Results of an Automated GPS Tracking System in Support of Topex/Poseidon and GPSMet

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BIOGRAPHIES

Ronald Mueller.vchoctt received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a Member of the Technical Staff in the Earth Orbiter Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on the development of efficient filtering/smoothing software for processing GPS data and the processing of '1'opcx/Poseidon-GPS data.

Dr. Stephen M. Lichten has worked at the Jet l'repulsion Laboratory since 1983, where he presently is the Earth Orbiter Systems Group Supervisor and Radio Metrics manager in NASA's Deep Space Network Advanced Technology Program. He received an A.B. degree from Harvard in 1978 and a 1%. D. in astrophysics from Caltech in 1983. His group specializes in high-precision orbit determination, including automated GPS tracking techniques and software, recently demonstrating 2-cm radial orbit accuracy for Topex/Poseidon. Dr. Lichten was a session co-chair for the ION GPS'93 meeting and a Technical Chairman for the 10N GPS'94 meeting.

Dr. Ulf J. Lindqwister received his Ph.D. in physics from Princeton University in 1988. Dr. Lindqwister is supervisor of the GPS Networks and Operations Group at JPL that operates NASA's permanent GPS stations in various global, regional, and local GPS networks (currently approaching 50 stations) and whose group also routinely produces media (ionospheric and tropospheric) calibrations for NASA's deep space and near Earth missions.

Dr. Winy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976, specializing in Partial Differential Equations. Following his Ph. D., 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 Chevron Oil Field Research. At Chevron, 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.

ABSTRACT

A fully automated near real-time GPS tracking system has been developed around JPL's GIPSY/OASIS II software. The system produces < 25 cm (3D rms) GPS orbits and one-half nanosecond (15 cm) clock estimates. The process starts automatically when a favorable global distribution of ground data from the IGS network (International GPS Service for Geodynamics) becomes available, Ionospherically corrected phase and pseudorange data arc optimally combined to remove satellite and ground receiver clock errors, including selective availability. After the GPS orbits arc determined within the data arc, they arc then propagated with empirically determined dynamic force models. Real-time < 2 meter (3D rms) GPS orbits arc always available. As a by-product of this process, other calibration estimates such as station clocks, troposphere estimates, and earth orientation parameters arc also produced. For daily arc fits, the process requires 7-8 hours of CPU time on an HP9000/735 workstation.

Additionally, a second process has been developed that automatically starts when data from the '1'opcx/Poseidon GI'S receiver and a favorable distribution of ground stations becomes available. An optimal selection of ground stations is determined and data from these sites arc then used to solve for the GPS clocks as well as the Topex/Poseidon orbit. This process makes use of the

previously determined predicted GPS orbits. The 'J'opcx/Poseidon orbits determined within the data arc arc precise to *5 cm* radial (rms) and 18 cm 3D (rms). Real-time predicted orbits arc also produced precise to 15 meters 3D (rms). 'J'his process has been adopted to also support the precise orbit determination of the GPSMct experiment.

INTRODUCTION

The Topcx/Poseidon ('J'/P) spacecraft was launched intoa 1334 km circular orbit in August 1992 and carries a high precision dual frequency GPS receiver. When the GPS Anti-Spoof function is off, the GPS receiver uscs P-code to obtain GPS pseudorange and carrier phase observables at L1 and L2 frequencies, providing ionosphere-free pseudorange and phase observables. When the Anti-Spoof function is on, the GPS flight receiver tracks only the 1.1 C/A signal which precludes the computation of ionosphere-free observables. Since January 31, 1994 (except for 2 three-week periods in June/July 1995 and April/May 1995), the Anti-Spoof function has been turned on and T/P's GPS receiver has been operating as a single frequency receiver [1].

GPSMct is an experiment on tbc MicroLab 11 satellite which was launched into a 790 km circular orbit in April 1995. It carries a modified version of a dual frequency TurboRogue™ GPS receiver [2]. When the Anti-Spoof function is on, the receiver tracks tbc L1 C/A signal and full wavelength L2 in cross-correlated mode. This provides tbc generation of ionosphere-free pseudorange and phase observables.

The Topcx/Poseidon spacecraft requires near real-time orbit determination for 1.) tbc production of Interim Geophysical Data Records [3] and 2.) integration with tbc U.S. Navy's Altimetry Data Fusion Center (ADFC) located at the Stennis Space Center. The ADFC's goal is to combine altimetry data from available sources into oceanographic products and to distribute them to the U.S. Navy in a timely manner. To make usc of the Topcx/Poseidon altimeter data, an estimate of T/P's radial orbit component to less than 1 meter must be available in lcss than 24 hours.

The goal of tbc GPSMct experiment is to make measurements of the Earth's neutral atmosphere such as refractivity index, temperature, and water vapor using radio occultations of GPS signals with the onboard GPS receiver [4], Precision orbit determination is necessary for proper calibration and processing of the GPS radio occultation data. Although near real-time orbits arc not necessary to perform tbc experiment, being able to demonstrate tbc capability of providing these measurements of the Earth's atmosphere in a timely matter is important.

