Orbit and Ranging Analysis of the INMARSAT AOR-West Geostationary Satellite

Thomas M. Kelecy and Dr. Alison Brown, *NAVSYS*
Willy Bertiger and Steven M. Lichten, *Jet Propulsion Laboratory*

BIOGRAPHIES

THOMAS M. KELECY

Tom Kelecy is a Navigation Engineer at NAVSYS Corporation, in Colorado Springs, CO, where he is involved with GPS navigation systems design and analysis. Dr. Kelecy has worked in the area of kinematic GPS and orbit determination for the past seven years. Prior to NAVSYS, he was employed as a geodesist for NOAA, where he worked on GPS kinematic positioning techniques for geodetic and oceanographic applications. As a guidance and control engineer with Martin Marietta Aerospace, he contributed to the design and analysis of the attitude determination and control system for the Magellan spacecraft now orbiting Venus. Dr. Kelecy holds a PhD in Aerospace Engineering Sciences from the University of Colorado at Boulder, MS from the Colorado School of Mines, and BS from the College of Charleston, SC.

ALISON BROWN

Alison Brown is the President of NAVSYS Corporation, which specializes in developing GPS customized products and services. Dr. Brown has over 15 years experience in GPS receiver design and has seven GPS related patents. She has published numerous papers on GPS applications and is on the editorial board for GPS World and GIS World magazines. She is currently the Space Representative for the ION Council. Dr. Brown received her BA and MA in Engineering from Cambridge University, an MS from MIT, and a PhD from UCLA.

WILLY BERTIGER

Willy Bertiger received his PhD in Mathematics from the University of California, Berkeley, in 1976, specializing in Partial Differential Equations. Following his PhD, he continued research in maximum principles for systems of partial differential equations while teaching at Texas A&M University. In 1981, he went to work for Cheveron Oil Field Research. At Cheveron, he worked on numerical models of oil fields and optimization of those models for super computers. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS for high precision orbit determination. GPS studies have included: high precision geodetic baseline determination, software development and analysis for the Topex/Poseidon-GPS orbit determination experiment, and filter software and algorithm development for gravity field determination.

SIEN WU

Sien Wu received his BSEE degree from the National Taiwan University, Taipei, Taiwan, and PhD degree from the University of Waterloo, Ontario, Canada. He joined the Jet Propulsion Laboratory in 1975 and is currently a Technical Group Leader in the Tracking Systems and Applications Section. Dr. Wu has been involved with the development of various tracking systems for deep-space as well as near-earth space vehicles, and their applications to precision geodesy. His current interest is in precision GPS applications.

STEPHEN M. LICHTEN

Stephen Lichten received his AB degree from Harvard in Astrophysics in 1978 and his PhD from the California Institute of Technologies in 1983 (also in Astrophysics). He has worked at the Jet Propulsion Laboratory since the summer of 1983 and presently is the Group Supervisor of the Earth Orbiter Systems Group and a manager in the NASA Deep Space Network Advanced Systems Program. He has focused his efforts recently on high precision orbit determination techniques, earth orientation from GPS, and other earth orbiter applications, emphasizing precise GPS tracking. As part of the GPS flight experiment on Topex/Poseidon, his group recently developed a capability for routine orbit determination accurate to better than 3 cm in altitude for Topex.

ABSTRACT

INMARSAT has designed a GPS (L1) transponder that will be carried on their third generation satellites. This transponder will broadcast a pseudo-GPS signal that can be used for navigation and timing, and also for disseminating integrity data or differential corrections for the GPS satellites. Use of this INMARSAT Geostationary Overlay (IGO) broadcast service will require accurate knowledge of the satellite positions. Orbit accuracies on the order of 1 m or less are achievable, and would support nanosecond level precise time transfer and dissemination over the INMARSAT area of coverage.

