microGPS: On-Orbit Demonstration of a New Approach to GPS for Space Applications

JEFFREY SRINIVASAN, YOAZ BAR-SEVER, WILLY BERTIGER, STEPHEN LICHTEN, RON MUELLERSCHOEN, TIMOTHY MUNSON, DONOVAN SPITZMESSER, JEFFREY TIEN, SIEN-CHONG WU, and LAWRENCE YOUNG
National Aeronautics and Space Administration's Jet Propulsion Laboratory / California Institute of Technology, Pasadena, California

Received September 1998; Revised January 2000

ABSTRACT: *In February 1998, the Student Nitric Oxide Explorer (SNOE) was successfully launched and began scientific observations. In addition to three instruments designed by the University of Colorado's Laboratory of Atmospheric and Space Physics to study nitric oxide in the atmosphere, the spacecraft carried a 600 gram GPS receiver designed and built by the Jet Propulsion Laboratory (JPL). This receiver, known as microGPS, is a combination of simple low-power hardware and portable, efficient software that was developed by JPL for spacecraft navigation in earth orbit. It is intended for micro- and nano-satellite applications in which mass and power budget margins are especially limited or as a robust second string to a conventional GPS receiver on board any satellite.*

This paper describes on-orbit operational experience with the microGPS receiver on the SNOE spacecraft. It also previews the next-generation, dual-frequency microGPS receiver, to be launched in 2000 on the Space Technology Research Vehicle (STRV-1c), a geostationary transfer orbit spacecraft. Comparisons are made between the expected performance of microGPS and actual observations. The design, expected, and actual performance of the orbit determination software, which is rooted in the techniques and algorithms pioneered in JPL's high-accuracy GIPSY/OASIS II software, is also described.

INTRODUCTION

GPS measurements can provide precise positioning for users on earth and in earth orbits. Positioning to 1 cm accuracy has been reported for users on earth [1, 2], and to 2 cm for a user in a low earth orbit [3, 4]. Such high-precision positioning requires a state-of-the-art GPS receiver on board 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 on-board receivers are not only costly, but also heavy and power hungry.

Many National Aeronautics and Space Administration (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. The Jet Propulsion Laboratory (JPL) and the University of Colorado have collaborated to develop a tracking system using a novel GPS technology, referred to as microGPS.

Two missions have carried or will carry a microGPS receiver. The first, Student Nitric Oxide Explorer (SNOE), a student-built spacecraft developed by the University of Colorado's Laboratory of Atmospheric and Space Physics (LASP), was launched successfully in February 1998. Although primarily an atmospheric science mission, it also carried the first flight microGPS into a 550 km, sun-synchronous circular orbit. The goal of the GPS experiment was orbit determination with better than 200 m accuracy. The second mission is the Space Technology Research Vehicle (STRV-1c) being developed by the Defense and Evaluation Research Agency (DERA) in the United Kingdom. Designed to be a new technology demonstrator, STRV-1c will be launched in 2000 into a geostationary transfer orbit (GTO). From this highly elliptical orbit, a second-generation microGPS will attempt

NAVIGATION: *Journal of The Institute of Navigation*
Vol. 47, No. 2, Summer 2000
Printed in the U.S.A.

to characterize the dual-frequency GPS signal strength from 300 km to geosynchronous orbit altitudes.

The microGPS hardware consists of lightweight antenna/receiver electronics that acquire occasional samples of GPS signals while consuming an average power of less than 100 mW. Peak power is 875 mW. The samples are stored in microGPS for subsequent processing. MicroGPS requires very low power because it awakens from a "sleep" mode only occasionally to sample GPS signals for a short duration. Because it employs this sparse sampling technique, microGPS has applications in tumbling/spinning satellites for routine navigation, as well as in safe-hold recovery for any satellite whose orientation is unknown.

