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# DEMONSTRATION OF MI CROGPS FOR LOW COST ORBIT DETERMINATION

**S. C. Wu†, D. Kuang†, S. M. Lichten†, S. Nandi†, L. J. Remans† and J. M. Srinivasan†**

The capability of low-cost orbit determination with a microGPS space receiver for a low earth satellite, SNOE, is demonstrated using actual GPS data from the GPS/MET satellite. The measurements acquired by the microGPS receiver will be snapshots of carrier doppler and ambiguous pseudorange. Among the challenges in orbit determination are the resolution of the pseudorange ambiguity, the estimation of the measurement timetag drift which affects the in-track orbit position solution, and the convergence of orbit solution from a cold start with essentially no knowledge of the orbit. The effects of data gaps and doppler data quality are investigated. An efficient data acquisition scenario for SNOE is derived.

## INTRODUCTION

GPS measurements can provide precise positioning for users on earth and in earth orbits. Positioning to l-cm accuracy has been reported for users on earth (Refs. 1, 2), and 2 cm for a user in low earth orbit (Refs. 3, 4). Such high-precision positioning requires a state-of-the-art GPS receiver onboard to acquire precise GPS carrier phase and/or pseudorange data, to be processed with ground data from a network of tracking sites over a period of time. Such full-blown onboard receivers are not only costly, but also heavy and power hungry.

Many NASA, military and commercial satellite programs have a need for tracking systems with ultra-low power, mass and cost for medium accuracy (few hundred meters) orbit determination of small, low-earth orbiting satellites. Jet Propulsion Laboratory (JPL) and the University of Colorado have collaborated to develop a tracking system using a novel GPS technology, to be called microGPS.

Two missions are scheduled to carry a microGPS receiver. The first is the SNOE (Student Nitric Oxide Explorer) mission, to be launched in October, 1997. It will have a

† Jet Propulsion Laboratory, California Institute of Technology, M/S 238-600, 4800 Oak Grove Drive, Pasadena, CA 91109. Phone: (818) 354-4937, Fax: (818) 393-4965

550 km circular orbit with a goal of 200 m orbit determination accuracy. The second is the STRV-1C (Space Technology Research Vehicle) mission, to be launched in early 1999. It will have a highly elliptical orbit with a goal to characterize GPS signal strength from 300 km to geosyncronous orbit altitudes.

The onboard microGPS receiver is basically a "bit grabber", consisting of one or more GPS patch antennas. an inexpensive oscillator, a signal sampler/downconverter, and a memory chip. Such a receiver will not only full-ill stringent power (<0.1 W) and mass (<1kg) constraints, but with the inclusion of an onboard processor could potentially offer autonomous tracking capability. The microGPS requires very low power because it awakes from a "sleep" mode only occasionally to sample GPS signals for a short duration.

The measurements acquired by the microGPS receiver are carrier doppler and ambiguous pseudorange, with an ambiguity of 1 msec (-300 km). Among the challenges in orbit determination are the resolution of the pseudorange ambiguity, the determination of measurement timetag which could drift off by up to one second, and the convergence of the orbit solution from a cold start with poor a priori knowledge of the orbit.

The processing procedure and the estimation scheme, as well as results of a simulation analysis have been reported earlier (Ref. 5). This paper reports the results of a demonstration for SNOE satellite using the actual space GPS data from GPS/MET satellite (Ref. 6). The Real-Time Gipsy (RTG) software system (Ref. 7) developed at JPL is used for the analysis. Based on the results of these demonstration, an efficient data taking scenario is determined. The maximum data gap is determined beyond which convergence of orbit solution may not be realized.

**BACKGROUND**

This section provides a brief description on the microGPS receiver architecture, the SNOE mission and the ambiguity resolution of GPS pseudorange data. A more detailed description has been given in Ref. 5.

## MicroGPS Flight Hardware

The microGPS flight receiver developed at JPL is an ultra-low mass and power flight receiver. It employs a new tracking paradigm we call sparse sampling. All signal processing functions are shifted from dedicated hardware to flexible, portable software. The ultra-low mass of the microGPS receiver is partly attributed to the use of a modified hardware/software architecture in which all GPS specific signal processing typically implemented in hardware has been moved to software (see Figure 1).

The microGPS receiver consumes less power than typical flight GPS receivers because it uses a sparse sampling technique in which the receiver awakens and acquires GPS data only periodically, remaining "asleep" between samples. The microGPS acquires and stores snapshots of raw GPS signal at a programmable rate (typically a few times per orbit). In addition, individual snapshots can be single, short duration samples (typically a few milliseconds) or bursts of samples whose number and sample spacing arc also programmable.