To support the near real-time orbit determination of both these spacecraft, a fully automated GPS tracking system has been developed. The core of this data reduction system is the second generation GPS data processing software system, GIPSY/OASIS II, developed at JPL [5]. This core software set is driven by a highly automated expert data processing system that incorporates various UNIX utilities such as c shell, awk, sed, and perl. When there is a sufficient global distribution of ground data available, the process automatically produces a 27-hour GPS orbit solution. The 27-hour data arc includes 3 hours of the previous day and 24 hours of data of the current day. In this way, 3 hours of GPS orbits in the overlapping data segments arc used to quickly asses the quality of the GPS orbits. After cacb daily GPS process completes, predicted GPS orbits arc also produced that span 3 additional days past tbc end of the data arc. It is primarily these precise predicted GPS orbits that arc used to support the near real-time orbit determination of Topcx/Poseidon and the GPSMct experiment.

After this GPS process has been completed, an c-mail message is automatically compiled and distributed to potential users. The message reports orbit precision, data residuals, data outliers, and any potential problems that may have arisen in the processing, All this occurs within 18 hours of UTC midnight (which is the end of the data arc) of the current processing day,

Both the predicted GPS orbits and GPS solutions within the data arc, along with GPS clock and yaw-rate solutions [6], along with earth orientation solutions, arc placed on an HP9000/735 workstation. These solutions arc available via anonymous FTP from sideshow.jpl.nasa.gov (128.149.70.41) under pub/gipsy_products/RapidService/orbits. A revolving buffer currently allows availability of the two most recent weeks of these RapidService orbits. This occurs on a daily basis and has been in operation since March of 1995.

Besides supporting orbit determination of Topcx/Poseidon and the GPSMct experiment, these GPS orbits and clock solutions arc also used by JPL's IGS Flinn Analysis [7] to screen all data from the IGS net work. Over 100 sites pcr day arc precisely point positioned with these GPS orbits and clock solutions. The technique of precise point positioning refers to processing ground data with fixed GPS orbits and fixed GPS clocks. Only the station's clock, troposphere, station location, and phase biases arc estimated. Large postfit residuals of the phase data arc a direct indication that data from a particular station may not bc valid.

The paper will cover briefly thc automated data acquisition of the IGS data, the determination of a global distribution of ground sites, problcm detection and correction within the automated GPS processing, and the results of this processing. The results will indicate orbit precision, both within the data arc and of the predicted GPS orbits, clock precision, cxpectcd user position error of using the predicted GPS orbits for WAAS, precision of the Earth orientation estimates, and precise point positioning of global stations. A comparison will bc made bctwccn the solutions produced by this automated processing and the solutions produced by JPL's IGS Flinn Analysis (JPL Flinn) *[7]*. The orbits and clock solutions produced by the automated process will bc rcfcrrcd to as the JPL quick-look solutions. The nomenclature "quick-look" refers to the fact that these solutions arc available within 18 hours of UTC midnight of the solution day, whereas the JPL Flinn solutions arc generally not available until two-weeks after UTC midnight of the solution clay.

The paper will conclude with the production and results of the near real-time Topcx/Poseidon orbits and of the MicroLab II satellite.

GROUND DATA ACQUISITION

JPL uploads data via regular telephone lines, Internet, and NASCOM (direct NASA communications lines from the three DSN stations) in 24-hour file segments. All routine data uploading and handling operations at the JPL have been automated. The data transfers start immediately after UTC midnight, and under ideal conditions all the data is obtained within 12 hours. In practice, 95+% of the data is collected automatically every day, with the remaining data uploaded the next day by the automated upload system.

The data is uploaded automatically via telephone lines or direct serial connections using Microphone Pro scripts running on Macintosh computers, The networked Macintoshes at JPL usc Telebit T2500 Trailblazer modems to dial up 30+ stations with standard telephone connections. Data from 8+ stations is uploaded from the receivers with direct serial connections via Internet. The resulting files arc stored on the Macintosh computers until a DEC 3000/500 Alpha workstation at JPL completes a successful FTP transfer. The Alpha workstation additionally decompresses, inventories, validates, formats, and distributes the data. The process requires about a minute of CPU time on the DEC workstation pcr station pcr day.

GPS ground data acquired from agencies besides JPL is additionally obtained via Internet. All data for a particular day is combined and may bc accessed via anonymous FTP from bodhi.jpl.nasa.gov (1 28.149.70.66) under pub/rinex. Approximately 100+ stations pcr day arc eventually acquired, with about 60+ stations available within 12 hours of UTC midnight.