To offer maximum flexibility in satellite design, the microGPS orbit determination software is designed for execution either on board the spacecraft or on the ground. In the latter case, used for the SNOE mission, the sparse GPS samples are telemetered to the ground and postprocessed to produce spacecraft orbits that can be uploaded to the satellite and projected ahead for real-time use. On board the spacecraft, the software can execute in the flight computer or in a special-purpose processor within the microGPS hardware unit (with slight increases in mass and power consumption). Inclusion of an on-board processor to execute detection and orbit determination software could potentially offer an autonomous tracking capability.

Each GPS signal sample is processed by software that implements an acquisition and observable extraction algorithm developed at JPL specifically to process microGPS data. Implementation of GPS processing normally performed by highly parallel hardware on a single-channel, sequential processor necessitated a specialized approach to making Doppler and pseudorange measurements with microGPS data. This approach reduced the computation required to search for GPS signals from order (N^2) to order ($N \log N$). The resulting observables are carrier Doppler and ambiguous pseudorange, the latter with an ambiguity of 1 ms ($\sim$ 300 km).

Among the challenges in orbit determination are resolution of the pseudorange ambiguity; determination of the measurement timetag, which, depending on clock stability, could drift off by up to 1 s between sparse measurement epochs; and 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 [5]. The results of a demonstration using actual space GPS data from the GPS/MET satellite have been reported in [6]. The present paper reports the results of an assessment of early SNOE in-flight data quality and orbit accuracy. The Real-Time Gipsy (RTG) software system [7], developed at JPL, is used for the analysis. The results presented demonstrate the expected data quality and the robustness of the pseudorange ambiguity resolution software, and confirm the orbit accuracy predicted by preflight analysis.

BACKGROUND

This section provides a brief description of the microGPS receiver architecture, specifics of the SNOE mission, the observable extraction software, the on-orbit receiver performance, and the ambiguity resolution of GPS pseudorange data. A more detailed description of ambiguity resolution is given in [5].

MicroGPS Flight Hardware

The microGPS flight receiver, an ultra-low mass and power flight receiver, was designed, built, and flight qualified at JPL. The ultra-low mass of the microGPS receiver is attributable partly to a modified hardware/software architecture in which all GPS specific signal processing typically implemented in hardware has been moved to software (see Figure 1).

In addition to power savings realized by this much-simplified hardware configuration, 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. microGPS acquires and stores short-duration snapshots (typically a few milliseconds) of raw GPS signals at a programmable rate (typically a few times per orbit). In addition, individual snapshots can be single, short-duration, or bursts of samples whose number and sample spacing are also programmable.

The raw GPS signal samples are timetagged by microGPS's real-time clock and then transferred to the spacecraft flight computer. Once received by the flight computer, the GPS sample bits are stored for later transmission to the ground and subsequent ground processing (as was done for SNOE and is

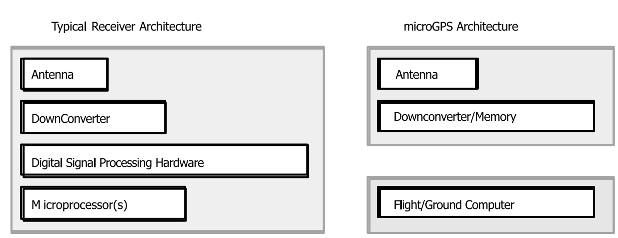

Fig. 1 – Receiver Architecture Comparison

planned for STRV) or processed in real or near–real time by on-board flight software. With proper processing software, these snapshots of the GPS constellation yield Doppler and pseudorange observables for all GPS satellites in view of the antenna, which can produce moderately accurate orbits.

SNOE HARDWARE CONFIGURATION AND DATA ACQUISITION

The SNOE spacecraft is a spinning satellite (~ 5 rpm) whose spin axis is perpendicular to the velocity vector as well as the nadir vector (i.e., it rolls like a barrel). The GPS antenna was placed on the satellite such that its boresight was perpendicular to the spin axis (see Figures 2 and 3), and thus rotating with the spacecraft from nadir pointing to zenith pointing and back 5 times/ min. This configuration is ideal for a sparse-sampling receiver and not very conducive to a continuously tracking receiver.