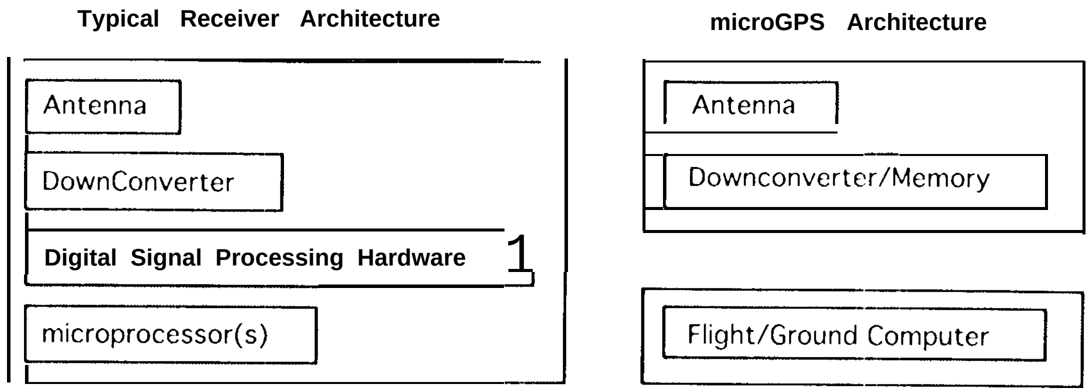


**Figure 1. Receiver Architecture Comparison**

The raw GPS signal samples are timetagged by the microGPS's real-time clock and then transferred to the flight computer. These transfers can occur at a convenient rate constrained by the depth of the instrument memory and the rate of the data transfer. Once received by the flight computer, the GPS sample bits will be stored for later transmission to the ground (and subsequent ground processing as planned for SNOE & STRV) or processed in real or near-real time by on-board software. With proper processing software, these snapshots of the GPS constellation can produce moderately accurate orbits.

## SNOE Mission

The first mission to use the microGPS technology is the Student Nitric Oxide Experiment (SNOE). It is a Student Explorer Demonstration Initiative (STEDI) mission funded by NASA through the University Space Research Association (USRA). The small scientific spacecraft has been designed, built and will be operated entirely at the University of Colorado, Laboratory for Atmospheric and Space Physics (CU/LASP) and will be launched into a sun-synchronous, 550 km orbit at 97.5° inclination. SNOE will carry the first microGPS instrument, whose development is a NASA sponsored joint effort between JPL and the Colorado Center for Atmospheric Research (CCAR). SNOE currently anticipates for a Pegasus launch scheduled for October 1997.

The goal of SNOE's microGPS will be to determine the SNOE orbit to within 200 m. Nominal data sampling time is 2 msec with only a few samples taken per orbit. The data volume will be a few tens of kbytes per day. The overall weight of the SNOE receiver will be about 0.5 kg. The power consumption will be <0.1 watt average and <2 watts peak.

## Ambiguity Resolution of GPS Pseudorange Data

**The** simplicity of the microGPS receiver precludes the acquisition of traditional GPS data types, namely, carrier phase and pseudorange. Instead, the data types available are carrier doppler and ambiguous pseudorange with an ambiguity of 1 ms (~300 km). These data types, acquired at a few time points, are not sufficient for orbit determination even at the kilometer level. However, the pseudorange ambiguity can be rL'solved with the help of the doppler data, promoting the ambiguous pseudorange into a far stronger data type.

The resolution of pseudorange ambiguity is done in two steps. First, a crude orbit solution accurate to better than 50 km is determined with the doppler data. Next, a crude but unambiguous pseudorange data set are computed based on this crude orbit and the known (to a far better accuracy) GPS orbits. The accuracy of these computed pseudorange measurements, which is better than 50 km, is well within the 300-km pseudorange ambiguity. This facilitates the resolution simply by direct comparison of these computed pseudorange measurements and the actual ambiguous pseudorange measurements. The process has been described in detail in Ref. 5.

## THE RTG SOFTWARE SYSTEM

The simulation analysis reported in Ref. 5 was performed using the GIPSY/OASIS I i software set (Ref. 8) developed in an epoch-state filtering architecture which is not ideal for real time applications or for use by an on-board computer. A new software set, the Real-Time Gipsy (RTG), has been developed at JPL (Ref. 7).

