50 cm accuracy CALIF/SPAIN baseline (1978) B) UTI to 2 m sec (1978)
ARIES (astronomical radio interferometry earth surveying)	JPL (NASA)	A) 3 cm vector repeatability on 18 km baseline (1978) B) 6 cm length agreement with NGS survey on 30 km baseline (1978)
Pacific Plate Motion Experiment	GSFC/HO/MIT (NASA)	A) Polar motion consistent with satellite doppler measurements at 30 cm (1978) B) 20-50 cm vector closure on various continental triangles (1978) C) Station location measurements consistent with geoceivers at 20-30 cm (1978)
DSN Operational VLBI	JPL (NASA)	Operational intercontinental VLBI system with weekly observations A) UTI/PM at 50 cm level (1980) B) Clock synch at 10 ns, freq. synch at 10^{-13} (1980)

Table 2. Interferometry: Specific Applications (In Progress)

Program	Institutions (Sponsors)	Expected Results
DSN VLBI Development	JPL (NASA)	5-10 cm vector repeatability on baseline
ARIES	JPL (NASA)	5-10 cm repeatability with high mobility 4m station over 200 to 2000 km baselines
SERIES (Satellite emission radio interferometry earth surveying) using GPS	JPL (NASA)	5-10 cm near real time accuracy with high mobility 1M antenna over 100 to to 500 km baseline
MITES (Miniature Interferometer terminals for earth surveying) using GPS	MIT (DOD-AFGL)	5-10 cm accuracy over 100 to 2000 km baseline
DSN Differential VLBI	JPL (NASA)	10 to 50 nrad angular accuracy for deep space navigation

determines its location in a geodetically referenced coordinate system. The radio interferometry techniques can be applied to both these functions provided some required system modifications are implemented.

Sensitivity analyses have been performed to determine the achievable orbit accuracy of the GPS satellites with an interferometric system. Three specific cases have been studied. In the first case, satellite position error has been computed after 3 hours of tracking assuming two baselines utilizing three ground stations. The baselines were assumed to be near orthogonal. Interferometric measurements with a random noise of 30 cm averaged over 10 secs were generated from a single GPS satellite. The analysis was performed such that the estimated parameters were the orbit state of the GPS satellite, two clock biases between the station pairs, and a solar radiation constant. The estimated covariance was adjusted to account for the effect of model errors in the solution. This covariance is termed "consider" covariance since it accounts for the data noise errors and the errors in the observational model. The "consider" parameters in this analysis were the relative station location errors of 1 m (1σ) and a sixth degree and order geopotential model error.

The results are tabulated in Table 3. Two baseline lengths of 2000 km and 4000 km were studied, as well as the sensitivity to addition of range rate data. The range rate data were weighted at 5 cm/sec in the first case and totally removed in the second case. Results indicate that the achievable accuracy improves by a factor of two by the inclusion of the range rate data. Results also show that the accuracy depends on the length of the baseline.

Table 3. Satellite Position Error After 3 hrs. of Tracking

Baseline Length (km)	Range Rate Data (1σ)	Position Error (Meters)		
		Radial	Intrack	Cross Track
2000	5 cm/sec	10	8	18
2000	--	26	18	16
4000	5 cm/sec	6	3	7
4000	--	13	12	9

In the second case, data from multiple GPS satellites were processed for a longer arc length. Similar to the previous case, three stations with two baseline of 2000 km length were used to generate the measurements. Interferometric measurements were generated from four GPS satellites and data coverage varied from 5 to 9 hrs/day among these stations. Range rate data were not processed along with interferometric data. Data were accumulated for 5 days whenever the satellites were visible from the assumed station pairs. In the analysis the four GPS satellite states (position and velocity components) were assumed to be uncorrelated between satellites and were estimated along with two clock biases between station pairs and the two baseline vectors. The unmodeled effects of a sixth degree and order geopotential field were treated as "considered" parameters. The results are given in Table 4.

Table 4. Satellite Position Error After 5 Days of Tracking

Satellite No.	Position Error (Meters)		
	Radial	Intrack	Cross Track
1	2	5	3
2	1	4	4
3	2	4	3
4	2	5	4

The viewing geometry in relation to the interferometric baseline is responsible for the difference in the achieved position accuracy among the four satellites. The level of accuracy was reached when 3 days of data were processed.