NAVSYS has built a ground station test-bed to generate the pseudo-GPS signal that is relayed via the IGO satellite transponder. The ground station includes a closed-loop control mechanism that precisely synchronizes the IGO broadcast signal to an external UTC time reference. This provides the capability for using the IGO signal to disseminate precise time on a global basis. Synchronizing the IGO signal to UTC and providing GPS differential corrections also improves the performance of the IGO service for aircraft navigation, as this technique eliminates signal degradation due to GPS selective availability.

The INMARSAT-2 AOR-West geostationary satellite, which is presently stationed over the Western Hemisphere, carries a transponder that was used for testing the IGO. Data were collected at two ground monitoring stations during system tests to measure the L-band signal transmitted by the satellite transponder. Specially modified receivers were set up at the National Institute of Standards and Technology (NIST) in Boulder, CO, and at the COMSAT Earth Station (ESTA) in Southbury, CT, to measure pseudo-range and carrier phase to the satellite synchronized to UTC (NIST) time.

A preliminary orbit adjustment based on the pseudo-range measurements demonstrates an orbit accuracy which is presently at the level of 5 m radial, 80 m cross-track, and 25 m along-track. With appropriate monitoring station distribution, group and atmospheric delay calibrations, and use of carrier phase measurements, orbit accuracies at the meter level or better are anticipated.

INTRODUCTION

The INMARSAT-3 constellation of four geostationary communications satellites will provide redundant coverage over most of the earth. In addition to the communications payload, the INMARSAT-3 satellites will also carry a specialized navigation transponder that will be used to broadcast simulated GPS-like signals at the GPS L1 (1575.42 MHz) frequency.

This simulated GPS broadcast can be received by GPS receivers with only slight hardware and software modifications. The IGO service will provide an additional satellite signal that can be used for navigation, thereby improving the available GPS and GLONASS satellite coverage. Another major motivation for the IGO is the requirement expressed by the aviation community for a GPS Integrity Channel (GIC) to monitor the health and status of the constellation. The GIC integrity data will be broadcast through the IGO in the form of a navigation message modulated on the simulated GPS signal.

The IGO signal will be generated at specifically established satellite earth stations. It will be controlled so that the IGO signal broadcast by each satellite will appear to be synchronized with the GPS satellite signals. It is also possible to use this architecture to precisely synchronize the IGO signal to a time reference. Since only a single satellite signal is required for precise time dissemination at fixed installations, the four INMARSAT-3 satellites can also provide redundant worldwide coverage for precise time dissemination.

Key to the effective use of the IGO are the calibration of the signal timing to a standard time reference such as UTC and accurate knowledge of the INMARSAT satellite orbits. Applications using the signals for navigation and precise time transfer require the orbital position be known to an accuracy consistent with the known accuracy of the GPS satellites. The goal is to eventually be able to determine the INMARSAT orbital positions to meter level or better.

Ranging data resulting from the signal generated at the IGO test-bed were collected over a two-week period and used to estimate improved INMARSAT orbits. The L-band GPS-like signal generated at the COMSAT ESTA in Southbury, CT, was broadcast by the AOR-West satellite and monitored from two receivers modified to track the signal. The signal monitoring sites were located at NIST in Boulder, CO, and at the Southbury ESTA. The tracking site geometry and AOR-West footprint are shown in Figure 1, where Leeds and Santiago are indicated as additional planned tracking sites for orbit improvement. The site coordinates at NIST were known at best to within 1 m, while the initial Southbury coordinates were in error by as much as 30 m for this test.