AN OPTIMAL GLOBAL DATA DISTRIBUTION

To obtain the GPS orbits and clock solutions within 6-7 hours of processing time on an HP9000/735 workstation, 18 stations arc selected from the available data base and used for the daily processing, An optimal selection of 18 stations is determined by computing the rms value over the Earth of the distance-to-nearest-site function [8]. At an arbitrary point on the Earth (θ,ϕ) the quantity

$$r_n(\theta,\phi) = R_c \cos^{-1}[\sin\theta \sin\theta_n \cos(\phi-\phi_n) + \cos e \cos\theta_n] \qquad (1)$$

is the great-circle distance from (θ,ϕ) to a ground site n located at (θ_n,ϕ_n). Let

$$r(\theta,\phi) = \min\,[r_1, r_2, \ldots r_N] \qquad (2)$$

bc the distance from (6,$) to the nearest of N ground sites. Define a function “zeta” as the rms value over the Earth:

$$\zeta = (4\pi)^{-1/2}\left[\int d\phi \int d\theta \,\sin\theta\, r^2(\theta,\phi)\right]^{1/2} \qquad (3)$$

For uniformally distributed stations:

$$\zeta \approx \frac{2}{\sqrt{6}} R_c \sqrt{\pi/N} \qquad (4)$$

22 uniformally geographically distributed sites arc nccdcd to achieve a zeta of less than 2000 km. Given however the non-uniformity of the IGS network, tbc smallest zeta that can bc achieved with 18 stations is 2800 km. In comparison, JPL's IGS Flinn Analysis, which uscs 34 stations to compute GPS orbits and clocks, realizes a 2400 km value for zeta.

As ground data is accumulated and the global distribution improves, the value of zeta for a particular solution day decreases. Table 1 shows the local PDT (Pacific Day-light Savings Time) time that tbc value of zeta crossed 3400 km in the first two weeks in August of 1995.

solution day	~.eta (km) for 18 stations	local PDT time zeta crosses 3400 ktn and auto processing starts
95aug01	3386	Aug 02 02:06
95aug02	3096	Aug 03 04:10
95aug03	**3022**	Aug 04 04:13
95aug04	3297	Aug 05 03:11
95aug05	3158	Aug 06 04:04
95aug06	3276	Aug 07 03:13
95aug07	2983	Aug 08 04:09
95aug08	3028	Aug 09 04:11
95aug09	2897	Aug 10 17:11
95aug10	2975	Aug 11 04:06
95aug11	**3000**	Aug 12 04:02
95aug12	2962	Aug 13 04:06
95aug13	2969	Aug 14 04:11
95aug14	2994	Aug 15 04:15

Table 1) Local PDT time when an 18 station distribution crosses the 3400 km "zeta" threshold.

When zeta crosses this 3400 km threshold, the automated GPS processing is initiated with the 18 optimally determined ground stations. An acceptable distribution of stations is generally available just after 4:00 AM PDT. This is 11 hours after tbc end of the processing day's UTC midnight, which is also the end of the processing day's data arc.

PROBLEM DETECTION AND CORRECTION OF THE GPS PROCESSING

Once an optimal distribution of stations is determined, a script is executed that computes the GPS orbits and clocks. This computation requires 6-7 hours of processing on an HP9000/735 workstation.

Onc of the first steps in the processing is to perform a fit to the broadcast ephemeris solution. This produces nominal starling conditions of the GPS spacecraft. The 3D rms of this fit is generally a few meters, which is the level of the precision of the broadcast orbits. Should the 3D rms of any GPS satellite exceed 100 meters, tbc satellite is automatically removed from the processing. In this way, GPS maneuvers arc automatically detected. GPS maneuvers were detected to have occurred on 95aug08 for GPS35, 95jul22 for GPS18, 95jul 19 for GPS15, 95jul12 and 95jul14 for GPS23, 95jul01 for GPS21, 95jun23 for GPS 10, 95jun22 for GPS34, and 95jun17 for GPS19.

Another step of this GPS processing is to perform linear fits to the ground clock solutions as computed with pseudorange data and the broadcast orbits and clocks. This serves four purposes. First, the prefit (pre-filter) residuals arc reduced to at most a few hundred meters. A simple prefit residual test in the filter is then used to remove gross data outliers. Second, clock jumps are detected and recorded. In the filtering process, since a reference clock is required in the system, it is undesirable to use a reference clock that has had a clock jump within the data arc. Third, this process aligns all the ground clocks to GPS time. This is particularly important since onc of these clocks will serve as the reference clock. And fourth, the detection of clock jumps can also aid in the removal of pseudorange outliers.

Even if a station appears to have a good clock based on pseudorange data, the phase data may not be acceptable. To determine this, after the first pass through tbc filter and smoother, the postfit residuals of the phase data arc examined to determine if there arc additional cycle-slips. If there arc, phase breaks arc inserted in the data file and tbc data is reprocessed through tbc filter/snloother. If excessive phase breaks need to be inserted, the entire pass is removed from the data file before reprocessing.

To remove outliers from the solution, a simple windowing method is used. If postfit (post-smoother) pseudorange residuals exceed 3 meters or postfit phase residuals exceed 5 cm, the outling data points arc removed with a decentralized SRIF downdating process [9]. When all the residuals arc less than their specified window, the GPS orbits arc then mapped within the data arc, and the smoothed GPS clocks are tabulated.