A simulation analysis was performed to evaluate the best fit ephemeris for two Phase I satellites assuming conventional range and accumulated range change data using four monitor stations. Results showed that radial errors are of the order 1 to 2 meters and horizontal errors (the root sum square of intrack and cross track) are of the order of 10 to 15 meters. (Results are published in an internal document by Bierman and Feess, 1979.) Here, by comparison it indicates that the interferometric data types perform as well or better in establishing the satellites orbits.

The third case was to evaluate the accuracy with which a user position can be determined with respect to a known point. In this case measurements have to be acquired at both the user location and the reference locations simultaneously and the data acquired at the reference location have to be transmitted to the user in real time. This data transmission can be accomplished by utilizing a communication satellite or via a voice channel communication line, depending on the relative distance and the data rate. If the raw measurements (time tagged radio signals at 20 Mhz) were transmitted, then a wideband data line through a communication satellite may be necessary. However, if range measurements after local model correlation have to be transmitted to the user, a low data rate voice channel can be utilized.

In this analysis, it was assumed that four GPS satellites were visible simultaneously from one reference station and two user systems. The users were selected such that they form a north-south and east-west baseline with respect to the reference station. Baseline spacings of 1°, 5°, 10° and 15° were assumed and interferometric measurements were generated with a 10 sec data rate for 10 min. Estimated parameters were the relative baseline length and orientation, the clock bias between the user, and the reference station. An orbit state error of 10 m spherically distributed is "considered" for the four GPS satellites. Results are given in Table 5.

Table 5. User Position Accuracy

Cases	Baseline Length (Degrees)	Relative Position Error (Meters)					
		North-South Baseline			East-West Baseline		
		Lat	Long	Altitude	Lat	Long	Altitude
After Processing Single Set of Measurements	1	0.8	1.9	1.4	0.8	1.9	1.4
	5	1.0	2.2	1.7	0.8	2.2	1.8
	10	1.4	3.1	2.4	1.0	2.9	2.6
	15	1.9	4.1	3.3	1.1	3.7	3.5
After Processing 10 mins of Measurements	1	0.2	0.3	0.3	0.1	0.3	0.3
	5	0.6	1.3	1.0	0.5	1.2	1.0
	10	1.1	2.4	2.0	0.7	2.1	2.0
	15	1.6	3.4	2.9	0.9	3.0	3.0

Two specific cases of the results are tabulated. The first set of solutions show the instantaneous result after processing the first set of measurements. This result would be directly applicable to a non-stationary user. The results for north-south and east-west baselines are very similar; however, the difference is due to the satellites-baseline geometry. The effect of satellite geometry is similar where either pseudo-range or interferometric are utilized by a user system.

It is interesting to note that the accuracy degrades as the baseline length is increased. This is because of the sensitivity to the GPS satellites orbit errors. The orbit errors can be categorized into two types: One is in the direction of the line of sight of the user which is similar to the radial error; and the other is in the plane normal to the line-of-sight direction. The latter is the combination of the intrack and the crosstrack errors. Now, when the interferometric measurements are formed, since these are instantaneous differenced range measurements, the radial component of the orbit errors explicitly get cancelled. However, the error component in the plane normal to the line of sight does not get cancelled totally. The sensitivity to this error component depends on the length of the baseline. The effect gets scaled by the ratio of the baseline length to the GPS satellite altitude.

Comparison between the first and second sets of results (after processing a single set of measurements and after processing 10 mins of measurements) reveals that no significant improvement exists in the achievable accuracy by processing a large number of data points, except for the case where the baseline length is 1 degree. This is because the limiting error source is the GPS satellite orbit errors except for the 1 degree baseline case. This example clearly suggests that the achievable accuracy for a stationary or non-stationary user for determining relative position using interferometric measurements is of the order of a few meters. This level of accuracy would satisfy the requirements of most of the users. It should also be noted here that the uncertainty in the reference station location in an absolute coordinate system would map one-to-one to the user location in that coordinate system, since this measurement will only provide relative information.

Some of the principal advantages of this measurement technique are as follows. The effect of satellite onboard clock errors does not affect the user location determination, since the clock error gets cancelled totally when the measurements are generated. This is the primary error source in the psuedo-range measurements. Similar to clock error, satellite orbit errors in the radial direction dominate the user range error when a range measurement is made. When an interferometric measurement is made, this error component gets cancelled and thus, the sensitivity to GPS satellite orbit errors is significantly reduced.