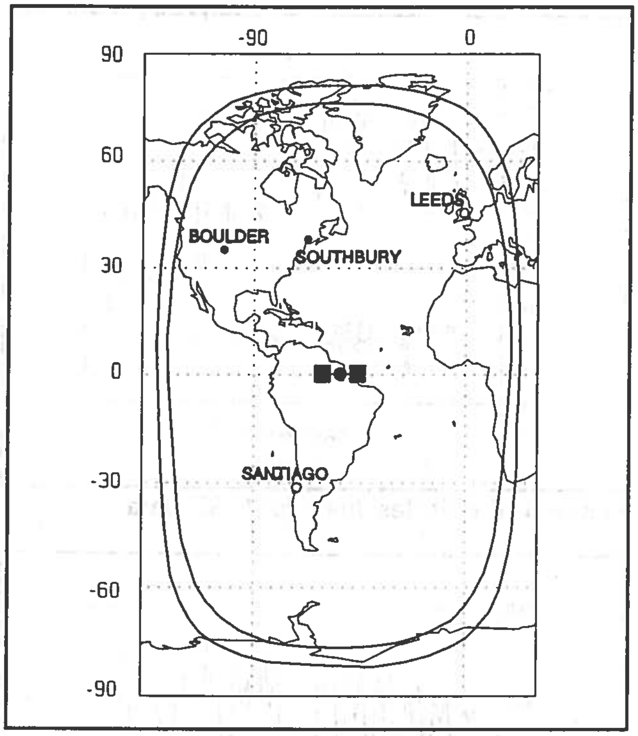

Figure 1 AOR-West Footprint and Monitor Sites

TEST-BED EQUIPMENT

The system architecture for the equipment used at the monitor sites is depicted in Figure 2. The IGO SIGGEN system was designed and built by NAVSYS to provide precise synchronization of the IGO signal to an external time reference. The system components include a Communication Server, a Precision Time and Frequency Reference, SIGGEN Controller, and SIGGEN Monitor.

SIGGEN Communication Server

The FAA is developing a network of ground-based reference stations, the Wide Area Augmentation System (WAAS), which will be used to continuously monitor the status of the GPS satellites and generate differential corrections for the observed range errors. These data are processed at a central facility to generate a GPS Integrity Broadcast (GIB) message for transmission by the IGO. The function of the communication server is to continuously receive the GIB message from the FAA central facility and pass the data to the SIGGEN controller for modulation on the IGO signal.

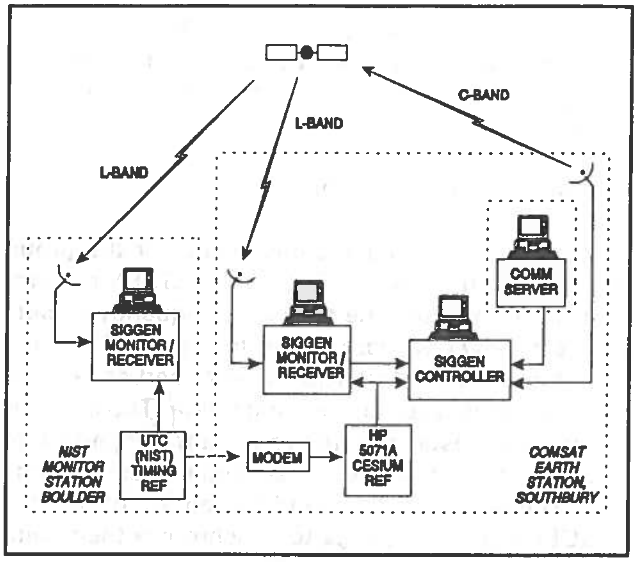

Figure 2 Test-Bed Configuration

SIGGEN Precision Time and Frequency Reference

The SIGGEN time and frequency reference provides the time standard to which the IGO signal is synchronized. In the initial test phase, an HP 5071A primary frequency standard was provided on loan by Hewlett Packard. The HP 5071A clock includes an improved cesium beam tube design that results in an accuracy of $\pm 2 \times 10^{-12}$. The HP clock was operated during the calibration phase under remote control from NAVSYS using monitor data collected at NIST to adjust the reference for time offset and synchronize it with the NIST UTC time standard. The INMARSAT-2 orbital elements at the time of the calibration allowed synchronization to about 1 μsec [1]. The HP clock at the ESTA was synchronized just prior to the two week data collection interval used in this analysis.

