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Fellowship: Final Report

Error Analysis of Real Time and Post Processed Orbit Determination of GFO Using GPS Tracking

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Introduction

The goal of the Navy's GEOSAT Follow-On (GFO) mission is to map the topography of the world's oceans in both real time (operational) and post processed modes. Currently, the best candidate for supplying the required orbit accuracy is the Global Positioning System (GPS). The purpose of this fellowship was to determine the expected orbit accuracy for GFO in both the real time and post processed modes when using GPS tracking. This report presents the work completed through the ending date of the fellowship.

Real Time Operational Mode Study

The purpose of the real time mode of operation is to supply the naval fleet with altimeter and orbit height data in near real time for mesoscale studies. Requirements for the orbits used in these applications are that they are smooth and that the orbit error contains no spectral power at mesoscale frequencies. There are space qualified GPS receivers that compute satellite orbits in real time, but the spectral components of the orbit errors are not known.

Due to it's light weight, low power consumption and low cost, the ROCKWELL AST V GPS receiver was chosen to be studied. A simulation software package was written to incorporate the relevant GPS error sources and the AST V GPS receiver navigation algorithm. Numerical simulations showed spikes in the GFO radial orbit error time series which were due to new GPS satellites being used in the navigation solution. An attempt was made to smooth these spikes by simultaneously de-weighting and weighting the data strength of the old and new GPS satellites, but the resulting orbit error still contained power at mesoscale wavelengths. Presently, other strategies for removing the signal power at mesoscale frequencies are being investigated.

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Post-Processed Precise Mode Study

The Global Positioning System (GPS) has the capability to supply post-processed positioning of unprecedented precision for low Earth orbiting (LEO) remote sensing satellites such as GFO. When the Department of Defense (DoD) enables their policy of Selective Availability/Anti-Spoof (SA/A-S), this positioning precision will be degraded for non SA/A-S qualified receivers because they will no longer be able to use a dual frequency mode of ionospheric calibration. However, there does exist a single frequency mode of ionospheric calibration called Differenced Range Versus Integrated Doppler (DRVID)[1] that may benefit GPS applications.

The OASIS[2] software package developed at the Jet Propulsion Laboratory was used to complete a series of covariance analyses for the GFO satellite using SA/A-S qualified (dual frequency ionospheric calibration) and non SA/A-S qualified (single frequency/DRVID ionospheric calibration) GPS receiver configurations. These covariance analyses showed that the radial orbit height of GFO can be determined to an accuracy of 3.5 cm root mean square (rms) if reduced dynamic tracking is used. Even more surprising, these analyses showed that the non SA/A-S qualified receiver configuration (DRVID calibration) can approach the 10 cm level in GFO radial uncertainty if all systematic errors are removed from the C/A pseudorange and reduced dynamic tracking is again used. The above results are discussed more thoroughly in the attached paper that was presented at the AIAA/AAS Astrodynamics Conference in Hilton Head, South Carolina[3].

Summary

The work completed under this fellowship has provided insight into using the GPS for real time and post processed satellite orbit determination of GFO. Analyses showed that the ROCKWELL AST V GPS receiver will not provide GFO radial orbit heights that are suitable for real time mesoscale studies. However, additional processing of the GPS orbit solutions may provide radial orbit heights of sufficient quality. In addition, covariance analyses showed that the post processed radial orbit height of GFO can be determined to an accuracy of 3.5 cm rms when using a SA/A-S qualified (dual frequency) GPS receiver configuration and reduced dynamic tracking. This level of accuracy increases to 10 cm rms when a non SA/A-S qualified (single frequency/DRVID ionospheric calibration) GPS receiver configuration and a reduced dynamic tracking strategy are used. A single frequency GPS receiver could greatly reduce the receiver mass, size, and power requirements and also receiver complexity because, SA/A-S hardware is not required. A trade-off must be made between expected orbit uncertainty and the cost and complexity of the GFO mission.

References

[1] MacDoran, P.F, "A First Principles Derivation of Differenced Range Versus Integrated Doppler (DRVID) Charged Particle Calibration Method", JPL Space Programs Summary 37-62, Vol. II, February 1970.

[2] Wu, S. C., J. S. Border, S. M. Lichten, R. F. Sunseri, B. G. Williams, and J. T. Wu. OASIS Users' Guide, V. 1.0; Jet Propulsion Laboratory, D-3138. April 1, 1986.