To minimize cost as well as impact on the SNOE mission, microGPS was designed with the same custom, serial flight computer interface as the three primary science instruments. It also was provided with the trigger signal from an on-board horizon crossing sensor so the GPS snapshots could be taken when the antenna boresight was near zenith pointing. The microGPS receiver that was delivered to the SNOE project for satellite integration was approximately 5 × 12 × 12 cm (see Figure 4). Including its integral patch antenna, its mass is 595 grams. The power consumption is 75 mW orbit average (in standby mode, ready for commands with oscillator warm) and 875 mW peak (during data acquisition, which lasts less than 25 ms).

For the SNOE mission, the nominal data snapshot duration was 20 ms, with samples being acquired every 15 min (~ 4 times per orbit). The data

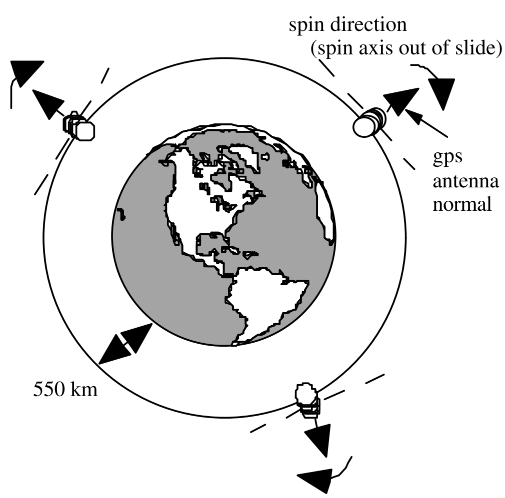

Fig. 2 – Simplified Spinning Satellite Configuration and Data Acquisition Scheme

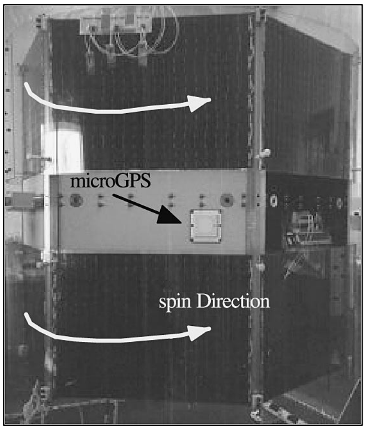

Fig. 3 – View of microGPS Antenna / Receiver after Integration on the SNOE Spacecraft

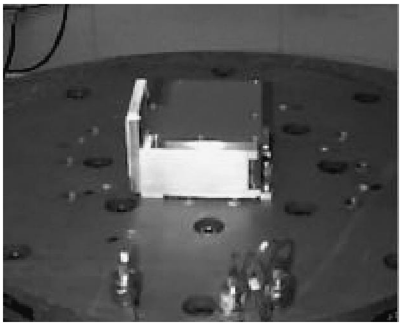

Fig. 4 – microGPS Receiver on Vibration Table

volume was about 450 kB/day. Based on preliminary orbit studies, the sampling time and the interval between samples could be reduced to 10 ms and 30 min, respectively, decreasing the daily data volume to ~ 100 kB without loss of orbit accuracy.

Observable Extraction

The parallel nature of typical hardware-based GPS processing permitted the implementation of order (N^2) computations in order (N) time using N parallel channels. To achieve practical implementation of GPS signal search and observable measurement in software (using an inherently sequential computation engine), an ANSI-C + + set of classes was written to implement the Fourier-based technique of time-domain correlation [10].

The basic algorithm for GPS signal search, acquisition, and observable measurement operates on an input that consists of a timetagged sequence of sampled antenna data. These data are, in the case of microGPS, downconverted, filtered, single-bit quantized, digital bit streams. The receiver samples the signal at ~ 20 Mbps, but can be programmed to perform a sum-and-dump filter and decimate function to reduce the data rate to ~ 2 Mbps (the latter is the SNOE default operational mode). The sampled data are searched in Doppler (up to ± 45 kHz) and in delay (over 1 repeat cycle of the C/A-code, 1 ms). The search takes place for each satellite predicted to be visible at the time of capture (or all possible pseudorandom numbers [PRNs] if the orbit and timetag offset are unknown).