RESULTS OF THE GPS PROCESSING

GPS Orbit Precision Within the Data Arc

Orbit overlaps provide a preliminary assessment of the orbit precision. Figure 1 compares the 3-hour orbit overlaps between the JPL Flinn GPS orbits and the JPL quick-look GPS orbits. The average 3D rms overlap for the Flinn orbits is 18 crn; the average 3D rms overlap for the quick-look GPS orbits is 34 cm. Assuming that the daily orbits arc relatively uncorrelated, dividing by $\sqrt{2}$ yields an approximate 3D orbit precision of 13 cm for JPL Flinn orbits and 24 cm for JPL quick-look orbits. This is a pessimistic estimate of the precision since only the tails of the orbits arc being used in this statistic. The overall precision of the orbits should bc better than this, and especially so in the middle of the data arc.

Figure 2 shows the 3D orbit difference between the JPL Flinn GPS orhits and the JPL quick-look GPS orbits, Tbc average 3D rms orbit difference is 21 en). Assuming that the Flinn orbits arc truth, the 3D precision and accuracy of the quick-look orbits arc then 21 cm. This is in close agreement with the 24 cm 3D precision obtained from the orbit overlaps

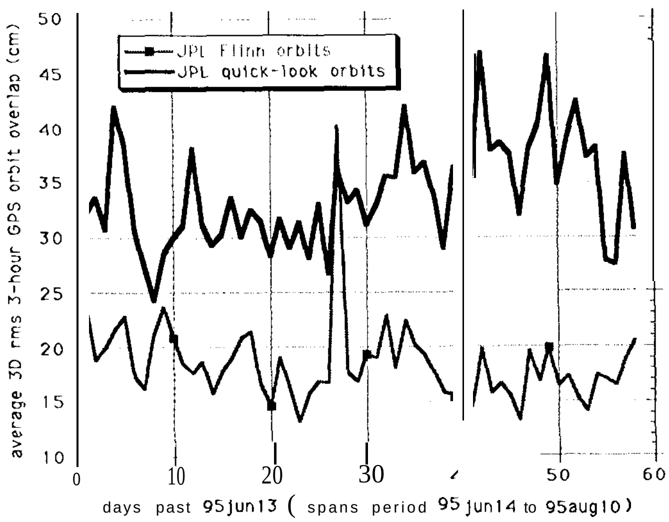

Figure 1) Orbit overlap comparison between JPL Flinn orbits and JPL quick-look orbits. **Overlaps indicate a 3D precision of 13 cm for the Flinn orbits and 24 cm for the quick-look orbits.**

Orbit Precision of Predicted GPS Orbits

After cacb GPS process completes, predicted GPS orbits arc produced by combining the orbits of the current day with orbits from three previous days. Cosine smoothing is used to remove discontinuities in the overlapping orbit segments. The combined 4-day solution is then fitted to empirically determined force models which include a solar-scale factor, a y-bias parameter, a constant down-track acceleration, and once-per-rev cross and down-track accelerations. Estimating twice-per-rev accelerations or going to longer or shorter than 4-day fits, degrades tbc precision of the predicted GPS orbits.

This solution is then integrated 3 days past the end of the data arc of the current day. Figure 3 shows the results of averaging 10 days (95jul27-95aug05) of GPS orbit differences between the predicted GPS orbits and the GPS orbits estimated within the data arc. After 24 hours, the 3D precision of tbc predicted GPS orbits is 1 meter (rms). After 42 hours, the 3D precision of tbc GPS orbits is 2 meters (rms). At the 42 hour mark, new GPS orbits from the next day's processing arc now available. (In Figure 3, the end of the next day's data arc occurs at 24 hours, the data is accumulated 11 hours after that, and the auto processing requires 6-7 hours to produce the next day's solution.) Therefore, < 2 meter 3D GPS orbits arc available in real-time.

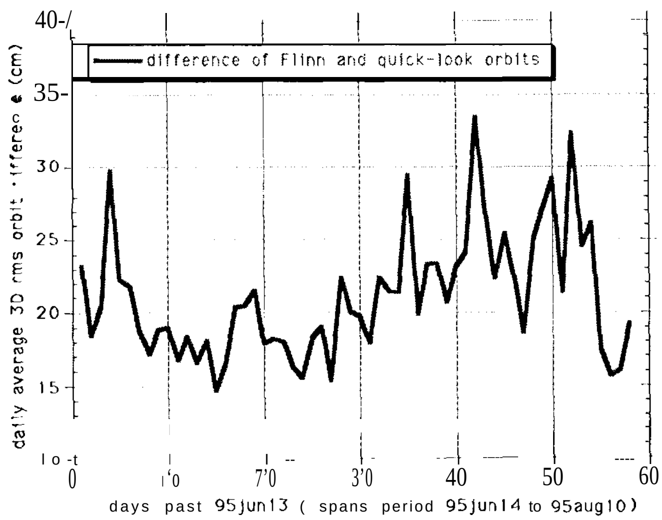

Figure 2) Orbit difference between JPL Flinn orbits and JPL quick-look orbits. The orbit difference shows the quick-look orbits have a 3D accuracy of 21 cm.