RTG is written in ANSI-C and is capable of processing general ra(iio-metric data types in real time on an on-board processor. RTG is also currently in use for the FAA's real-time GPS Wicic-Area Augmentation System (WAAS). It is near its completion and is capable of processing microGPS data types as well as the usual GPS data types (phase and pseudorange).

A numerical integrator is used to allow arbitrary extension of the dynamic models. A current-state, general process-noise UD factorized filter (Ref. 9) is implemented in RTG.

Currently, RTG executes on HP workstations under UNIX, and on PCS. Its target platforms for the SNOE anti STRV missions arc ground based PowerPC Macintosh and HP9000 workstations. The software has been written in such a way that eventual migration to a real-time, flight processor will be straight forward.

## GPS/MET DEMONSTRATION

The feasibility of microGPS has been investigated with simulated GPS data and reported in Ref. 5. Short of in-fright microGPS data before SNOE is put in orbit in October 1997, a demonstration with actual GPS data from a satellite of similar orbit characteristics would be highly desirable. Here, the GPS data acquired from a low earth satellite GPS/Met (Ref. 6) were adopted. GI'S/Met has a circular orbit at 71 S-km altitude and 70° inclination while SNOE will have a circular orbit at 550-km altitude and 97° inclination. To perform atmospheric occultation experiments, GPS/Met orients its GPS receiver to be aft pointing, limiting the number of GPS satellites in view. The orbit determination from such sub-optimal observing geometry should provide an upper bound estimate for SNOE orbit solution error with microGPS.

Precise, after-ti~c-fact GPS ephemerides from a worldwide ground network tracking were used. However, oniy iong-term linear drifts of the GPS clocks were corrected for; the effects of SA dithering were not taken out. The precise GPS/Met orbit solutions with differential GPS, believed to be accurate to better than 20 cm (Ref. 6), were used as the truth for assessing the orbit determi nation accuracy.

To simulate a cold start situation, very poor a priori orbit and clock were assumed: 500 km in orbit altitude, 2000 km in cross-track and in-track orbit position, 2 km/sec in orbit velocity, 100 sec in SNOE clock (timetag) anti i μsec/sec in clock rate.

GPS/Met data from two consecutive days, July 1 (~-17, 1996, were used. The L i pseudorange data were sampled at I 5-, 30- and 45-minute intervals and converted into ambiguous pseudorange measurements by retaining only the fractional mscc parts. L 1 carrier phase data at consecutive time points separated by 10 scc were differenced to form carrier doppler measurements and then sampled at the same 15- to 45-minute intervals. A random-walk user clock error was added onto these data **and** their timetags. Additional data noise was aiso added to investigate the effect on orbit convergence anti accuracy.

The orbit determination algorithm first tries to obtain a crude orbit solution using oniy a single epoch of doppler data to resolve the pseudorange ambiguities. If this fails, doppler data at two epochs are collected to solve for the crude orbit and to resolve the pseudorange ambiguities. The effects of SA on the doppler data are estimated to be about 0.3 m/see. The actual doppler measurements from the microGPS receiver on SNOE arc expected to have a higher data noise, -2 m/sec. To account for this, white noise of different sizes were added to the doppler data to simulate different level of data noise. At each level of data noise, a total of 6 trials were made to investigate the data noise effects on orbit convergence (and hence successful pseudorange ambiguity resolution). These trials were taken at 1 hour apart from the first day of data.

The clock on-board SNOE will be drifting and may have an offset from GPS system clock by many seconds. This will affect the GPS measurements in two respects. First, a common pseudorange offset error will exist on measurements from all GPS satellites. Secondly, the data timetags will also have a common offset which translates into an in-track SNOE orbit error of -7 km for each second of timetag error.

It is a common practice to assume that timetag bias is consistent with pseudorange bias and can be adjusted in the filtering process as a common parameter, if needed. This is indeed true with common GPS (unambiguous) pseudorange measurements. However, the assumption is invalid with ambiguous pseudorange data acquired with a microGPS receiver, even after resolving the ambiguity: while the timetag bias could approach the full clock error (as large as many seconds), the common bias on the ambiguity resolved pseudorange data is limited to its ambiguity cycle, 1 msec. Therefore, the timetag offset anti the pseudorange offset should be simultaneously adjusted in the filtering process with different partial derivatives. A frequency bias was also adjusted with doppler data.