[3] Schreiner W.S., George H. Born, Peter F. MacDoran, Kristine M. Larson, "Error Analysis of Post Processed Orbit Determination of GFO Using GPS Tracking AAS Paper 92-4435, AIAA/AAS Astrodynamics Specialist Conference, Hilton Head, South Carolina, August 10-12, 1992.

ERROR ANALYSIS OF POST-PROCESSED ORBIT DETERMINATION FOR THE GEOSAT FOLLOW-ON ALTIMETRIC SATELLITE USING GPS TRACKING

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Abstract

The Global Positioning System (GPS) has the capability to supply post-processed positioning of unprecedented precision for low Earth orbiting (LEO) remote sensing satellites. When the Department of Defense (DoD) enables their policy of Selective Availability/Anti-Spoof (SA/A-S), this positioning precision will be degraded for non SA/A-S qualified receivers because they will no longer be able to use a dual frequency mode of ionospheric calibration. There does exist a single frequency mode of ionospheric calibration called Differenced Range Versus Integrated Doppler (DRVID) which creates a new ionosphere-free carrier phase observable with a noise level equal to half the magnitude of the C/A pseudorange noise level. This paper presents a series of covariance analyses for the Navy's GEOSAT Follow-On (GFO) altimetric satellite using SA/A-S qualified (dual frequency) and non SA/A-S qualified (single frequency) GPS receiver configurations. These covariance analyses show that the 10 cm GFO post-processed radial orbit accuracy requirement can be met with a SA/A-S qualified GPS receiver when using reduced dynamic tracking. Even more surprising, the analyses show that the non SA/A-S qualified receiver can also approach this 10 cm radial uncertainty level if all systematic errors are removed from the C/A pseudorange and reduced dynamic tracking is again used.

I. Introduction

Satellite altimetry was first used to infer ocean circulation with SKYLAB (1973), and continued with GEOS-3 (1975 - 1978), SEASAT (1978), GEOSAT (1985 - 1990), ERS-1 (1991) and will continue with TOPEX (1992) and GEOSAT Follow-On (GFO, ~1995). Altimetric satellites do not measure oceanographic signals directly, but use a combination of altimetry data and radial orbit height data to produce sea surface height measurements. Therefore, the resultant error in the sea surface height measurement will be the addition of the altimeter measurement error and the satellite radial orbit error. The precision of the altimeter measurement has improved from 1 meter root mean square (rms) for SKYLAB[1] to an estimated 2.4 cm for TOPEX[2]. Currently, the post-processed radial orbit error for the GEOSAT Exact Repeat Mission (ERM) has been limited to 35 cm using 6 day dynamic arcs of TRANET Doppler tracking[3]. The post-processed radial orbit accuracy for TOPEX is expected to be less than 10 cm rms after gravity field tuning with laser ranging tracking[4]. Even at this 10 cm level, satellite orbit determination is still the factor limiting the accuracy of post-processed sea level determinations.

Because of the success of the GEOSAT altimetric mission, the U.S. Navy has decided to launch two or three GEOSAT Follow-On replenishment satellites. The GFO mission will provide the Naval operations with ocean topographic data for use in tactical situation evaluations under all weather conditions. The payload will include a single frequency (K band) radar altimeter, a water vapor radiometer, a Doppler beacon, and a precision tracking system. The purpose of the precision tracking system is to provide post-processed orbits precise at the 10 cm rms level in the radial direction. Currently, the best prospect to provide the required post-processed orbit precision of GFO is the Global Positioning System.

The Global Positioning System (GPS) is a satellite based positioning system that offers Coarse Acquisition (C/A) and Precise (P) code pseudoranges and highly precise carrier phase (integrated Doppler or biased range) observations on two frequencies (L1 = 1575.42 MHz and L2 = 1227.6 MHz) for determining the position of a receiver on the surface of the Earth or on low Earth orbiting (LEO) satellites. Studies on the TOPEX altimetric mission[5,6] have shown that the GPS has the potential to supply post-processed radial orbits precise at the 10 cm level if reduced dynamic tracking is used.