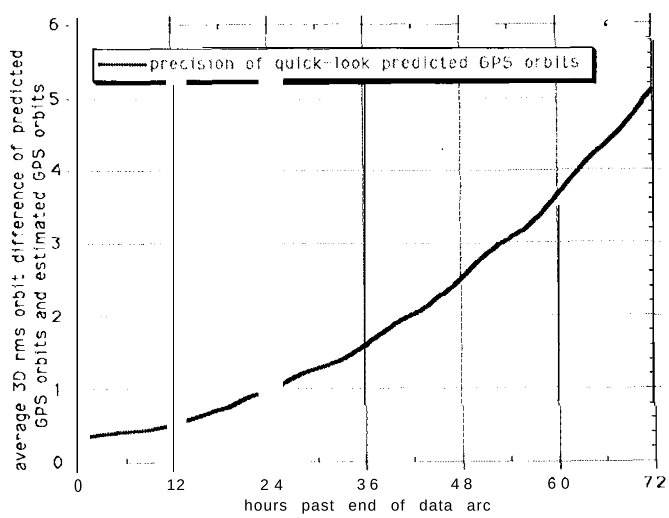

Figure 3) Precision of JPL quick-look predicted orbits. At 42 hour mark, next day's GPS orbits arc available.

GPS Clock Precision

GPS clock precision can also be assessed by compiling the differences in the overlapping clock solutions of the daily fits. Table **2 shows the GPS** clock overlap differences for the JPL Flinn and JPL quick-look solutions. Averaging these numbers and assuming the overlapping clock solutions are uncorrelated, the JPL Flinn GPS clock precision is **0.27** nsec and the JPL quick-look GPS clock precision is 0.57 nsec.

overlap period	rms of quick-look clock overlaps (nsec)	rms of Flinn clock overlaps (nsec)
95jul23-95jul24	0.952	0.285
95jul24-95jul25	0.713	0,354
95jul25-95jul26	0.783	0.318
95jul26-95jul27	0.675	0.356
95jul27-95jul28	0.912	0.581
95jul28-95jul29	0.703	0.436
95jul29-95jul30	0.897	0.367

Table 2) Differences of overlapping clock solutions, Overlaps indicate 0.27 nsec precision of the JPL Flinn GPS clocks and 0.S7 nsec precision of the JPL quick-look GPS clocks.

Table 3 shows the clock differences between the JPL Flinn clock solutions and the JPL quick-look clock solutions. There are two days in this table with unusually high clock differences. On 95jul 11, the reference clock selected by the quick-look processing was the receiver in Arequipa, Peru, This receiver's clock is not linked to a hydrogen maser. Since the Flinn reference clock is always linked to a hydrogen maser, the unusual large clock differences on 95jul11 reflects the instability of Arequipa's clock. On 95jul 16, the quick-look process selected the receiver at Algonquin, Canada as a reference clock. Within the 27 hour data arc, the Algonquin receiver had a data outage of 80 minutes. This caused all the clocks in the system to float with a common error, and hence caused the large clock difference with the **JPL** Flinn solutions, Since this occurrence, additional measures have been built into the automated procedure to detect data outages at receivers and disallow their selection as a reference clock.

solution day	rms difference of clock solutions (nsec)
95jul02	0.52
95jul03	0.37
95jul04	0.48
95jul05	0.41
95jul06	0.41
95jul07	0.30
95jul08	0.43
95jul09	0.50
95jul10	0.52
95jul11	114.25
95jul12	0.42
95jul13	0.52
95jul14	0.53
95jul15	0.61
95jul16	249.28
95jul17	0.50

Table 3) Clock differences between JPL quick-look and JPL Flinn clock solutions. The clock differences show that the quick-look clock solutions have an accuracy of 0.46 nsec.

Assuming that the JPL Flinn GPS clocks are truth, and excluding the days 95jul11 and 95jul16, the quick-look GPS clock precision and accuracy is 0.46 nsec. This is in close agreement with the 0.57 nsec precision as obtained from clock overlaps.

Precise Point Positioning

Precise point positioning uses the pre-determined GPS orbits and clocks to compute estimates of a receiver's clock, troposphere, station location, and phase biases. The processing time to point position a single station day on an HP9000/735 workstation is 2-3 minutes. Once the GPS orbits and clocks have been determined, this method can quickly and accurately compute the 100+ station locations of the IGS network.