SIGGEN Controller

The purpose of the SIGGEN controller is to generate the IGO signal and control its timing relative to the SIGGEN precision time reference. The IGO signal is steered so that the timing elements of the signal (the C/A code and data epochs) appear to be synchronous with the SIGGEN time reference when they are transmitted by the INMARSAT satellite. In order to achieve this, the signal output by the SIGGEN controller must be advanced in time to compensate for the delays on the up-link path through the satellite transponder. Uncalibrated group delays will result in an apparent timing error in the SIGGEN signal transmit time [2]. These show that the group delay can be calibrated during the obit determination process to better than one meter.

SIGGEN Monitor/Receiver

In order to dynamically compensate for the group delays and frequency offsets, the SIGGEN monitor is used to measure the time and frequency offsets of the received signal relative to the SIGGEN time and frequency reference. It also serves as the receiver for measuring the range data. The SIGGEN control loop estimates the range and range-rate to the satellite from the two-way range measurements [2]. These are subsequently used to offset the SIGGEN signal time-tags to synchronize them with a transmission time.

RANGE DATA

Range data were collected at both the Southbury ESTA and the NIST monitor station. The data were collected in two 1-week segments beginning on December 22, 1993 and running through January 6, 1994. The modeled ranges and range-rates were computed from the Keplerian orbital elements for AOR-West to determine the measurement residuals needed for estimating the initial clock offset and for examining possible orbit errors. The average range from NIST to AOR-West is about 39,500 km and varies by about ±182.5 km from the mean. At Southbury, the average range to the satellite is about 37,900 km and varies by about ±195 km from the mean. The range-rate at both sites is about ±13 m/s. The C/A code pseudo-ranges have a noise level of about 1 m.

The range residuals were computed by taking the differences between the measured C/A code pseudo-ranges and the ranges computed from the Keplerian elements. The Keplerian elements, provided by INMARSAT operations in London, were used in Matlab algorithms to compute satellite positions at the measurement times. These positions were used with nominal site coordinates to compute the theoretical ranges for computing the residuals. Pseudo-range measurements were collected at 1-minute intervals at each site.

Figure 3 shows the residuals for the data collected at NIST over the 2-week period (with a 1-day gap). Although a new set of Keplerian orbital elements was available on a weekly basis, the residuals were computed using a single set of Keplerian elements to avoid inducing "jumps" which might mask any inconsistencies in the continuity of the measurements. These residuals have a mean offset of -19.1 m and a standard deviation of 1895.5 m. Obvious diurnal and longer scale features can be seen in the residuals, strongly indicating the presence of orbit errors. The steady increase in amplitude is another indication of the degradation of the orbital elements over the 2-week period.