Doppler space is searched sequentially, with the entire delay space searched at each Doppler point in order ($N \log N$) time. The time correlation of the sampled data with an appropriately formed model is accomplished by multiplying their Fourier transforms and inverse transforming the product back to the time domain, forming the full cross-correlation function, which can be checked for amplitude as a function of delay or pseudorange. Both pseudorange and Doppler observables are interpolated from within the correlation function with peak amplitude (pseudorange), and between the peak correlation function and its two nearest Doppler neighbors (Doppler).

It is important to distinguish between pseudorange produced with microGPS and the usual GPS pseudorange observable. While the usual GPS receiver pseudorange represents absolute, unambiguous range (plus transmitter and receiver clock offsets), microGPS can reliably produce only a 1 ms (300 km) pseudorange. The reason for this limitation is that 20 ms of sampled data produced each epoch by microGPS is not sufficient either to decode the navigation data message (so that GPS time is unavailable) or to determine reliably the location of the bit transitions of the navigation message. As discussed below, this deficiency is overcome by clever processing of ambiguous pseudorange along with Doppler measurements from multiple satellites.

The current version of the observable extraction software executes on PowerMacintosh computers. In the future, it will be ported to the GPS-on-a-Chip receiver, codeveloped by JPL, Goddard Space Flight Center, and Stanford University [11] for space flight applications.

On-Orbit Receiver Performance

The on-orbit performance of the SNOE microGPS hardware and observable extraction software is summarized in Table 1.

The Doppler and pseudorange measurement accuracy can be compared favorably with post-fit residual plots shown later in Figures 8 and 10. Note that the pseudorange post-fit residual includes effects of Selective Availability (SA). Figure 5 shows a plot of detected signal-to-noise ratio (SNR) versus measured Doppler for a typical day's worth of data. The skewing of the peak SNR toward positive Doppler can be explained by the value of the "trigger delay" parameter programmed into microGPS

Table 1 – Summary Statistics for April 8, 1998

Mean GPS Satellites Detected per Snapshot	6.4
Mean Signal-to-Noise Ratio (SNR) (C/N_0)	45.5 dB-Hz
Doppler Accuracy ($1\ \sigma$)	6.5 m/s
Pseudorange Accuracy ($1\ \sigma$)	14 m

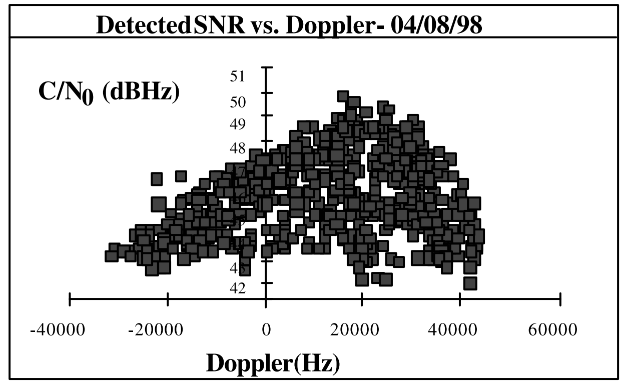

Fig. 5 – Signal-to-Noise Ratio vs. Doppler Plot of All GPS Satellites Detected on April 8, 1998

on that particular day, which resulted in the time of each snapshot occurring slightly after the GPS antenna was zenith pointing. At the actual capture moment, the antenna boresight was pointed slightly forward, toward the velocity vector, and the gain pattern was thus peaked at satellites with slightly positive Doppler shifts.

Ambiguity Resolution of GPS Pseudorange Data

The sparse sampling technique used in the microGPS receiver precludes the acquisition of traditional GPS data types (carrier phase and unambiguous pseudorange). Instead, the data types available are carrier Doppler and ambiguous pseudorange with an ambiguity of 1 ms (~ 300 km or the C/A-code repeat period). 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 resolved with the help of the Doppler data, making the ambiguous pseudorange 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, an unambiguous pseudorange dataset is computed on the basis of 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 is described in detail in [5].