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However, the Department of Defense's (DoD's) policy of Selective Availability/Anti-Spoof (SA/A-S) that will most likely be implemented when the system becomes operational will have a large impact on real time and post-processed positioning with the GPS. Selective Availability is an intentional degradation of the broadcast orbital elements atomic clock parameters and/or a dithering of the oscillator on-board the GPS satellite that will result in degraded single receiver positioning accuracy for the unauthorized user. Most of the effect of SA can be removed with differential processing. Anti-Spoof is a change from the unclassified pseudo random noise P code to an encrypted (secure) Y code which will remove access to the L2 frequency for code-correlating receivers and thus remove the capability to dual frequency calibrate for the ionospheric delay. Other techniques for calibrating the ionospheric delay from GPS measurements include dual frequency codeless P code and carrier tracking, but have not yet been applied to space qualified GPS receivers[7,8]. There does exist a single frequency mode of ionospheric calibration called Differenced Range Versus Integrated Doppler (DRVID)[9]. This DRVID technique combines the C/A pseudorange and carrier phase on the L1 channel to create a new carrier phase observable. This new carrier phase observable is free from the systematic ionospheric delay, but contains noise at half of the C/A pseudorange noise level. If this new single frequency data type is able to provide post processed orbits near the decimeter level, dual frequency receivers may not be needed. This would greatly reduce the GPS receiver mass, size, and power requirements and also receiver complexity because the SA/A-S hardware is not required.

This paper presents a series of covariance analyses completed for the Navy's GEOSAT Follow-On (GFO) altimetric satellite using both SA/A-S qualified (dual frequency) and non SA/A-S qualified (single frequency) GPS receiver configurations. These covariance analyses show the expected post-processed radial orbit accuracy of GFO for the single and dual frequency receiver configurations when using dynamic and reduced dynamic tracking strategies.

II. Ionospheric Calibration

The Earth's ionosphere consists of positive and negative ions that are formed when the sun's radiation interacts with atmospheric molecules. Electromagnetic waves that travel through this ion filled region are affected by the negative ions in as many as seven ways[10] of which only two are discussed here. The first effect is called group delay and occurs because the ionosphere is dispersive (frequency dependent) and creates a group delay for a spread signal of some bandwidth. The second effect is called phase advance and arises from the fact that the group delay slows the spread signal down and actually allows more carrier cycles to pass in a certain time. This is interpreted as a phase advance in the measured carrier phase data. Because of this effect, the group delay and phase advance are of equal magnitude but opposite sign. To first order, the group delay and total phase delay equations can be expressed as[10]:

$$\tau_g \cong \tau + \frac{k \cdot TEC}{f^2} \tag{1}$$

$$\tau_\phi \cong \tau - \frac{k \cdot TEC}{f^2} \tag{2}$$

where τ represents the geometric and all other non-ionospheric delays, k is a constant (40.3), TEC is the Total Electron Content (electrons/meter^2) along the ray path and f is the transmitting frequency in Hertz. The next two subsections show how the ionospheric delay is calibrated out of the carrier phase (biased range) observable in both the dual and single frequency modes.

Conventional Dual Frequency Calibration

Because the ionospheric delay is a function of frequency, it is possible to combine measurements acquired on two frequencies and create a new measurement that is free of ionospheric delay. Following Yunck[10], τ_1 and τ_2 are delay (group or phase) measurements on the L1 and L2 frequencies and are given by

$$\tau_1 \cong \tau + \frac{k \cdot TEC}{f_1^2} \tag{3}$$

$$\tau_2 \cong \tau + \frac{k \cdot TEC}{f_2^2} \tag{4}$$

The above two equations can be linearly combined to form a ionosphere-free observable τ_c as shown below.

$$\tau_c = \left(\frac{f_2^2}{f_2^2 - f_1^2}\right)\tau_2 - \left(\frac{f_1^2}{f_2^2 - f_1^2}\right)\tau_1 \cong \tau \tag{5}$$

The data noise of the combined observable can be shown to be about a factor of 3 greater than the original data noise.

Differenced Range Versus Integrated Doppler (DRVID) / Single Frequency Calibration

The first application of calibrating charged particle effects on single frequency Doppler and range data occurred at the Jet Propulsion Laboratory (JPL) when tracking the Mariner VI and VII interplanetary spacecraft[11]. This technique became known as Differenced Range Versus Integrated Doppler (DRVID)[9]. This DRVID technique was then generalized to exploit the GPS signal structures[7]. Currently, most precise positioning applications use dual frequency calibration of charged particle effects which eliminates the motivation to use the DRVID data type. However, the DoD's policy of A-S will eliminate dual frequency ionospheric calibration of non A-S capable GPS receivers, and may create a unique niche for the DRVID data type in GPS applications.