Further analyses continue to evaluate the achievable accuracy when the reference station is also moving with an uncertainty in position as well as an uncertainty in its velocity. Studies will determine the sensitivity of the velocity error of the reference station to the stationary or non-stationary user. In addition, studies will also establish how accurately the user velocity can be determined, and how this result will vary when the user is moving with continuous acceleration.

A prototype operational system concept using interferometric techniques is being currently designed. The details of such a system will be presented in another paper. Analyses indicate that the state of the art technology seems viable and currently available.

3. ORBIT PREDICTION

Accurate orbit prediction of a natural or an artificial satellite has always been a difficult problem in celestial mechanics. This is primarily due to the inability to model the perturbing forces. In the case of GPS satellites, from a user's point of view there are two parts to the orbit prediction problem. The user not only needs the accurate ephemeris of the GPS satellites, but also the accurate time information from the onboard clock. All the various clocks on the various GPS satellites are time referenced with a master clock at the master control station. However, these clocks drift with a varying drift rate. Thus each clock has a model which represents its predicted behavior. These clock model parameters and the orbit ephemeris parameters are simultaneously estimated for each satellite by processing the radiometric data acquired from the various monitor stations. Thus, the clock parameters and orbit parameters are correlated. However, since the user utilizes the clock parameters in combination with the ephemeris information, the independent error of one set of parameters (e.g., ephemeris) is not apparent to the user. It is thus essential to improve both the clock prediction models as well as the predicted ephemeris models to achieve better accuracy for the user.

The performance of onboard clocks determines the success of the GPS concept as currently developed. Research and development of highly stable clock systems are a continuing process, and significant progress has been made in the last few years. The Timation program and the Navigation Technology Satellite program by the U.S. Navy have contributed considerably to the advancement of satellite-borne, highly stable cesium frequency standard systems. The history, development, and some of the details of this technology have been reviewed by Bartholomew (1978). The Phase I and the ongoing Phase II activities of the GPS program are providing a large volume of data to evaluate the performance of onboard rubidium and cesium frequency systems.

Frequency stability performance as observed in the laboratory for various types of clock systems are shown in Figure 3. The fractional frequency variations as a function of sampling interval for both satellite-borne clocks and experimental ground based hydrogen maser systems are shown in

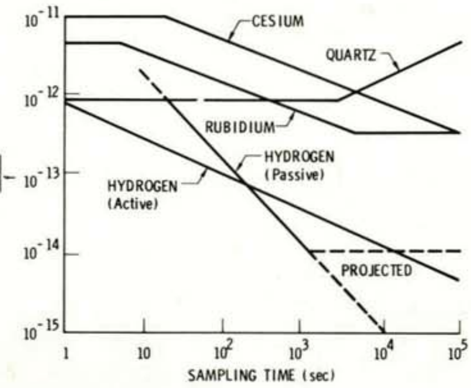

Figure 3. Frequency stability of onboard satellite clocks and experimental hydrogen masers

the figure. Data for long time stability (a number of days) performance analysis are limited. Evaluation of GPS data has shown that the fractional frequency variation of a rubidium frequency system for a sampling interval of 1 day is in the range of 1 to 2 × 10^{-13} (Feess and Hendrickson, 1980, internal document). The ultimate anticipated performance level for the Phase III clock system is an improvement by a factor of 2 to 4.

This paper reviews some of the studies which are currently underway to develop requirements and capabilities to achieve GPS satellite orbit prediction accuracy (inclusive of both onboard clock and ephemeris) to the order of 10 to 20 m for a two to four-week period. There also exists an ongoing research activity related to the rubidium frequency standard. The primary objectives are to investigate the physical processes that limit the performance of the rubidium gas cell frequency and to improve the stability and ongoing characteristics of this frequency standard (P. F. Jones, 1980, personal communications).

Three independent studies have been initiated to achieve accurate orbit prediction capability. These are 1) to develop system requirements and capabilities to reduce prediction errors due to perturbative force model errors; 2) to investigate the feasibility and application of satellite-to-satellite radiometric measurements when augumented with conventional ground based radiometric measurements to achieve better orbit knowledge and thus better prediction capability; and 3) to develop better navigation messages in format and content such that polynomial evaluation error is minimum when predicted ephemeris is evaluated over a longer period of time. We shall briefly examine how these studies are being carried out. The results of these studies will be reported in separate publications.