THE REAL-TIME GIPSY SYSTEM

The simulation analysis reported in [5] was performed using the GIPSY/OASIS II software set [8] developed in an epoch-state filtering architecture, which is not ideal for real-time applications or for use by an on-board computer. RTG, developed at JPL [7], is written in ANSI-C and is capable of processing general radiometric data types in real time on an on-board processor. RTG is also currently in use for the Federal Aviation Administration's (FAA's) real-time GPS Wide Area Augmentation System (WAAS). It is nearly complete 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 upper-diagonal (UD) factorized filter [9] is implemented in RTG. Currently, RTG executes on HP workstations under Unix and on PCs. Its target platforms for the SNOE and STRV missions are ground-based PowerPC Macintosh and HP9000 workstations. The software was written in such a way that eventual migration to a real-time flight processor will be straightforward.

ORBIT RESULTS FROM SNOE IN-FLIGHT DATA

A few segments of SNOE data acquired during the first few weeks of its flight have been investigated. The timetable of the investigated data segments is as shown in Figure 6. The first data segment, acquired on March 4, 1998, at variable intervals for a period of 2.3 h, was used as a software robustness test. The second data segment, acquired on March 29 at a 16 min interval over a period of 2.7 h, was used for data quality assessment. The third data segment covered a continuous 2.4 day period on April 7–9, also at a 16 min interval. Only this long data segment was used for orbit quality assessment.

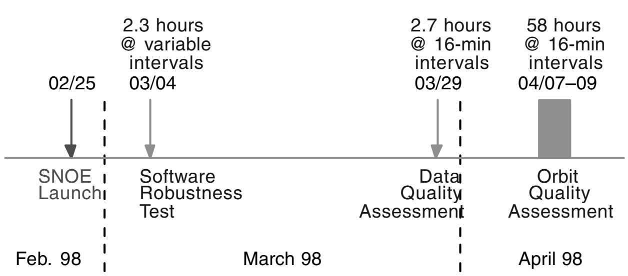

Fig. 6 – Early SNOE Flight Data Segments

Software Robustness Test

The software robustness that needs to be demonstrated is the ability to resolve pseudorange ambiguities. For this test, 10 epochs of data separated by 102 s on March 4 were investigated. In particular, the ambiguous pseudorange residuals were examined, after removing integer milliseconds, as determined by fitting to the Doppler-inferred SNOE orbit. The key factor for ambiguity resolution is the clustering of the 6 or 7 measurement residuals at each epoch. Any data residual with a deviation greater than about 0.2 times the millisecond ambiguity from the cluster mean is labeled as an outlier and discarded. Of the 62 data residuals, 59 satisfy this criterion. Only 2 are labeled as outliers and 1 nearly so, labeled as "??" in Figure 7. The clustering of the remaining data residuals is very good (better than 0.06 ms) in general. It should be noted that after these pseudorange outliers were discovered, the observable extraction software was improved to detect and measure pseudorange with higher fidelity. Since then, outliers have been virtually nonexistent.

Data Quality Assessment

Data quality is assessed by examining the post-fit residuals of each data type. Three classes of post-fit residuals are assessed. First, the Doppler residuals are computed using the best-fit Doppler-inferred SNOE orbit. For the March 29 data segment, the Doppler residuals have a root-mean-square (RMS) value of 6.8 m/s, as shown in Figure 8; this result is in agreement with the expected data-noise error.