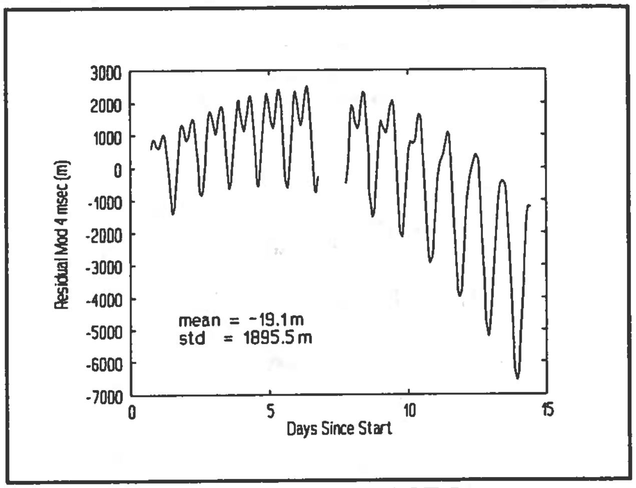

Figure 3 Pre-fit Residuals for NIST Data

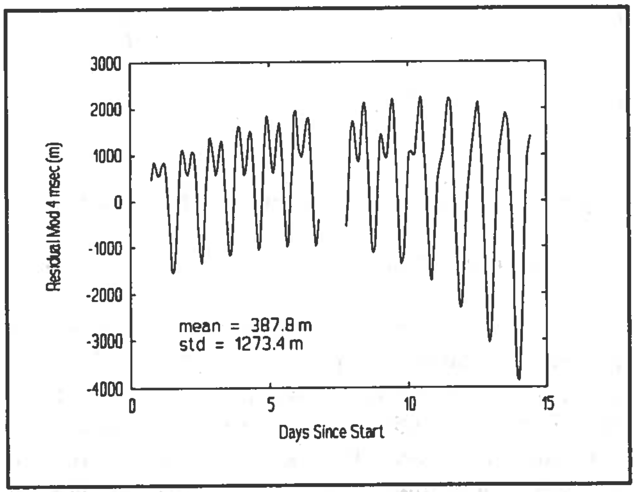

Figure 4 Pre-fit Residuals for Southbury Data

Figure 4 shows the residuals for the Southbury data of the same period. The same set of Keplerian elements was used to compute these residuals. The mean offset is 387.8 m with a standard deviation of 1273.4 m. These residuals also show features similar to those at NIST, reaffirming the presence of orbit error.

INMARSAT PRECISE ORBIT DETERMINATION PROCEDURE

The INMARSAT orbit was adjusted using the range data collected during the second week through the GIPSY-OASIS II software system developed at the Jet Propulsion Laboratory (JPL) for precise processing of radiometric data. This software has been used in positioning the TOPEX/Poseidon spacecraft with GPS data to radial accuracy of 3 cm [3] and in monitoring positions on the earth to cm level [4].

The second week of data was broken into two adjacent arcs of 3.5 days, arc 1 (12/30/93 15:55 UTC to 1/3/94 04:30) and arc 2 (1/3/94 04:31 to 1/6/94 15:44 UTC). This allows an assessment of orbit consistency between the two independent orbit fits, as will be shown later. For each 3.5 day data arc, an epoch state, a solar scale factor, and a transponder delay were adjusted to obtain the best least-squares fit to the range data.

POSSIBLE ERROR SOURCES

Since this is a single frequency system, the ionosphere is a significant error source. Figure 5 shows a plot of the simulated ionosphere using the Bent model [5]. This model is accurate to within a factor of two. The change in range due to the ionosphere is from 1-6 m with a dominant period at the INMARSAT orbital period of 1 day.

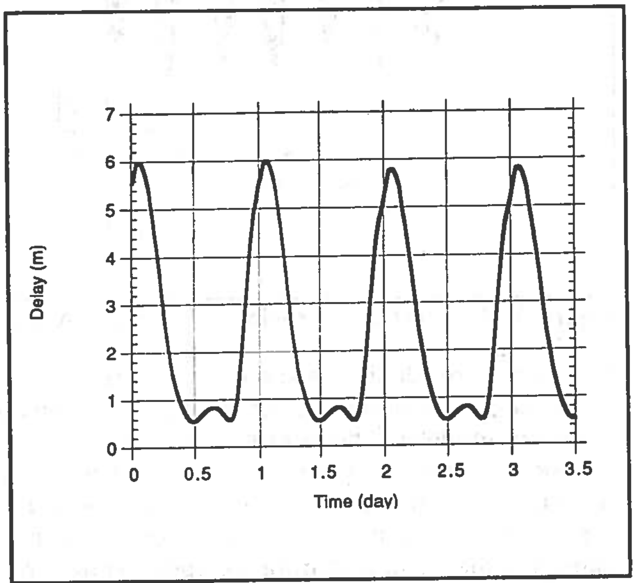

Figure 5 Range Delay Due to Simulated Ionosphere

Figure 6 shows the effect that this simulated signal would have on the recovery of the INMARSAT orbit. The errors are broken down into an orthogonal coordinate system with the radial direction being from the center of the earth to the center of gravity of the INMARSAT AOR-West satellite, cross-track in the direction of the cross product of the INMARSAT velocity vector, and the radial vector and along-track completing the right handed orthogonal coordinate system (very close to the velocity direction). The largest errors occur in the cross-track component at a once-per-day period with an amplitude of about 150 m. The effect remains about the same when the simulated error is propagated outside the interval of data collection (arc 1).