In order to explain the DRVID calibration technique as in MacDoran[9], it is necessary to work with equations modeling range change. Both the pseudorange and the carrier phase can provide measures of range change over an interval from the beginning of an arc at time 0 (0) to any later time i (i). Using equations (1) and (2), the range changes over an interval from 0 to i can be shown as

$$\tau_\phi(i)-\tau_\phi(0) = \tau(i)-\tau(0) - \frac{k}{f^2}\left(\mathrm{TEC}(i)-\mathrm{TEC}(0)\right) \qquad (6)$$

$$\tau_g(i)-\tau_g(0) = \tau(i)-\tau(0) + \frac{k}{f^2}\left(\mathrm{TEC}(i)-\mathrm{TEC}(0)\right) \qquad (7)$$

where $\tau(i) - \tau(0)$ is the true range change over the interval. It should be noted that if the term $k(\mathrm{TEC}(i) - \mathrm{TEC}(0))/f^2 \equiv k\Delta\mathrm{TEC}(i,0)$ is added to equation (6) the result is a carrier phase or biased range observable free from ionospheric delay. Two times this term can be obtained by subtracting equation (6) from equation (7) as shown below.

$$\left(\tau_g(i)-\tau_g(0)\right)-\left(\tau_\phi(i)-\tau_\phi(0)\right) = \frac{2k}{f^2}\left(\Delta\mathrm{TEC}(i,0)\right) \qquad (8)$$

The procedure used in equation (8), which includes differencing code range change with carrier range change (or integrated Doppler) to determine ΔTEC, is the reason the DRVID acronym was created. When equation (8) is divided by two and added to both sides of (6) and then the i^{th} terms are combined and the 0^{th} terms (which are biases) are added to the right side, a new biased range observable from time 0 to i is generated. This new observable is a function of the phase and group delays at time i as shown below

$$\frac{\tau_\phi(i)}{2} + \frac{\tau_g(i)}{2} = \tau(i) - \tau(0) + \mathrm{bias} \qquad (9)$$

Equation (9) represents an ionosphere-free carrier phase observable which is dominated by noise of half the magnitude of the group delay noise. The procedure for creating an ionosphere-free carrier phase or biased range observable from single frequency pseudorange and carrier phase data is to add the phase observable (in meters) to the pseudorange observable and divide by two.

It should be noted that there are a couple of potential problems that could arise when using the DRVID calibrated carrier phase data. One area of concern is that the pseudorange or group delay measurement must be calibrated to remove all non-bias systematic errors generated by the GPS receiver. Any systematic error in the pseudorange will be added directly to the calibrated carrier phase data and corrupt solutions. Multipath is another systematic error in the pseudorange measurement that cannot be removed, only minimized. Another problem that may affect the pseudorange is a drifting oscillator. An unstable oscillator may cause the receiver to adjust its clock to stay close to GPS time which will cause abrupt (non-physical) jumps in the measured pseudorange. These abrupt jumps in pseudorange will appear as cycle slips in the DRVID calibrated phase data and will therefore degrade the solution if they are not corrected. If the systematic errors in the pseudoranges are minimized, the DRVID calibrated phase can be a powerful data type in long arc applications such as orbit determination.

III. Post-Processed Orbit Determination Strategies

The GPS can use pseudorange and carrier phase observations to determine the position of LEO satellite (such as GFO) with unprecedented precision[5]. A proposed system to provide this precise positioning is shown in Figure 1. In this tracking scenario, the positions of the LEO and the GPS satellites are determined in an Earth based reference frame that is defined by well known (fiducial) station locations. The parameters that are estimated in this tracking scheme are the LEO and GPS states, non-fiducial station locations, receiver and satellite clock offsets, all carrier phase biases, tropospheric zenith delays and other satellite force parameters. Because the GPS satellites are in high orbits (i.e. the dynamics of the motion are well known) conventional dynamic tracking supplies precise GPS satellite orbit solutions. At altitudes of 800 km, mismodeling of the Earth's gravity and atmospheric drag limits the precision of the GFO solution. However, if the dynamic information is augmented with kinematic (geometric) information, the expected LEO radial uncertainty can be brought below the decimeter level[5,6].