In addition to the uncertainties in the models for perturbing forces, the predicted trajectory error strongly depends on the accuracy with which the orbit can be determined by processing the acquired data. Thus, efforts need to be taken to achieve significant improvement in the orbit knowledge. The current Phase I control segment of GPS processes only the range and accumulated range change data. It has been shown in the previous section that the interferometric differenced range measurements alone can provide orbit accuracy on the order of a few meters. Thus, one of the objectives of this study is to determine operational data combinations including data weighting, optimal arc length, and parameter sets that need to be estimated.

Preliminary analyses of the predicted orbit error budget indicate that the largest error contribution next to the mismodel effect of the clock is due to the model error in the solar radiation pressure effects. This effect is sensitive to the orbit geometry in relation to the satellite-sun direction. Efforts are directed to minimize the error contribution due to the force by 1) improving the model of the satellite geometry facing the sun, 2) redefining a combination of parameters that when estimated would reduce the predicted error, and 3) by improving data processing strategy.

Another perturbation force which causes the long term prediction error is the mismodel effect of the earth's geopotential field. The geopotential model currently in use in the Phase I and II GPS program is WGS72 (Seppelin, 1974) truncated to degree and order eight. Analyses by Laubscher (private communications, 1980) have shown that a different gravity model "GEM 9" outperforms WGS72 in the prediction processes for some of the satellites, but is worse for the other satellites. This indicates that better knowledge of the gravity model tailored to the GPS orbits may reduce the prediction error. Thus, further analysis will be performed to evaluate the sensitivity of these gravity coefficients and to evaluate the achievable accuracy utilizing a tailored geopotential model.

It is not currently clear whether the required accuracy improvement in the predicted trajectory by an order of magnitude is achievable by the proposed techniques outlined here. However, once the sources of large error contributions are identified, it may be possible to develop requirements on the system to reduce the error contributions. For example, if the clock error dominates over a long period, the long term stability of the clock will have to be improved to achieve the required accuracy.

The analyses so far performed in order to determine the orbit of GPS satellites assume that the orbit states of these satellites are totally uncorrelated and independent. The conventional process is that the ground tracking stations acquire radiometric data from each satellite and transmitted to the master control station after which independent orbit estimates are generated. However, since same ground stations, master control station clock, geopotential model, pole wander model, and other ground system related models are utilized in the data processing of all the satellites, there exists an indirect correlation between the state parameter of the various satellites. This aspect has not been fully exploited to achieve a better orbit determination accuracy. In this paper, a brief review of an analysis which is being done to currently evaluate the information content of an additional data type, i.e., relative (satellite-to-satellite) radiometric measurements, is presented. Preliminary results from the analysis are given by C. C. Chao (internal document, 1981).

The use of satellite-to-satellite measurements either taken onboard or generated on the ground by explicitly differencing the ground-based measurements to each satellite has been studied previously. Most of the application of this technique in the literature is found in the interplanetary navigation studies (Ananda et al., 1980; and Chao et al., 1976). The relative measurements provide the relative information without any degradation due to the mismodel effects of ground tracking system. Thus, the purpose of this study is to evaluate the application of this concept in the GPS satellite ephemeris determination scheme.

There will be two antennas onboard the Block II GPS satellites. The primary antenna is designed such that it points always towards the earth and the continuous emission of radio signals (L_1 and L_2) to the users is achieved. The purpose of secondary antenna is to achieve cross-link communications among the GPS satellites at UHF. Analyses have shown that a GPS satellite with a GPS receiver onboard does not have a sufficient number of visible satellites with "good" geometry conditions when the data are transmitted using the primary antenna, mainly because of the earth occultation. In addition, it is not clear whether one can transmit and receive data continuously with the same antenna using the same frequency due to intermodulations of the transmitted and received signals. Since the secondary antenna power distribution is designed to achieve crosslink communication in all directions except in the earth occultation cone, the choice of a secondary antenna for transmitting radio signals among GPS satellites seems to be promising. However, there exists a major concern about the required satellite changes in order to accomplish transmission of navigation messages at a frequency other than L_1 and L_2.