Next, the residuals of the ambiguity-resolved pseudorange data as fitted to the same Doppler-inferred orbit are examined. Because of the drift in the SNOE on-board clock, the data residuals are examined independently at each epoch. The pseu-

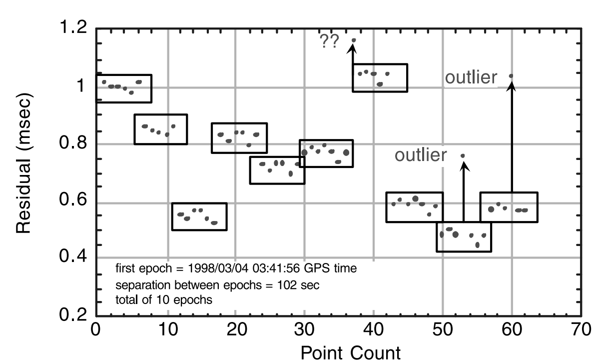

Fig. 7 – Ambiguous Pseudorange Residuals (integer milliseconds removed) as Fitted to Doppler-Inferred Orbit

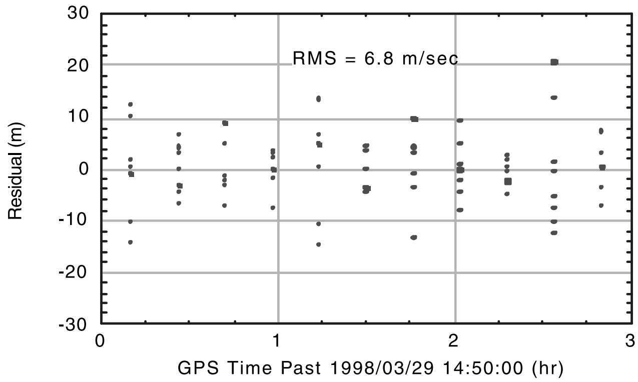

Fig. 8 – Post-Fit Doppler Residuals

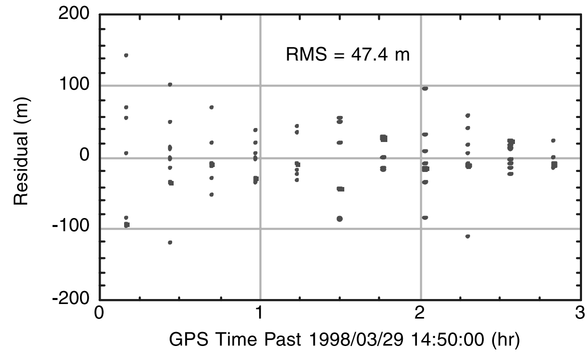

Fig. 10 – Post-Fit Pseudorange Residuals

dorange residuals have an RMS value of 25.8 μs (see Figure 9). While this RMS residual does not reflect the pseudorange data quality because of the large errors in the Doppler orbit, it provides another assessment of how well the pseudorange ambiguities were resolved.

The quality of the ambiguity-resolved pseudorange data is assessed by the post-fit residuals derived using the best-fit pseudorange-inferred SNOE orbit and white-noise clock solutions. The residuals have an RMS value of 47.4 m, as shown in Figure 10. Note that the effect of SA clock dithering is of the order of 30 m; the actual pseudorange data quality is believed to be of the order of 30 m, somewhat higher than predicted by system noise alone. This deviation is not understood at present, but would include contributions by multipath.

Orbit Quality Assessment

The long data segment on April 7–9 is processed, one day at a time, to derive independent SNOE orbit solutions. The orbit quality is assessed by propagating the first-day solution into the second day and comparing it with the second-day solution using a different number of data epochs. Results of the comparison using 2 and 4 data epochs are shown in Figure 11. In general, the orbit is better than 100 m in all three components within the data span. The error increases when the orbit is predicted into the future, but is still below 300 m (mostly in-track) after 0.5 h of prediction. A further comparison shows that a 1 day orbit solution has a prediction error of $\sim$ 10 m/h in radial, 100 m/h in track, and no cross-track degradation.

Another assessment of the orbit solution is performed by examining the associating SNOE clock solutions. The clock was treated as a white-noise process to allow unconstrained variations. Figure 12 compares the clock solutions for two consecutive 1 day data segments. The clock shows an apparent drift of 350 ms/day. The drift is continuous across the boundary of the two solution sets, implying consistent clock, and thus orbit, solutions.