Processing continuous GPS pseudorange and carrier phase measurements will allow orbit determination of GFO based on dynamics, kinematics (geometric solution), or a combination of the two called reduced dynamic tracking[5]. Conventional dynamic tracking derives the state transition information from the satellite equations of motion and is therefore susceptible to dynamic mismodeling. Kinematic tracking derives the state transitional information from the precise range change of the data and is, therefore, not corrupted by dynamic mismodeling. However, kinematic tracking is sensitive to observing geometry. Therefore, an optimal weighting of dynamic and kinematic information should provide the best results. The weighting of the dynamic and kinematic information is controlled by varying the steady state uncertainties (σ_{SS}) and time constants (τ) of three process noise parameters in the filter that represent three fictitious forces on the satellite. Dynamic tracking can be enforced if $\sigma_{SS}=0$ and $\tau=\infty$, and kinematic tracking will be imposed if $\sigma_{SS}=\infty$ and $\tau=0$, and σ_{SS} and τ will be in between these extremes for reduced dynamic tracking . Studies have been carried out that show reduced dynamic tracking will yield results better than dynamic or kinematic tracking separately[5,6]. Reduced dynamic tracking has also been shown to remove the effect of geographically correlated orbit error that is prevalent in conventional dynamic tracking[6]. Reduced dynamic tracking will also help reduce the atmospheric drag error caused by periods of high solar activity if kinematic information is used.

IV. Covariance Analyses for GFO

Method of Covariance Analysis

Consider covariance analysis has become a design tool to determine the effects of model errors on the estimated parameters and to predict the accuracy of an estimate prior

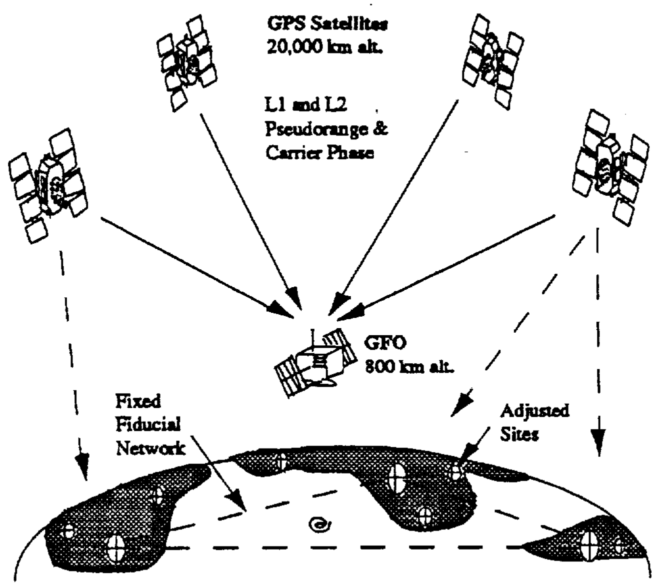

Figure 1 In precise GPS-based orbit determination, the GPS and GFO satellite orbits are solved for simultaneously with respect to a subset of ground receivers serving as a fixed (fiducial) reference frame.

to the occurrence of the actual event. Covariance analysis can calculate the sensitivity of the estimate to systematic biases in the considered but unestimated parameters. These parameters are considered rather than estimated for one or more of several reasons:

- it is desirable in terms of computer costs to have as small a state vector (estimated parameters) as possible;
- the physical effect of certain parameters cannot be adequately modeled;
- many parameters are necessary to sufficiently model certain phenomena; and
- some parameters must remain unadjusted to define a reference frame and/or avoid singularities.

In covariance analysis, the state vector is estimated, but the uncertainties in the considered parameters are included in the covariance results. The considered parameters are assumed to be constant with known a priori estimates (usually zero) and covariance. By not including the effects of these unestimated parameters in the filter run, the formal error (i.e., the computed covariance) is overly optimistic. The consider covariances are used to increase the covariances over the values generated by the filter to better reflect the uncertainty in the solution based on inexact models. It should be noted, however, that covariance analyses cannot include the effects of all error sources that are present in real world applications.