Table 4 lists the 3D rms station coordinate repeatabilities of 17 globally distributed stations over the 5 week period 95jul02 to 95aug05. Most of the 3D rms repeatability can be attributed to the vertical precision of the station coordinates, while the horizontal precision is in general a few millimeters. The average 3D rms station coordinate repeatability when using the JPL Flinn solution is 16 mm; the average repeatability using the **JPL** quick-look solutions is 21 mm.

station	Flinn solutions (mm)	quick-look solutions (mm)
Algonquin, Canada	12.7	14.1
Tidbinbilla, Australia	8.9	17.9
Fairbanks, US.	14.6	12.7
Kokee Park, US	9.7	8.5
Kootwijk, Netherlands	7.5	11.1

Madrid, Spain	9.5	9.8
Santiago, Chile	31.7	43.6
Tromso, Norway	8.7	11.6
Arcquipa, Peru	20.7	40.7
Bermuda, UK	16.1	18
Kerguelen, France	17.2	25.1
Kitab, Uzbekistan	16.2	28.3
Maspalomas, Canary 1s.	10.6	13,2
NyAlsund, Norway	11.8	15.8
Richmond, US	30.9	41.9
Shanghai, China	17.4	27.5
Usuda, Japan	27.2	24.9

Table 4) 3D station coordinate repeatabilities. Average 3D repeatability is 16 mm (rms) with JPL Flinn and 21 mm (rms) with JPL quick-look solutions.

User Position Error For a WAAS Network

The Wide-Area Augmentation System (WAAS) being developed by the FAA to aid in aircraft navigation is proposed to combine pseudorange data from 20-30 stations in the WAAS network and provide a combined GPS ephemeris and clock correction to the users of the system. Unlike the clock correction which must be computed in real-time, tile ephemeris correction is predictable. '1'able 5 lists the user position errors computed in a WAAS network as a function of the type of GPS ephemeris employed. The method to obtain these user position errors is to simulate users throughout the WAAS network with precise GPS orbits and GPS clocks, and then solve for tile user's position and clock at every data epoch using the WAAS GPS ephemeris (the "slow" correction), and estimated GPS clocks (the "fast" correction) as determined by a WAAS network [10]. For this table, the estimated GPS clocks were computed with pseudorange data from 13 stations in the WAAS network,

type of orbit	vertical rms (meters)	3D rms (meters)
broadcast ephemeris orbit	1.79	2.29
dynamic orbit computed with WAAS network	0.76	**0.90**
quick-look orbit	**0.43**	**0.49**
1 -day predicted	0.49	0.55
2-day predicted	0.58	0.64
3-day predicted	**0.60**	**0.68**

'J'able S) User position error as a function of orbit. The "2-day predicted" orbits arc real-time GPS orbits.

Although the broadcast ephemeris orbits arc accurate to 8 meters (3D rms), the resulting 3D user position error after estimating the GPS clocks is 2.3 meters (rms). This is a result of the clock correction absorbing much of the orbit error. The column labeled "dynamic orbits computed with the WAAS network" arc filtered orbits which use pseudorange data from the WAAS network. The 3D precision of these orbits over the WAAS network is 2.5 meters (rms). The resulting 3D user position error is 0.9 meters (rms). The quick-look and predicted orbits arc those generated by the described quick-look GPS processing. The 2-day predicted orbits arc essentially real-time GPS orbits, The corresponding 3D user position error is 0.64 meters (rms).

Estimates of Earth Orientation

An important by-product of this GPS process is to provide timely estimates of Earth orientation parameters, pole motion and UT] R-UTC. The two components of polar motion can be directly observed by GPS. However only a time rate of change of UT] R-UTC can be observed since the GPS constellation is insensitive to absolute UT I R-UTC. By integrating this time rate of change, UT1R-UTC can be recovered except for an initial bias. The initial bias must be provide' by an external source such as VLBI measurements. The error introduced into the estimate of UT1R-UTC computed in this fashion behaves like a random-walk. Therefore it is not so much tbe scatter in the estimate of derivative of UT1R-UTC, but the mean of this estimate that will determine how far UT1R-UTC will wander from the truth.

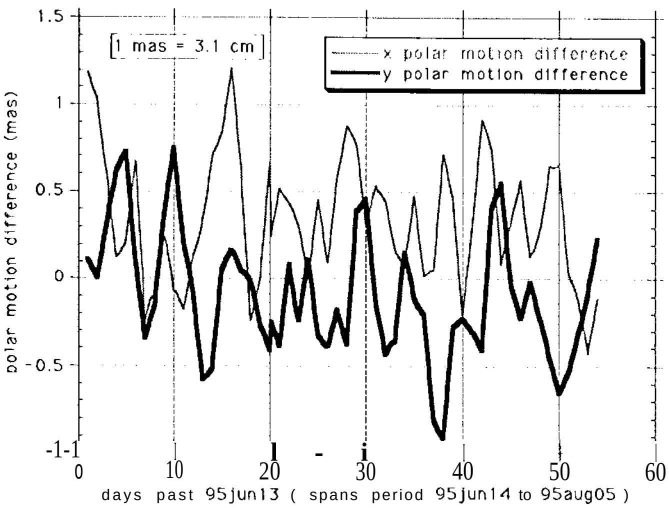

Figure 4) Difference of the JPL quick-look polar motion series and the IERS Bulletin B Final series.