SUMMARY

The innovative microGPS architecture, a simplified flight receiver coupled with software designed to extract radiometric measurements and produce orbits, has been demonstrated to produce spacecraft orbits with $\sim$ 75 m accuracy. This performance is quite comparable to that of conventional GPS receivers that cost more, weigh more, and consume more power.

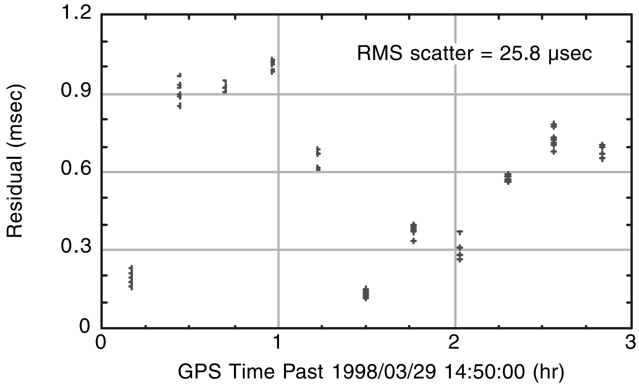

Fig. 9 – Ambiguity-Resolved Pseudorange Residuals as Fitted to Doppler-Inferred Orbit

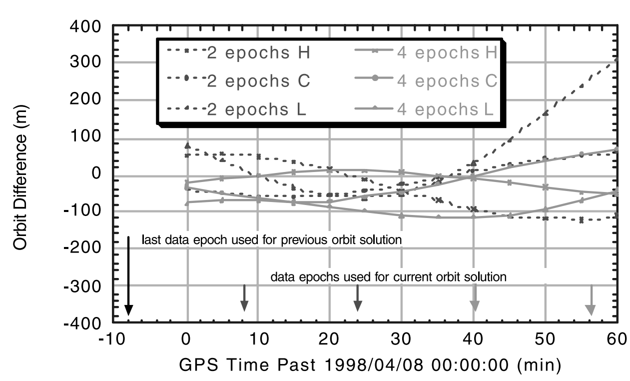

Fig. 11 – SNOE Orbit Difference from Propagated Previous-Day Solution (H = radial, C = cross-track, L = in-track)

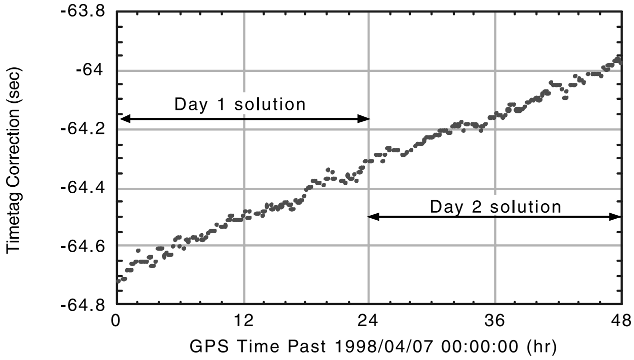

Fig. 12 – SNOE Clock Solution for Two Consecutive Data Segments

To accomplish this advance, a patent-pending algorithm was developed that can process Doppler plus ambiguous pseudorange observables collected with widely spaced epochs (i.e., sparse sampling). In addition, a new low-power, high-stability, multi-frequency radio-frequency downconverter was designed and space-qualified. These key advances led to a system that exceeded orbit accuracy goals by almost a factor of 3.

ACKNOWLEDGMENT

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Funding was provided by NASA and the Department of Defense's BMDO Office.

The microGPS project was carried out by JPL in partnership with the Colorado Center for Atmospheric Research, and the authors acknowledge the valuable contributions of Dr. Penina Axelrad and Angie Reichert. The authors would also like to acknowledge the much-appreciated efforts of Dr. Charles Barth and his SNOE science and engineering team at the University of Colorado's Laboratory of Atmospheric and Space Physics, who integrated and currently operate the microGPS payload. The authors further would like to recognize the early conceptualizations of Tomas Svitek of Stellar Innovations Inc. and Tom Meehan of NASA/JPL that eventually led to the development of microGPS.