Covariance Model Assumptions

In order to compute realistic radial uncertainties for GFO, it was necessary to model the system characteristics as accurately as possible. The system characteristics and all the estimated and considered parameters (with their associated uncertainties) that are used in the following analyses are given in Table 1. The most critical of these is the gravity error model, because at an altitude of 800 km gravity mismodeling produces the largest error on LEO radial uncertainty. Limits on the disk space and CPU of the computer used in the analyses forced a subset (276 out of the original 2595 coefficients) of the full Goddard Earth Model for TOPEX (GEM-T3, complete to degree and order 50) covariance to be created using the method described by Mitchell[6]. Only those coefficients whose uncertainties could produce GFO radial uncertainties of 1.5 cm or larger were included in the gravity error model. The next largest error source at an 800 km altitude is mismodeling of the atmospheric drag. This error was modeled by considering an error in the atmospheric drag coefficient of 20 % of the nominal value. Another characteristic that has a large impact on the positioning accuracy is the GPS receiver tracking strategy. The GFO receivers modeled in these analyses follow JPL's[12] algorithm which considers: 1)how long the GPS satellites will remain in view, 2) whether the satellites are in common view with at least one ground station, and 3) the level of the Position Dilution of Precision (PDOP) of the selected satellites. This algorithm causes the receiver to track all visible satellites, from a minimum of 4 to a maximum of 6. A 6 station ground tracking network (TOPEX baseline network), including 3 Deep Space Network sites (DSN) operating as fiducial stations, was used in the analyses[12].

Three different GFO receiver configurations were studied in the following analyses. The first configuration represented a SA/A-S capable receiver which generates dual frequency calibrated pseudorange and carrier phase data with precisions equal to the ground network receivers. Configuration 2 modeled a non-SA/A-S capable receiver which generates single frequency (DRVID) calibrated phase data with noise at half the 7.5 meter C/A pseudorange level (for 1 second integration time). This 7.5 m C/A pseudorange level is currently available from the Rockwell AST-V space qualified receiver[13]. Since the observation interval used in the analyses was 5 minutes, the associated DRVID phase noise was computed by scaling the 1 second C/A noise by the square root of n=300 samples and then dividing by 2 because of the way the observable is formed (i.e. 7.5/sqrt(300)/2 = 21.7 cm). The third configuration is the same as the second, but used C/A pseudorange with noise at the 2 meter level (for 1 second integration time) which is expected to be available from the Trimble Navigation TANS receiver[14]. At a 5 minute observation interval, this phase noise scales to 5.7 cm. The third case is considered a best case for a single frequency receiver using a DRVID ionospheric calibration. In addition, the C/A pseudorange used to calibrate the phase data in the second and third configurations was modeled as having pure white noise with no systematic effects which is an optimistic assumption. Because the C/A pseudoranges are used to calibrate the ionospheric delay from the phase data in the second and third configurations, the C/A pseudorange data strength was not used in the orbit determination filter (i.e. carrier phase only solutions).

Table 1. Error Model for GFO Covariance Analyses

System Characteristics	
GFO Orbit:	800 km, inc. = 108°
Number of Ground Sites:	6 (3 DSN sites)
Number of GPS Satellites:	21
Ground Rcvr. Tracking Capacity:	6 GPS satellites
GFO Rcvr. Tracking Capacity:	4,5,or 6 GPS
Receiver Elevation Cutoff Angle:	10°
Data Arc Length:	8 hours
Data Acquisition Interval:	5 minutes
Data Types at Ground Sites:	L1 & L2 pseudorange and carrier phase
Data Noise at Ground Sites:	5 cm (pseudorange) 0.5 cm (carrier phase)
Data Types on GFO, Config. 1:	L1 & L2 pseudorange and carrier phase
Data Noises for Config. 1:	same as ground sites
Data Types on GFO, Config. 2:	DRVID carrier phase
Data Noise for Config. 2:	22 cm , worst case
Data Types on GFO, Config. 3:	DRVID carrier phase
Data Noise for Config. 3:	5.7 cm, best case
Adjusted Parameters and A Priori Uncertainties	
GFO State:	2 km; 1 cm/sec in xyz
GPS Satellite States:	1 km; 1 cm/sec in xyz
All Carrier Phase Biases:	10 km
GPS and GFO Clock Biases:	3 μsec (white process noise)
Non-Fiducial Station Locations:	5 cm each component
Zenith Tropo. Delay Error:	10 cm (random walk)
Consider Parameters and Uncertainties	
Earth Gravity Error Model:	Selected GEM-T3 Covariance (see text)
Atmospheric Drag on GFO:	20 %
GM of Earth:	1 part in 10^8
Fiducial Station Locations:	5 cm each component
Solar Pressure on GFO:	20 %

Results

Covariance analyses were performed on the above receiver configurations using both dynamic and reduced dynamic tracking. Purely kinematic tracking was not used, because periods of poor observing geometry caused the radial uncertainties to climb to the meter level. The results of each analysis are presented as the rms of the computed and considered radial uncertainty of GFO over an 8 hour arc. The considered uncertainty is equal to the computed uncertainty plus the uncertainty introduced from the consider parameters (GM of Earth, gravity, drag coefficient, fiducial station locations and solar pressure coefficient). The results here were completed with the Orbit Analysis and Simulation Software (OASIS) developed by JPL[15].