Figure 2 shows the success rate of orbit convergence out of the 6 trials as **a** function of doppler data noise. In general, two epochs of data are needed for the orbit to converge, except for onc of (he six trials at the lowest 2m/sec data noise. A 15-min data separation works well for all data noise up to 1 5 In/see while onc out of the 6 trials with a 30-min data **separation** fails to converge. No solution will converge with a data **separation** 45-min or longer. The need of doppler data **at two** epochs can be explained by the formal error of the doppler inferred orbit solution as shown in Figure 3. With single epoch of data, the formal error is far greater than the -300-km pseudorange ambiguity. The error drops by almost 2 orders of magnitude with data at two epochs, even at a small separation of 3 minutes. At larger separation, the formal error remains at the same level; but the error due to mismodeled velocity and dynamics will dominate, keeping the orbit from converging with a data interval of 45 minutes or larger.

The 3-D RSS error of the crude orbit solution for a 30-rein data separation is shown in Figure 4, again as a function of doppler data noise. The error' is calculated by

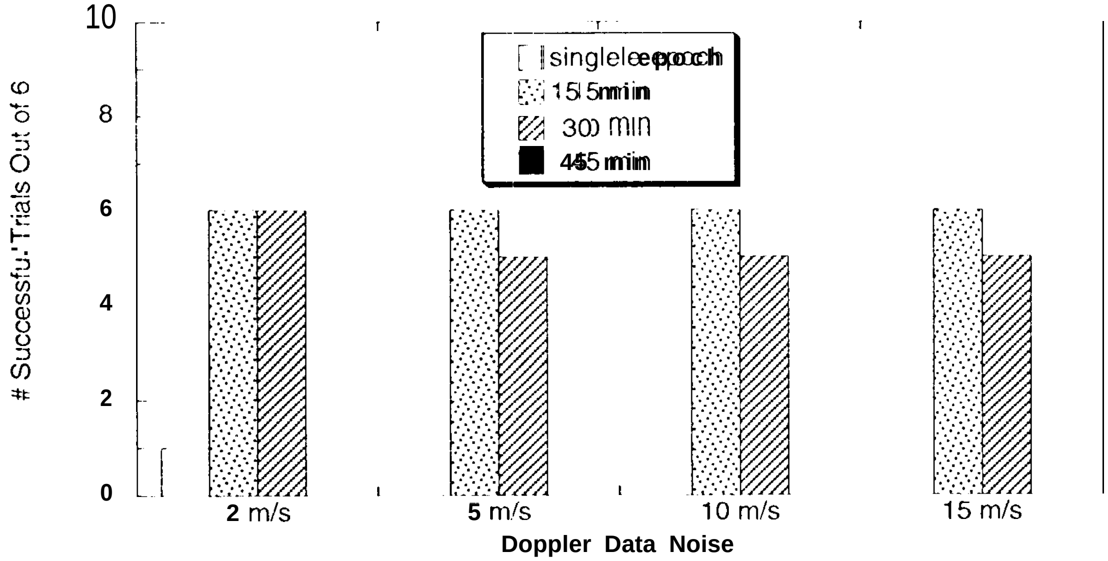


**Figure 2. Success Rate of Convergence of Doppler Inferred Orbit**

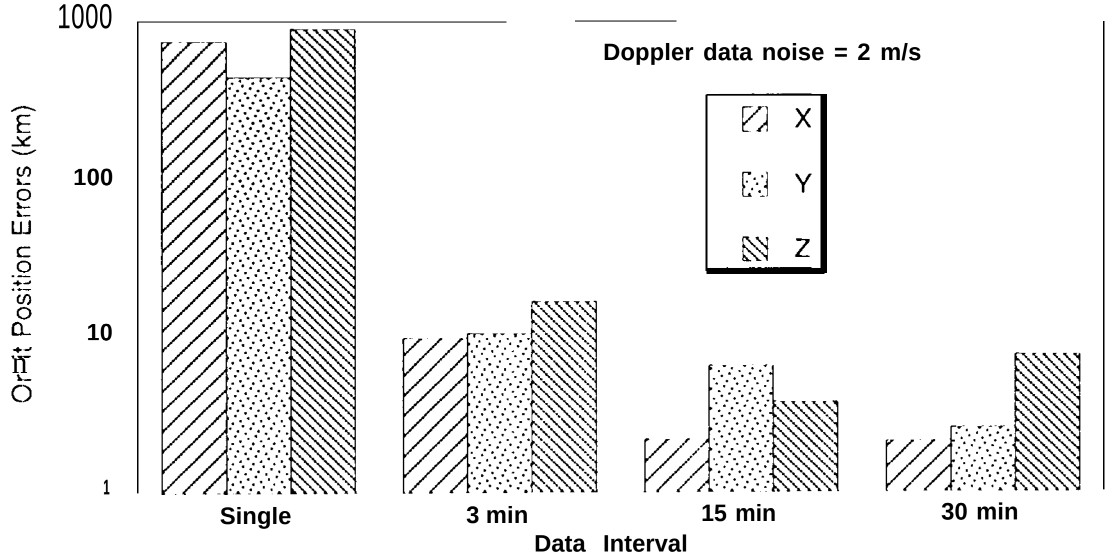


**Figure 3 Formal Errors of Doppler Inferred orbit Components**

differencing the doppler inferred orbit solution from the truth orbit (the precise GPS/Met orbit ). The error is lower than 50 km for a data noise 5 m/see or better. Note that pseudorange ambiguity resolution was successful in one case when the crude orbit error was as large as 120 km.

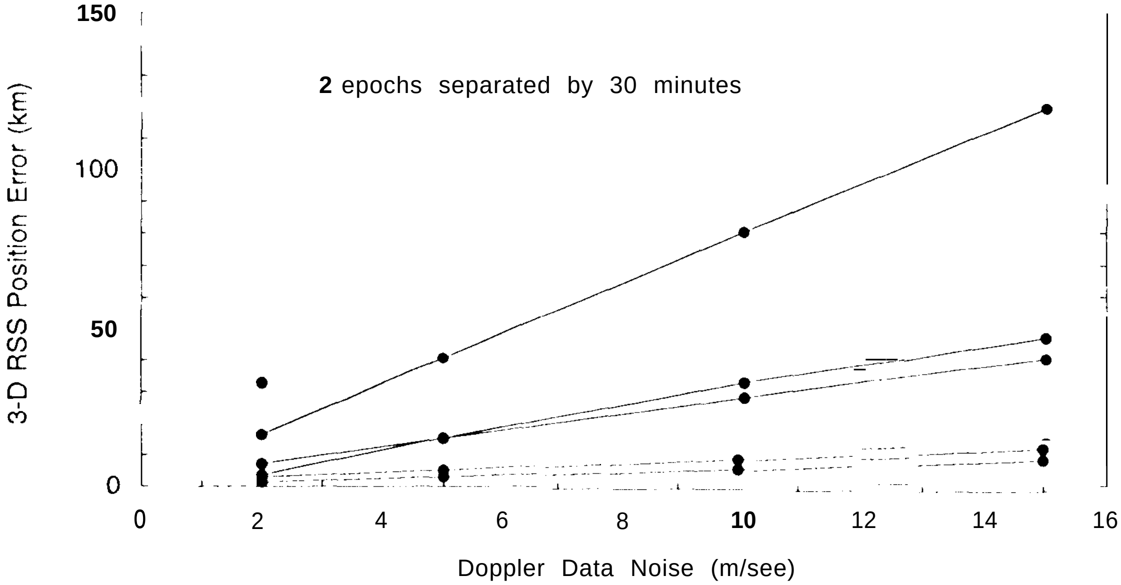