Based on a paper presented at The Institute of Navigation ION GPS-98, Nashville, Tennessee, September 1998.

REFERENCES

1. Yunck, T. P., S. C. Wu, J. T. Wu, and C. L. Thornton, *Precise Tracking of Remote Sensing Satellites with the Global Positioning System*, IEEE Transactions in Geoscience and Remote Sensing, Vol. 28, No. 1, January 1990, pp. 108–116.
2. Heflin, M. D., D. Jefferson, Y. Vigue, F. Webb, J. Zumberge, and G. Blewitt, *Site Coordinates and Velocities from the Jet Propulsion Laboratory Using GPS*, SSMC(JPL) 94 P 01, IERS Tech. Note 17, 49, 1994.
3. Yunck, T. P., W. I. Bertiger, S. C. Wu, Y. E. Bar-Sever, E. J. Christensen, B. J. Haines, S. M. Lichten, R. J. Muellerschoen, Y. Vigue, and P. Willis, *First Assessment of GPS-based Reduced Dynamic Orbit Determination on TOPEX/POSEIDON*, Geophysical Research Letters, Vol. 21, No. 7, 1994, pp. 541–544.
4. Bertiger, W. I., Y. E. Bar-Sever, E. J. Christensen, E. S. Davis, J. R. Guinn, B. J. Haines, R. W. Ibanez-Meier, J. R. Jee, S. M. Lichten, W. G. Melbourne, R. J. Muellerschoen, T. N. Munson, Y. Vigue, S. C. Wu, T. P. Yunck, B. E. Schutz, P. A. M. Abusali, H. J. Rim, M. M. Watkins, and P. Willis, *GPS Precise Tracking of Topex/Poseidon: Results and Implications*, Journal of Geophysical Research, Vol. 99, No. C12, December 1994, pp. 24449–24464.
5. Wu, S. C., W. Bertiger, J. Srinivasan, and A. Reichert, *MicroGPS for Orbit Determination of Earth Satellites*, presented at The Institute of Navigation's National Technical Meeting, Santa Monica, CA, January 1996.
6. Wu, S. C., D. Kuang, S. M. Lichten, S. Nandi, L. J. Romans, and J. M. Srinivasan, *Demonstration of MicroGPS for Low-Cost Orbit Determination*, AAS/AIAA Astrodynamics Specialist Conference, Sun Valley, ID, August 1998.
7. Bertiger, W. I., Y. E. Bar-Sever, B. J. Haines, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoen, T. N. Munson, A. W. Moore, L. J. Romans, B. D. Wilson, S. C. Wu, T. P. Yunck, G. Piesinger, and M. Whitehead, *A Prototype Real-Time Wide Area Differential GPS System*, presented at The Institute of Navigation's National Technical Meeting, Santa Monica, CA, January 1997.
8. Webb, F. B. and J. F. Zumberge (eds.), *An Introduction to GIPSY/OASIS II*, JPL Internal Document D-11088, July 1993.
9. Bierman, G. J., *Factorization Methods for Discrete Sequential Estimation*, Academic Press, New York, NY, 1977.
10. Cathey, W. T., *Optical Information Processing and Holography*, Wily-Interscience, New York, NY, 1974.
11. Meehan, T. K. et al., *"GPS-On-A-Chip"—An Advanced GPS Receiver for Spacecraft*, presented at The Institute of Navigation GPS-98, Nashville, TN, September 1998.
12. Solomon, S. et al., *The SNOE Spacecraft, Integration, Test, Launch, Operation and On-orbit Performance*, Proceedings of the 12th AIAA/USU Conference on Small Satellites, SSC98-IV-3, 1998.
13. Blott, R. J., N. S. Wells, and J. Eves, *The STRV1 Microsatellite Series: Exploiting the Geosynchronous Transfer Orbit*, IAF Conference, 1997.