This study assumed an 18-satellite constellation with six orbital planes and three satellites placed in each plane. The six-plane constellation is shown in Figure 4. The operational

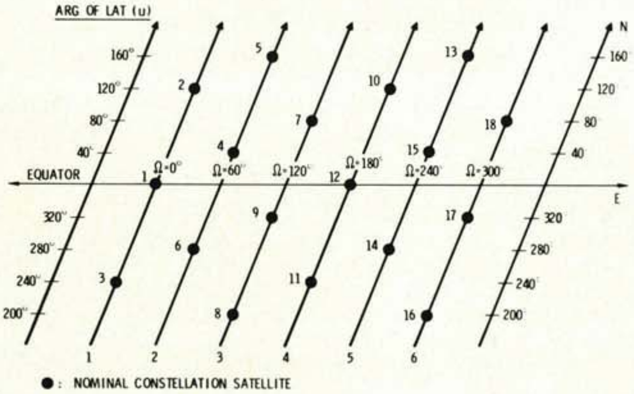

Figure 4. GPS 6 plane constellation

Phase III constellation decision has not yet been made. The paper by Book et al., (1980) discusses some of the principles in determining the optimum constellation for maximum coverage. Figure 5

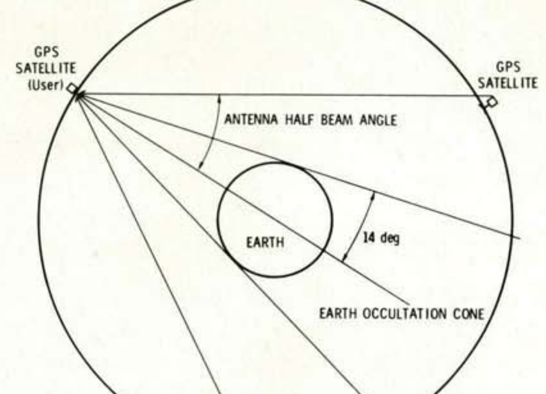

Figure 5. Geometry of GPS satellite to satellite tracking

shows the viewing geometry for satellite-to-satellite tracking. The antenna beam half angle determines the number of visible satellites from a particular GPS satellite. Instantaneous position determination for a user requires data from at least four satellites with favorable geometry. However, for most satellite users, real-time, instantaneous knowledge of the orbit is not required. The concept of "geometric dilution of precision" (GDOP) has been used to determine a measure of navigation accuracy. The application of GDOP was first introduced in relation to the LORAN navigation system. The GDOP is defined as the square root of the trace of the covariance matrix with three user position parameters and the user clock bias term. The variations in GDOP for a user GPS satellite over a period of 24 hours has been computed assuming visibility conditions constrained by both primary and secondary antennas. The analysis indicates that an improvement by a factor of 5 to 6 is achieved when the secondary antenna is utilized compared to the primary antenna. Figure 6 shows the variation in GDOP when the secondary antenna is used. The pattern repeats every six hours and only about an hour within the 6-hour period the geometry is relatively unfavorable. The GDOP values are comparable to a ground based user.

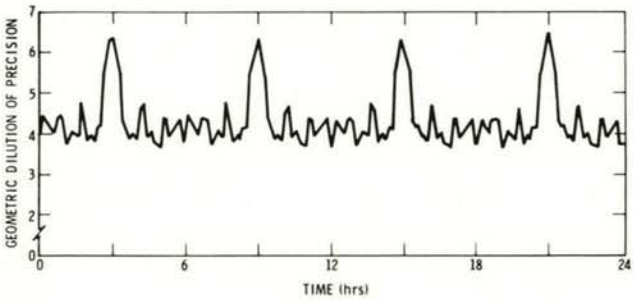

Figure. 6. Variation of GDOP at a GPS satellite

Thus the GDOP analysis indicates that with satellite-to-satellite measurements alone it is possible to determine the satellite position and thus its orbital state to the required accuracy. The use of a combination of earth based measurements and satellite-to-satellite measurements in determining the orbits is currently under investigation. However, it is expected that the relative measurements would provide information which is insensitive to some of the common error sources such as station locations UTI, polar motion and media effects, that would help in achieving better orbit prediction accuracies.

Another area of research is to evaluate whether it is possible to develop a better navigation message in both format and content with reduced error over a longer period of prediction. The Phase I and II navigation message format is discussed in detail by Van Dierndock et al., (1978). The Phase III message format is a little different. The only additional parameter is the inclination rate term which would help to reduce the crosstrack error.

A brief review of the Phase III satellite ephemeris related message format as currently planned is given here. The ephemeris data set will cover a 14-day span. A 15-parameter set for each hour of the first day will be available. For the next 13 days there would be a parameter set for each four-hour period. However, each parameter set will continue to be valid for a period after the next set has become valid. For the first day parameter sets the additional validity period is three hours, whereas for the next 13 days' parameter sets the additional validity in period is only two hours. If one uses the parameter set beyond the validity period, the accuracy degrades rapidly.