Figure 4 shows the difference between the IERS Bulletin B Final series [11] and the JPL quick-look polar motion solutions. 1 mas (milli-arcsecond) is equivalent to 3.1 cm at the Earth's surface. The statistics of these differences are compiled in Table 6. The mean in the statistics represents a known misalignment of the station coordinates, hence the sigma is a more representative number of the precision.

component	mean (mas)	sigma (mas)	rms (m as)
x pole motion	**0,34**	0.33	**0.48**
y pole motion	-010	0.34	0.35

Table 6) Difference of the JPL quick-look polar motion series and the IERS Bulletin B Final series. The quick-look solutions yield an equivalent 1-cm precision of the Earth's pole position.

The time derivative of UT1R-UTC is more commonly expressed as a length-of-day (LODR):

$$LODR \equiv -86400 \frac{d}{dt} (UT1R-UTC) \qquad (5)$$

Figure 5 shows the LODR for the JPL **quick-look** solutions and the IERS Bulletin B Final series. The rms difference between these series is 0.042 msecs (milli-seconds); the mean of 0.0002 msecs. The rms difference between the JPL quick-look series and JPL's Kalman Earth **Orientation** Filter (KEOF) **which** makes use of VLBI measurements **over the period** 95jun14 to 95aug28 is 0.034 msecs; the mean of 0.001 msecs.

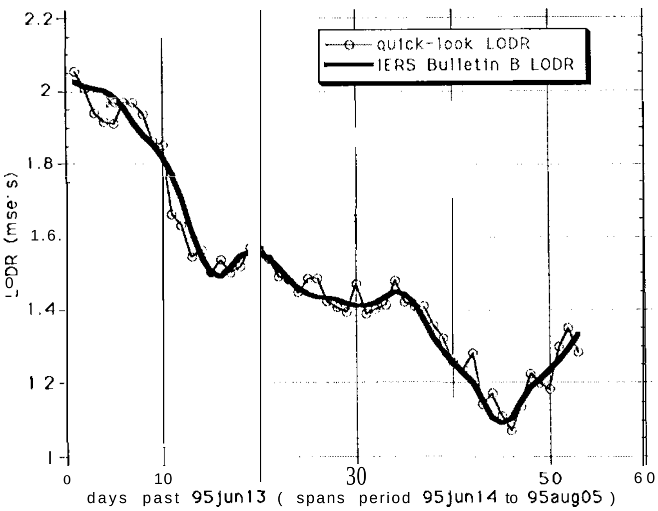

Figure 5) Length-of-day of the JPL quick-look solutions and of the IERS Bulletin B Final series.

Figure 6 shows the difference between the integrated LODR quick-look series and the IERS Bulletin B Final UT1R-UTC series. An initial bias was first removed from the integrated LODR series so that the difference of these series would start at zero. The rms difference is 0.18 msecs over the 2 month period. This amount of rotation corresponds to 8.3 cm on the Earth's equator. The random-walk nature of the integrated error is clearly evident.

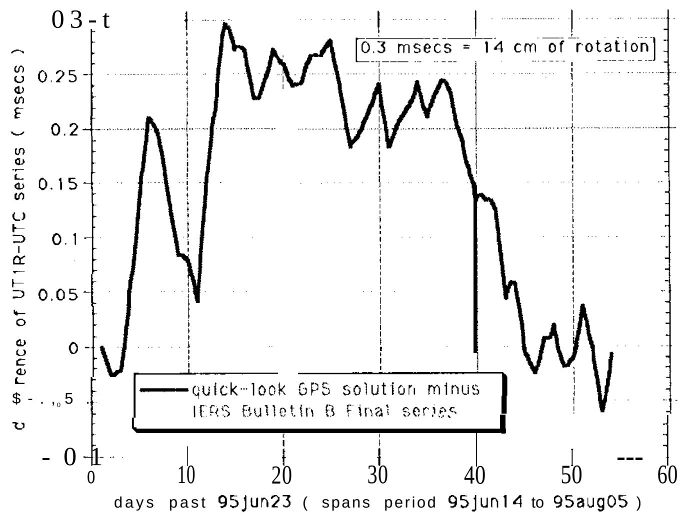

Figure 6) Difference of JPL quick-look integrated LODR solution and IERS Bulletin B Final series for UT1R-UTC.

TOPEX PROCESSING RESULTS

The method to compute the Topex/Poseidon orbit is to make use of the predicted GPS orbits and solve for the GPS clocks. It is sufficient to use a network of 12 stations for this purpose. Table 7 shows the local PDT time that the value of zeta, as computed for an optimal distribution of 12 ground stations, crosses 4000 km for the first two weeks of August 1995.

solution day	zeta (km) for 12 stations	local PDT time zeta crosses 4000 kms
95aug01	3807	Aug 01 22:13
95aug02	3827	Aug 02 22:03
95aug03	3956	Aug 03 22:07
95aug04	3873	Aug 05 02:11
95aug05	3899	Aug 06 02:06
95aug06	3901	Aug 07 02:13
95aug07	3930	Aug 07 22:05

95aug08	3877	Aug 08 22:04
95aug09	3995	Aug 10 09:01
95aug10	3827	Aug 10 22:14
95aug11	3865	Aug 1121:10
95aug12	3762	Aug 13 02:03
95aug13	3807	Aug 13 22:03
95aug14	3792	Aug 15 01:11

Table 7) Local time when a 12 station distribution crosses the 4000 km "zeta" threshold.