Figure 2 shows the rms of the computed and considered radial uncertainty of GFO using GPS dynamic tracking for the SA/A-S qualified (dual frequency) receiver configuration. The radial rms of the considered uncertainty for conventional dynamic tracking is 12.7 cm, which is predominantly due to the gravity model uncertainty. This means that even if perfect observations were available, the radial uncertainty would be limited to ~13 cm because of gravity field mismodeling. Also shown in Figure 2 are the computed and considered radial uncertainty of GFO for the GPS reduced dynamic 8 hour arc analysis. The radial rms of the considered uncertainty is 3.5 cm, which is a large improvement over the dynamic tracking technique. The steady state uncertainties and time constants in the filter were tuned ($\sigma_{SS} = 0.05\ \mu m/s^2$, $\tau =$ 15 minutes) to provide an optimal weighting of dynamics and kinematics. The steady state uncertainty found in this analysis is less than the $0.5\ \mu m/s^2$ found in Wu[5] because the GEM-T3 gravity model provides a better dynamical model. This 3.5 cm rms radial uncertainty agrees closely with similar studies performed for TOPEX[6].

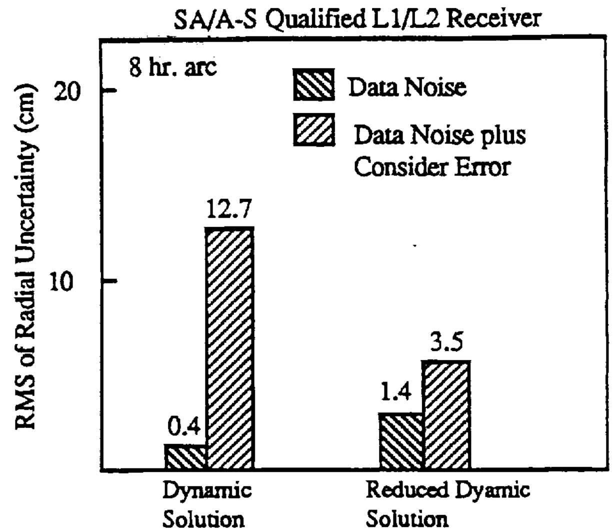

Figure 2. Shown are the RMS values of the GFO radial uncertainty over an 8 hr. arc for configuration 1.

The first half of Figure 3 shows the rms of the computed and considered radial uncertainty of GFO using GPS dynamic tracking for the second configuration. The radial rms of the considered uncertainty is 16.9 cm. Kinematic information was not used for this configuration because the GFO carrier phase data noise was high and caused the considered radial uncertainty to increase above the 16.9 cm level.

The second half of Figure 3 shows the rms of the computed and considered radial uncertainty using GPS reduced dynamic tracking for the best case single frequency receiver configuration. The reduction in GFO carrier

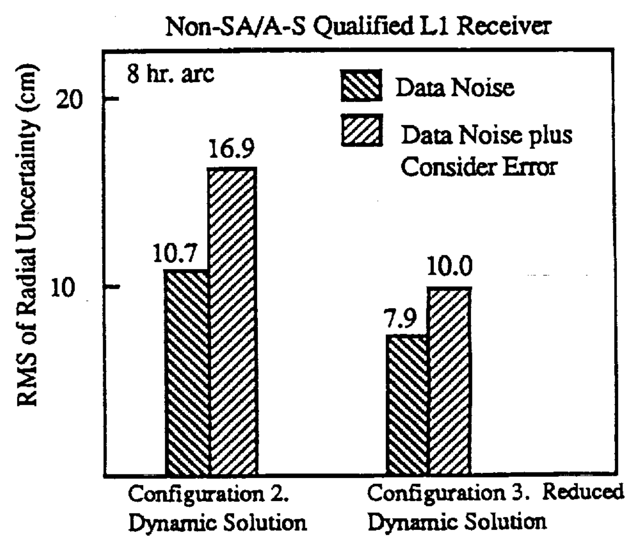

Figure 3. Shown are the RMS values of the GFO radial uncertainty over an 8 hr. arc for configurations 2 (left) and 3 (right).

phase noise allowed some kinematic information to be used and resulted in a considered uncertainty of 10.0 cm. The steady state uncertainties and time constants in this filter run were $\sigma_{SS} = 0.05\ \mu m/s^2$ and $\tau = 15$ minutes.