**Figure 4. Crude Orbit Solution Error from 2 Epoch of Doppler Measurements Separated by 30 Minutes**

As mentioned earlier, it is desirable to have a low data sampling interval in order to conserve power consumption and keep the data volume low. From t-he above analysis, it appears that a 30-min sampling interval is appropriate with 2-m/sec dopper data. With a higher doppler noise, a smaller data interval may be needed at cold start; thereafter, a larger interval can be used as will be demonstrated in the following. This will require the receiver to wake up only a few times per orbit revolution. In the following analysis, a 2-m/sec dopper noise with a W-rein data sampling interval will be assumed.

With two epochs of doppler measurements, the orbit solution converges in a few iterations, as shown in Figure 5. Here, the orbit position components are given in terms of the inertial coordinate system used in orbit integration.

Once the pseudorange ambiguities arc resolved using a crude orbit determined from doppler measurements, the resulting mbi:uous-free pseudoranges were used to solve for precise orbit position and velocity. Although the information contained in doppler measurements is much weaker than that contained in pseudorange measurements, the former was also included in the final solution with very little additional computational cost.

With two epochs of ambiguity resolved pseudorange measurements, the precise orbit solution converges in one or two iterations, as shown in Figure 6. The converged orbit position and timetag solutions are typically better than 100 m and 20 msec, respectively. The orbit position will, in general, degrade with time due to the errors in orbit velocity and dynamic models. Without any modeling of the atmospheric drag, the orbit can drift away by as much as a few hundred meters in 30 minutes when the next data batch is available. However, pseudorange ambiguity resolution is guaranteed at this level of orbit error even without the help of doppler measurements. Therefore, once a converged orbit solution is obtained with the first two epochs of measurements (separated by 30 minutes), single epoch of ambiguous pseudorange measurements alone will be sufficient to update the orbit every 30 minutes.