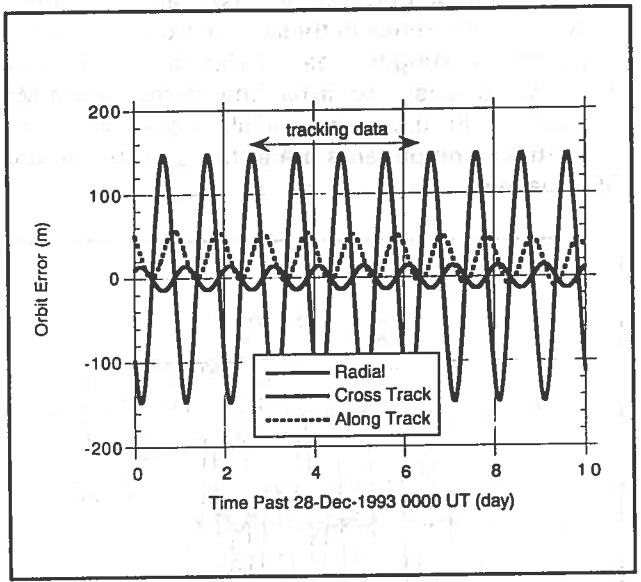

Figure 6 Simulated Ionospheric Effects on INMARSAT Orbit Determination

The data are not really one-way range data, but three-way range data. A signal under active control is uplinked at C-band and then transponded and received at L-band at each of the two ground receivers. Errors in the control loop of the uplink signal would be common to all receivers at the same instant of time and would be indistinguishable from delays due to other common sources such as the transponder. However, the two receivers did not sample the data simultaneously, but at a time separation of about 20 seconds. The effects of uncalibrated group delay errors in the control loop are being investigated. Simultaneous collection of the data at all receivers could eliminate this error source in the future. These delays are expected to be fairly constant over the data arc.

A covariance analysis was performed that considered the error in orbital position due to a 1 m error in each component of the two sets of station coordinates for a full 7-day arc. The errors are fairly constant, the largest component being 25 m along-track, with cross-track and radial errors of less than 1 m. An ESTA antenna location error of as much as 30 m has been estimated.

The tropospheric delay is expected to be small compared to the other error sources. A nominal zenith delay was applied at both receivers (2 m dry and 10 cm wet).

ORBIT DETERMINATION RESULTS

A good indication of orbit accuracy is obtained by comparing the orbits between the two 3.5-day arcs integrated to a common time. Note that there is no overlap in data between the two arcs. Figure 7 shows the difference in these two orbits over a 10-day period starting two days before any of the data and ending one day after the data. The RMS differences in the three radial, cross-track, and along-track components are at the 5 m, 80 m, and 35 m levels.