V. Conclusions

Satellite altimetry has become a very useful tool in the study of climate and global change. Currently, satellite orbit uncertainty is limiting the amount of oceanographic information that can be inferred from satellite altimetry data. This paper presents covariance analyses that show the radial orbit component of GFO can be determined with 3.5 cm uncertainty if a SA/A-S qualified GPS receiver and a reduced dynamic tracking strategy is used. But even more surprising, the analyses show that the non SA/A-S qualified (single frequency) receiver can approach the 10 cm level if all systematic errors are removed from the C/A pseudorange (which is an optimistic assumption) and reduced dynamic tracking is again used. This could greatly reduce the GPS receiver mass, size, and power requirements and also receiver complexity because SA/A-S hardware is not required. A trade-off must be made between expected orbit uncertainty and the cost and complexity of the mission.

Acknowledgements

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References

[1] Born, G. H., R. H. Stewart, and C. A. Yamarone. "TOPEX-A Spaceborne Ocean Observing System"; Monitoring Earth's Ocean, Land, and Atmosphere from Space-Sensors, Systems, and Applications, Vol. 97 of Progress in Astronautics and Aeronautics series, AIAA, pp. 464-497, 1985.

[2] JPL. TOPEX/POSEIDON Project Mission and System Requirements; JPL Report D-5901, April, 1989.

[3] Haines, B. J., G. H. Born, J. G. Marsh, and R. G. Williamson. "A Summary of Precise Orbit Computation for the GEOSAT Exact Repeat Mission"; Johns Hopkins APL Tech. Dig., Vol. 10, No. 4, pp. 393-404, Oct-Dec, 1989.

[4] JPL. TOPEX/POSEIDON Project Orbit Determination Subsystem Functional Requirements and Design; JPL Report D-7837, Sept., 1990.

[5] Wu, S. C., T. P. Yunck, and C. L. Thornton. "Reduced-Dynamic Technique for Precise Orbit Determination for Low Earth Satellites"; AAS Paper 87-410, AAS/AIAA Astrodynamics Specialist Conference, Kalispell, Montana, August 10-13, 1987.

[6] Mitchell, S. J. "A Study of Geographically Correlated Orbit Errors for TOPEX-Using GPS Tracking", PhD. Thesis, University of Colorado, Aug. 1990.

[7] MacDoran, P.F. and D.J. Spitzmesser, "Method and Apparatus for Deriving Pseudo Range from Earth Orbiting Satellites", U.S. Patent No. 4,797,677 issued January 10, 1989.

[8] MacDoran, P. F., G. H. Born, K. L. Gold, W. S. Schreiner, "A Conceptual Design for a Codeless GPS Receiver for Space Applications"; AAS Paper 91-539, AAS/AIAA Astrodynamics Specialist Conference, Durango Colorado, August 19-22, 1991.

[9] MacDoran, P.F, "A First Principles Derivation of Differenced Range Versus Integrated Doppler (DRVID) Charged Particle Calibration Method", JPL Space Programs Summary 37-62, Vol. II, February 1970.

[10] Yunck, T.P., "Coping with the Atmosphere and Ionosphere in Precise Satellite and Ground Positioning", IUGG Union Symposium 15, Vienna, Austria, Aug. 22, 1991.

[11] MacDoran, P. F., and W. L. Martin, "DRVID Charged Particle Measurements with a Binary-Coded Sequential Acquisition Ranging System" JPL Space Programs Summary 37-62, Vol. II, February 1970.

[12] Wu, S. C., T. P. Yunck, and G. A. Hajj. "Toward Decimeter Topex Orbit Determination Using GPS"; AAS Paper 89-359, AAS/AIAA Astrodynamics Specialist Conference, Stowe, Vermont, August 7-10, 1989.

[13] Rockwell International, "Advanced Satellite Technology V (AST V) GPS Receiver Software Design Documentation", March 8, 1991.

[14] P. F. MacDoran and K. M. Larson, "Space Qualified GPS Receivers", CCAR Memo, Feb. 20, 1991.

[15] Wu, S. C., J. S. Border, S. M. Lichten, R. F. Sunseri, B. G. Williams, and J. T. Wu. OASIS Users' Guide, V. 1.0; Jet Propulsion Laboratory, D-3138. April 1, 1986.