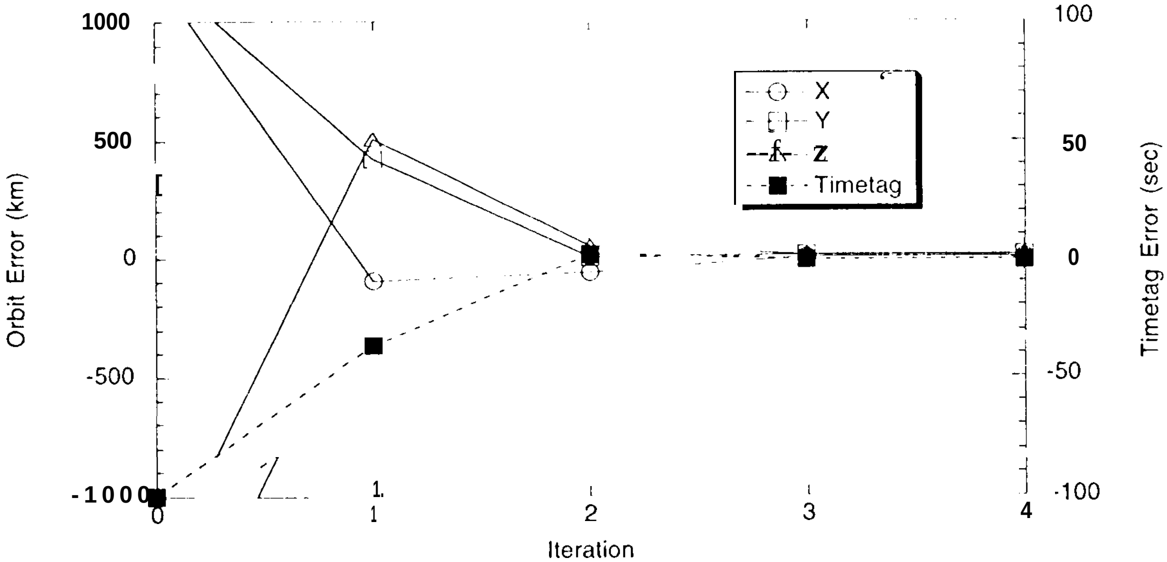


**Figure 5. Crude Orbit Convergence with Doppler Measurements**

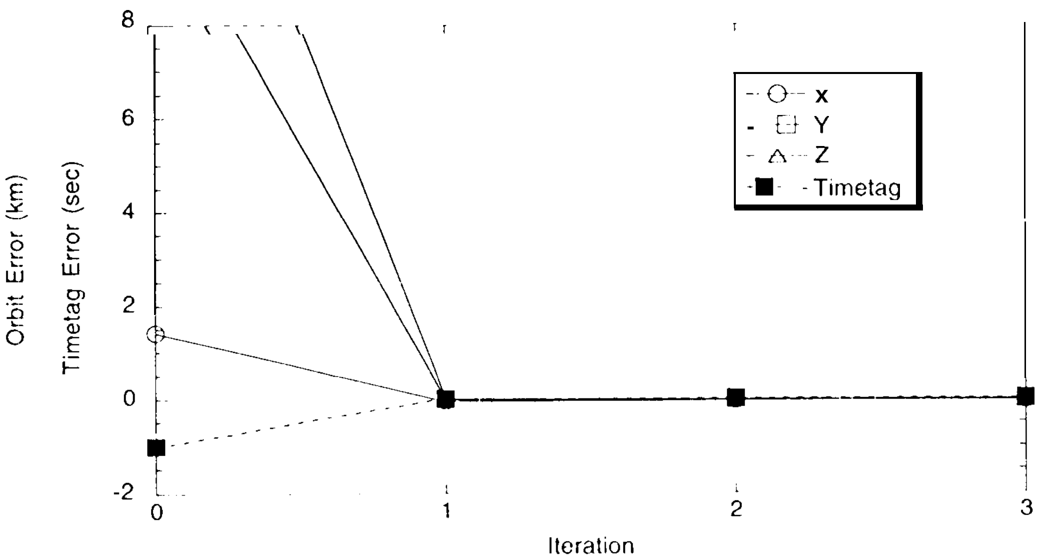


**Figure 6. Orbit Convergence with Pseudorange Measurements**

To demonstrate that snapshots of GPS measurements at epochs separated by 30 minutes are indeed sufficient to maintain the orbit to within a few hundred meters, two consecutive days of GPS/Met space flight GPS data, of length 18 and 15 hours respectively, were processed. Here, GPS doppler and ambiguous pseudorange measurements were taken at 30-min intervals. A 2 m/sec noise was added to the doppler data and a 15-m noise to the pseudorange data (in addition to the ~30-m SA error). A random-walk user clock drift at the level of 0.1 sec every 30 minutes was also added to both data types. The treatment of all estimated parameters in the filter is summarized in Table 1. The 3-D orbit velocity components were treated as process-noise parameters to reduce the sensitivity to mismodeled dynamics. The quadratically added 0.54 cm/sec velocity uncertainty at every data epoch is equivalent to a steady-state process-noise force Of 3 μm/sec$^2$.

TABLE 1

FILTER PA RAM ETERIZATION

| Parameter | Type | apriori σ | added σ between epochs |
|---|---|---|---|
| Orbit Position | integrated | 2000 km | — |
| Orbit Velocity | process noise | 2 km/sec | 0.54 cm/sec (random walk) |
| Timetag | random walk | 100 sec | 0.5 sec (random walk) |
| Pseudorange Bias | white noise | 300 km | 300 km (white noise) |
| Clock Rate | process noise | 1 μsec/sec | 1 μsec/sec (white noise) |

The filter UD matrix, which contains the parameter estimates and their covariances, from the previous data batch was mapped to the new data epoch after adding the process noise described in the last column of Table 1. The estimates were then used to update the nominal values of the measurement models and then reset to zero. This modified UD matrix was then efficiently combined with the UD matrix of the *converged* filter