The use of Tchebysheff's polynomial for representing Cartesian position coordinates rather than the orbital elements is currently evaluated. Instead of storing coefficients for representing velocity components, the polynomial representing the position components can be differentiated to obtain the velocity components. Error analyses are being performed to evaluate the achievable accuracy. Preliminary results indicate that fewer of parameters can provide the same level of accuracy for a longer period of time.

4. HIGH ACCURACY APPLICATION

Several investigators have examined the application of the GPS to civil and scientific uses. The civil application is discussed in detail by Euler and Jacobson (1980). Some of the scientific applications include precision time transfer (Allan et al., 1980), space navigation (Farr, 1979; Van Leeuween et al., 1979) and geodetic positioning (Fell, 1980; Anderle, 1980). In this paper we shall limit our investigation to evaluating the use of GPS to achieve high accuracy orbit estimates for low altitude earth orbiters.

The use of low altitude earth satellites has been extremely valuable for both geodynamics and oceanographic research. One of the primary limitations has been the accuracy with which the orbital state of the satellites can be determined, (Tapley and Born, 1980). The orbit determination of the satellites is conventionally achieved by processing radiometric tracking data from a net of ground based tracking stations. The continuous tracking of the low altitude satellites is practically impossible because of the limited availability of the number of ground stations. This, coupled with the current uncertainty in modeling the perturbing forces on the satellites, limits the achievable accuracy. The use of ground based laser ranging measurements has shown that the accuracy can be improved considerably provided laser tracking is available over the better part of the satellite orbit. Due to the restricted number of currently available laser ranging stations and the strong dependency of laser tracking on weather conditions, this data type may not be suitable for improving orbit determination accuracy.

The best achievable accuracy utilizing ground based radiometric techniques is currently on the order of one to two meters (Tapley and Born, 1980). For geodynamic applications such as gravity field modeling for studying both earth's interior and generating other geophysical models and oceanographic studies to model ocean surface topography and ocean currents, it is essential to determine the geoid to an accuracy of about 10 cm. When a satellite referenced sensor such as a laser or radar altimeter with an accuracy of 5 cm is used, the knowledge of the satellite orbit to a similar level of accuracy, employing observables other than altimeter measurements, is

needed to fully utilize these measurements. However, by conventional radiometric methods the required accuracy may not be achievable.
Thus, an alternate measurement technique may be needed if the desired accuracy has to be achieved. The use of the GPS has been examined previously, as mentioned earlier, to achieve satellite navigation. However, the improved accuracy on the order of tens of cms was not the criterion of the previous studies. In addition, our analyses indicate the pseudo range and the accumulated range change (integrated Doppler) measurements which are available to the user satellite from GPS satellites can only provide an orbit accuracy of 1 to 2 m. This accuracy limitation is primarily due to the sensitivity of the user satellite orbit error to the orbit error of the GPS satellites. The radial error in the knowledge of the GPS satellite orbit contributes significantly to the uncertainty of user satellite orbit error. Since the required accuracy is about an order of magnitude higher than that which can be achieved by processing direct measurements from the GPS satellites, a new technique utilizing radio interferometry is being investigated.

The interferometric measurements are generated by simultaneous reception of radio signals by two antennas separated by a distance. Here, the measurements are generated by simultaneous reception of radio signals from the GPS satellites by the user satellite and a ground station. A small number of ground stations are optimally placed such that any pair consisting of one of the ground stations and the user satellite can always see a constellation of four or more GPS satellites. The selection of ground stations is further refined by constraining their location to achieve good GDOP conditions. Figure 7 shows the distribution of a possible set of ground stations.