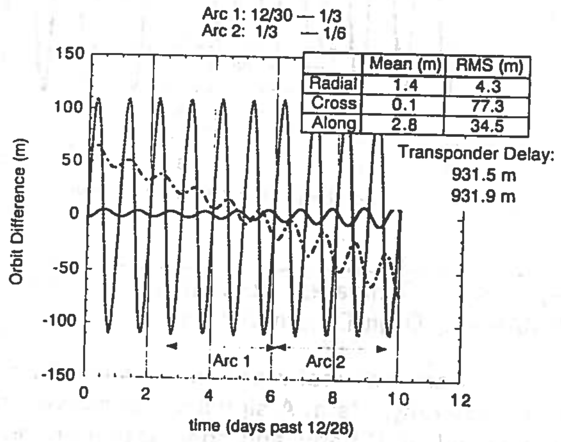

Figure 7 Difference of Predicted Orbits Using Data Arcs 1 and 2

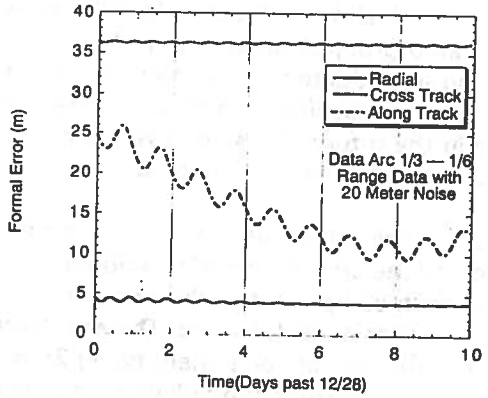

Figure 8 Formal Errors with Data Arc 1

The formal errors (errors due to the data noise determined by the covariance matrix resulting from the data fit) are shown in Figure 8. A large data noise of 20 m (1-σ) was used in this computation to account for some of the systematic effects observed in the post-fit residuals which had an RMS of 17 m for both data arcs. The largest formal errors are in cross-track at about 35 m. This is the result of using only observation stations located north of the equator (one side of the satellite orbit). The along-track error is at the 10-15 m level during the data interval and rises to 25 m outside the data interval. Errors in the radial component are at the 5 m level. With a data noise of 2 m, the scale in Figure 8 would be reduced by a factor of 10.

The formal errors and the errors shown in the ionospheric simulation are consistent with the orbit prediction plot as an indication of orbit accuracy.

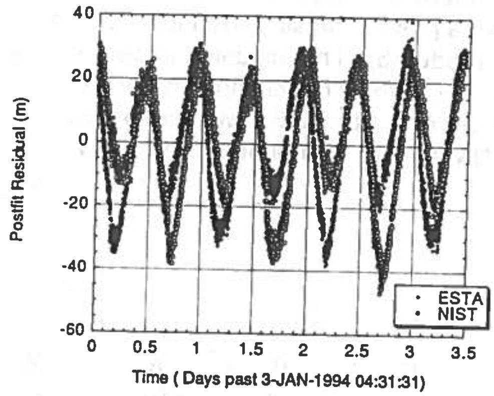

Figure 9 Post-fit Range Residuals for Data Arc 2

The post-fit residuals are shown in Figure 9. Since some large systematic effects (e.g. ionosphere) were not modeled, those effects should appear in the post-fit range residuals. The post-fit range residuals are periodic with periods of 12 hrs and 24 hrs, with an amplitude of about 20 m. Possible causes of the 12-hr signature are epoch state errors or the control loop group delays. Note that the control loop sees a Doppler signal from the satellite with a 12-hr period.

IMPROVEMENTS WITH THE CURRENT DATA SET

Several improvements are possible with the current data set. Part of the ionosphere error can be removed using the Bent model [5]. Other approaches could utilize global or regional ionospheric maps, incorporating GPS dual-band ground data when available [6-8]. Software changes in the data preprocessing can correct the lack of coherency in the phase data and allow use of the phase and the range data to correct for the ionosphere by adding the phase data to the range data [9]. Data from the control loop of the uplink can be used to process the data as true three-way range and phase.

FUTURE ACCURACY

To examine possible future accuracy, a covariance analysis was conducted using the same solution strategy discussed above but with increased data strength from additional ground stations. Figure 10 shows the formal errors for a three station tracking network in the northern hemisphere using range data with an assumed data noise of 3 m (1-σ) when INMARSAT's epoch state, solar scale, and transponder delay are adjusted. Along-track and radial errors are less than 1 m, while the cross-track error is less than 2 m. Figure 11 shows that by adding a receiver in the Southern Hemisphere (Santiago, Chile), all components of the formal error can be brought below 1 m.