solutions resulting from processing the new data batch alone. This post-filter UD combining process is necessary to assure proper weighting between the previous UD matrix and the new data batch wherever an iteration process is involved. A cheaper way of combining the information would be treating the previous UD matrix as a priori for starting the filter iteration. However, this would tend to put more weight on the new data batch as the number of iterations increases.

The user orbit solution error components for the entire periods are shown in Figures 7 and 8. The filter orbit position errors arc at integer multiples of half-hour where snapshots of data are taken. Between these half-hour points, the orbit prediction errors from the previous data epochs arc shown. The RMS filter orbit errors for the first day (Figure 7) are 19 m radial (H), 7 m cross-track (C) and 67 m in-track (L). The predicted orbit errors are slightly larger at 31 m (H), 8 m (C) and 75 m (L).

The large error for the predicted orbit near the beginning of the second day (Figure 8) is due to large velocity error as a result of using single epoch of data for the orbit determination from cold start. The filter orbit errors for the second day, are 23 m (11), 15111 (C) and 98 m (1.); and the predicted orbit errors (excluding the first 0.5 hour) are 33 m (H), 15 m (C) and 99 m (L). The velocity errors are about 0.1 m/sec (1 [ ), 0.01–0.03 m/sec (C and L). The timetag error is 10--20 msec.

These results indicate that an efficient data acquisition and filtering scenario is such that snapshots of GPS doppler and ambiguous pseudorange measurements are taken every 30 minutes. At cold start, two epochs of data are used for pseudorange ambiguity resolution as well as for orbit determination and prediction. Afterward, only single epoch of data are used for orbit updating. To ensure stability at the coldstart, it might be useful to use several more closely spaced epochs 0! doppler data with noise greater than 2 III/sCc.