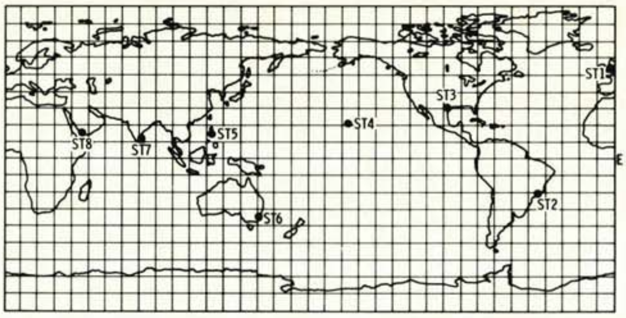

Figure 7. Selected ground station locations

The interferometric measurements can be generated in two ways. The first method requires cross correlation of radio signals acquired at the user satellite and one of the ground stations. This provides the delay in the arrival time of the radio signal emitted from a GPS satellite between the user satellite and a ground station. This time delay corresponds to the range difference between the satellites and the ground station from the GPS satellite. However, the cross correlation method requires transmission of a large data volume to the ground. In the second method, the cross correlation technique is not utilized.
The interferometric measurements are generated by explicitly differencing the simultaneous range measurements obtained at the user satellite and the ground station. These range measurements can be made by using the GPS receiver equipments which are capable of performing the P-code signal processing. However, the orbit determination is achieved in a postflight data processing mode and not in real-time.

The expected accuracy of these interferometric measurements is on the order of 20 cm for an averaging time of 10 s. Ionospheric calibrations using L_1 and L_2 frequencies and topospheric calibrations are needed at the ground stations. Depending on the altitude of the user satellite, the ionospheric calibrations may not be required at the satellite end. The analysis performed in this study assumed a user satellite geometry shown in Table 6. The assumed GPS constellation

Table 6. User Satellite Geometry and Error Analysis Parameters

Satellite Geometry:
Period = 100.9 min
a = 7179.992 km e = 0. I = 72. deg ω = 0. Ω = 31.91 deg
Estimated parameters:
User satellite orbit state, relative station locations(baseline vectors), clock synchronization biases between the user satellite and ground stations.
Unadjusted "Consider" parameters:
GPS satellites orbit errors, Absolute single station location error, eighth degree and order harmonic coefficients geopotential model error.

is shown in Figure 4. The viewing periods in order to generate interferometric measurements utilizing the ground stations are shown in Figure 8. The ground stations are assumed to have 5° elevation mask to generate measurements. Figure 8 clearly shows that there are at least five GPS satellites visible from both ends of the baseline (user satellite and one of the ground stations) during one orbital revolution of the user satellite. However, there exists a few minutes of data gap which is primarily due to another constraint on the system that the interferometric measurements are only generated when the baseline distance (the line of sight distance from one of the ground stations to the user satellite) is less than 4000 km.

Detailed error analyses have not been completed. However, preliminary results indicate the desired accuracy on the order of tens of cm for the user satellite orbit position can be achieved by this method. The analysis assumed the error parameters given in Table 6. The covariance analysis

** Ground Stations \ GPS* Sats	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	19-32	14-32		14-32			14-32				14-32			14-32		14-32		
2	10-29	10-29		10-29			10-29				10-29		10-29	10-29		10-29		
3	0-15							0-15			0-15		0-15	0-15		0-15		
4			84-98		84-98	84-98		84-98		84-98								84-98
5		59-72	53-72		53-72					53-72		68-72			53-72		53-72	
6			66-80		66-80			66-80							66-80		66-80	66-80
7			37-55		37-55			37-49		37-55	37-55				37-55		37-55	
8		7-36		17-36			17-36				17-36		31-36	17-32		17-32		

* GPS satellites are numbered as shown in Figure 4
** Ground stations are numbered as shown in Figure 7

Figure 8. Viewing periods; start and end times in minutes for generating interferometric measurements employing the user satellite and the ground stations

showed that the sensitivity of the user satellite position accuracy to the GPS satellite orbit errors is minimized by processing the interferometric measurements. Detailed analysis to evaluate the sensitivity to processing the interferometric measurements. Detailed analysis to evaluate the sensitivity to processing arc lengths, unmodeled gravity parameters, polar motion parameters, relative clock drift, and other unmodeled force parameters is being done and the results of this study will be published separately.

5. SUMMARY

Three specific areas of advanced studies related to improving system capabilities of the GPS have been reviewed. These areas are radio interferometric navigation, accurate satellite ephemeris prediction, and high accuracy GPS application. Some preliminary results of the studies in these areas have been presented with a brief discussion of the study scheme.

Several other areas of research and development activities are also being pursued to improve the GPS performance. Some examples are 1) the use of a highly stable hydrogen maser frequency system at the control center, 2) evaluation of ionospheric scintillation effects on the radio signal, and 3) analysis related to the long term (several weeks) stability of satellite-borne frequency systems.

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