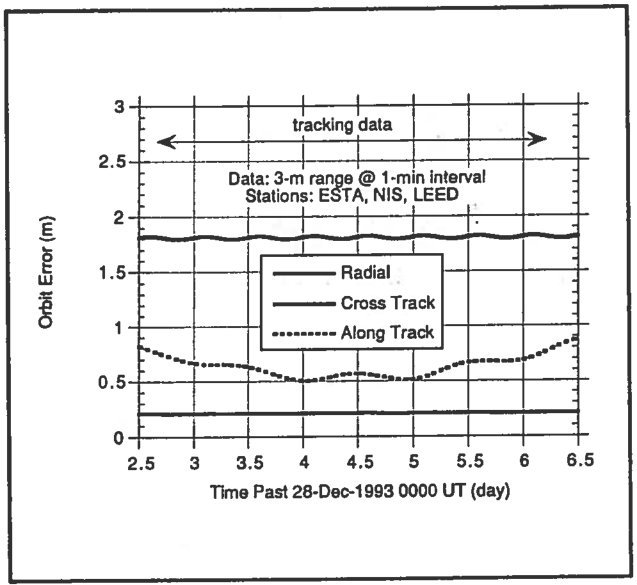

Figure 10 Formal Errors: ESTA, NIST, Leeds

To obtain accuracy below 1 m, other systematic effects must be controlled. Ionosphere and troposphere errors can be controlled by receiving the IGO signal in a dual-frequency GPS receiver that is simultaneously observing the GPS constellation. This technique has been demonstrated in tracking the TDRS geosynchronous satellite [10]. Since the receiver is using the same clock to track both GPS and INMARSAT, double difference techniques can be used to eliminate clock errors [10]. If the measurements are all sampled simultaneously (within a few microseconds), then errors in the uplink will look like common errors from the transponder and will also be eliminated in a double difference. With these measures in place, the formal errors shown in Figure 10 and Figure 11 should be representative of the achievable accuracy.

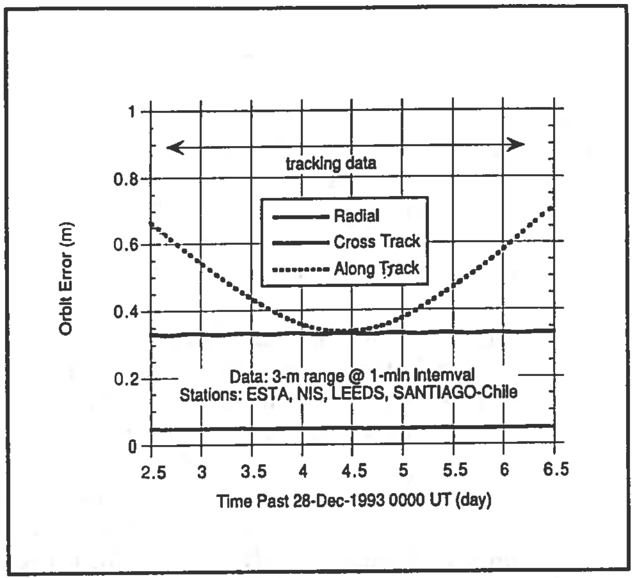

Figure 11 Formal Errors: ESTA, NIST, Leeds, Chile

CONCLUSION

Orbit accuracy is achievable at the level of 5 m RMS radial, 80 m RMS cross-track, and 35 m along-track, as demonstrated by orbit prediction comparison and error analysis. This level of accuracy meets the current requirements for navigation and integrity monitoring. Since only about 20% of the cross-track and along-track errors go into range errors, the current orbital accuracy would allow time transfer at the 60 nanosecond level. In the future, with enhancement to the tracking system, it will be possible to obtain orbit accuracies of a meter or better, which would support time transfer at the level of a few nanoseconds with the appropriate ionospheric and tropospheric calibrations.

The time transfer accuracies mentioned previously are equivalent to the user range error (URE), assuming no uplink transmitter clock errors. This implies a present URE of about 20 m and a URE of less than 1 m if enhancements to the tracking system are implemented. These values can be considered an upper bound over the INMARSAT coverage area, and should be somewhat less over the continental US.

In the next phase of testing, a precise orbit for the satellite will be determined by combining data from multiple monitor stations. Data will be collected from NIST in Boulder, the Southbury ESTA, and the University of Leeds, UK. This will be used to compute the precise orbital elements and calibrate the HP 5071A reference at the earth station. In order to achieve nanosecond timing accuracy, the orbit must be determined to meter level.

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