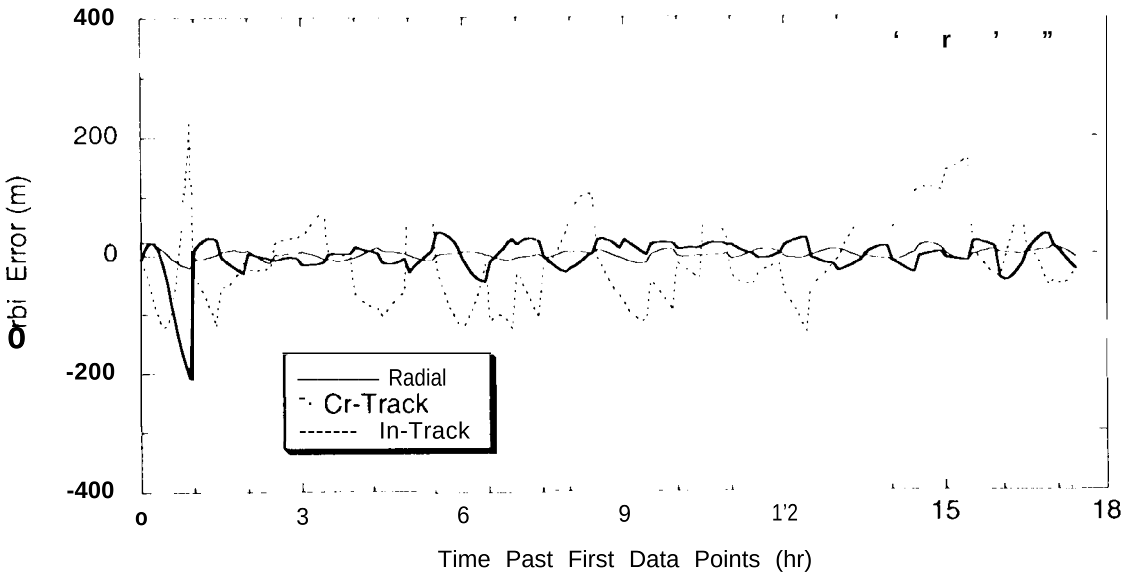


**Figure 7. Final Orbit Solutions for Day 1**

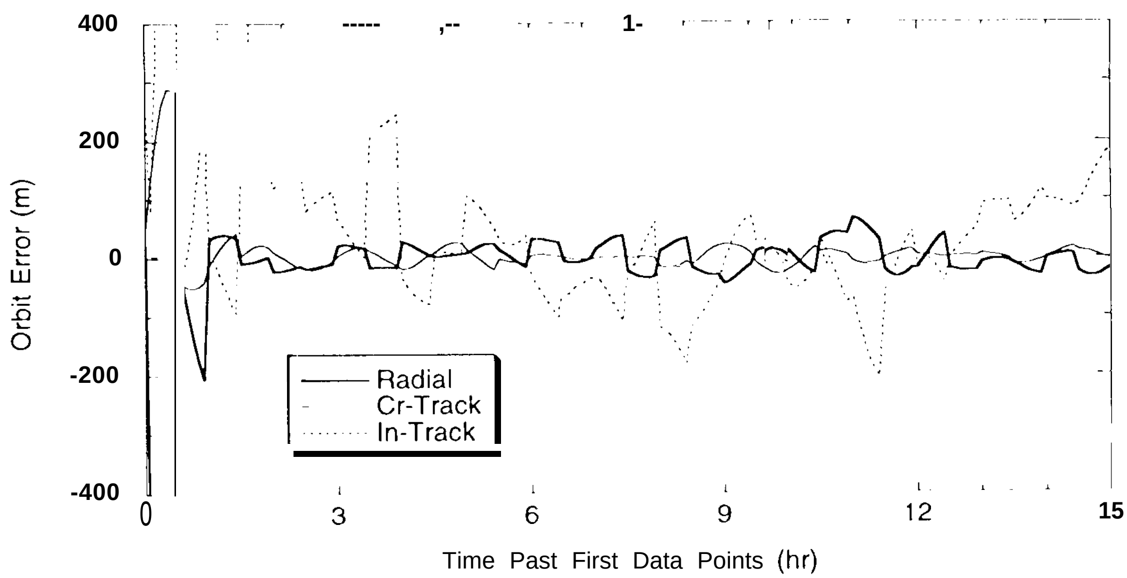


**Figure 8. Final Orbit Solutions for Day 2**

## SUMMARY

The feasibility of medium-precision orbit determination for a low earth orbiting satellite carrying a simple microGPS receiver has been demonstrated with two days of actual GPS data from the GPS/Met satellite. The results of this demonstration indicate that snapshots of GPS carrier doppler and ambiguous pseudorange measurements taken ever-y 30 minutes are sufficient to maintain the orbit within a few hundred meters. Such sparse data acquisition is the key to ultra-low mass and power for the microGPS receiver. The few-hundred orbit accuracy can bc arrived only with the pseudorange ambiguities resolved using the doppler data. At cold start, two epochs of data are used for pseudorange ambiguity resolution as well as for orbit determination and prediction. Afterward, only single epochs of data at a time are used for orbit updating.

The success of pseudorange ambiguity resolution depends on carrier doppler data quality. Doppler data of 2–5 m/see quality are shown to be appropriate. On the other hand, the final orbit accuracy depends on the pseudorange data quality. We anticipate, based on the GPS/Met data demonstration, that SNOE orbit can be determined to better than 100 m ( 1 $\sigma$) and O. 1 m/sec ( 1 $\sigma$); and the data timetag can be determined to better than 20 msec ( 1$\sigma$).

## ACKNOWLEDGMENT

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