When z.eta crosses 4000 km, a secondary process is automatically initiated with the 12 optimally determined ground stations. An acceptable distribution of stations is generally available just after 2:00 AM PDT. 'l'his is 9 hours after the end of the processing day's UTC midnight. The process to determine the GPS clocks and T/P orbit requires 2-3 hours on an HP9000/735 workstation. By 5 AM PDT, 12 hours after the end of the data arc, T/P orbits arc available. If the radial component of the orbit overlap with the previous day is less than 20 cm, the orbit solution is FTP'ed to the sponsor's computer. An "c-mail message is compiled reporting the orbit overlaps, residual information, and any problems that may have occurred during the processing.

Figure 7 shows the radial and down-track components of the orbit overlaps for the period 95jul26 to 95sep02. The average radial, cross-track, and down-track overlaps for this period arc 7.8 cm, 8.8 cm, and 22.1 cm, respectively. This would imply a radial orbit precision of 5.s cm (rms) and a 3D orbit precision of 18 cm (rms).

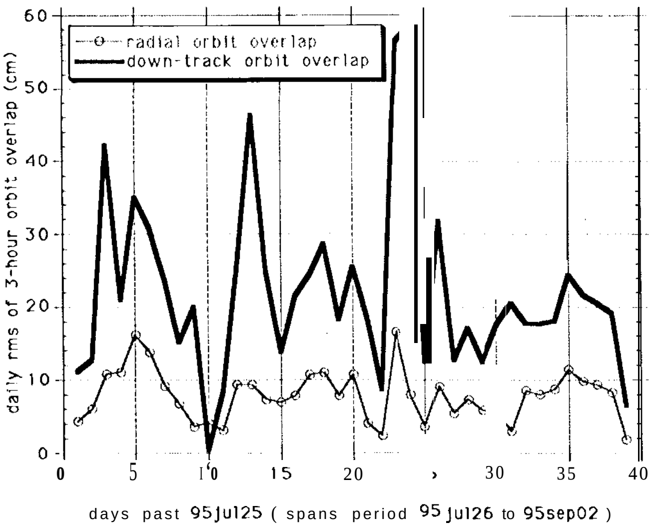

Figure 7) Radial and down-track components of Topex/Poseidon orbit overlaps.

An additional method for assessing the radial orbit accuracy relics on altimeter data collected by the spacecraft. T/P carries a nadir-pointing radar altimeter that can measure the range to the sca surface. These range measurements can be used together with the radial ephemeris to determine the geocentric height of the sca surface. At the points in the ocean where the satellite ground tracks intersect on ascending and descending passes, two such determinations of sca height can be made. In the absence of errors in the orbit and in the media corrections to the altimeter range, the height difference at the crossing point location is a measure of the true variability of the ocean surface. The difference of the crossover variances with the NASA Precise Orbit Ephemeris, which has a radial precision of < 3.5 cm (rms), indicates that the radial precision of the GPS determined T/P orbits produced by the described processing is 5.0 cm (rms). This is in close agreement with the 5.5 radial precision obtain by computing the orbit overlaps.

Figures 8 and 9 show a 10-day average (95jul27-95aug05) of the predicted radial and 3D orbit precision after 48 hours of integration. At the 36 hour mark, a new T/P orbit solution is available from the next day's processing. Hence real-time T/P orbits with a radial precision of 50 cm (rms) and a 3D precision of 15 meters (rms) arc available in real-time.

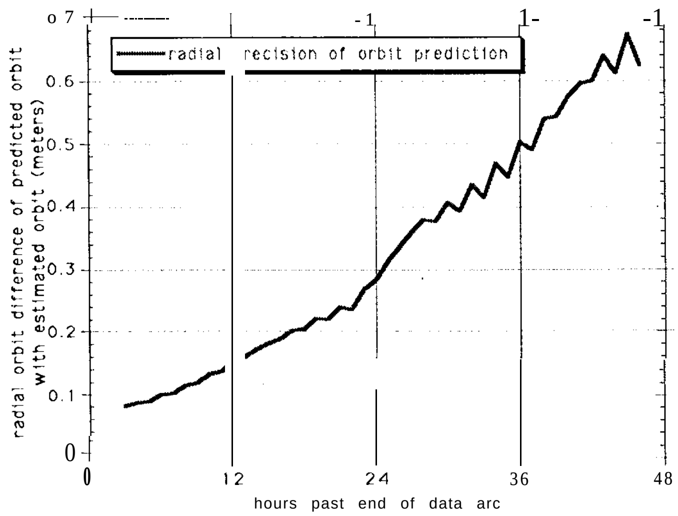

Figure 8) Radial difference of T/P's predicted orbit and the estimated orbit within the data arc.

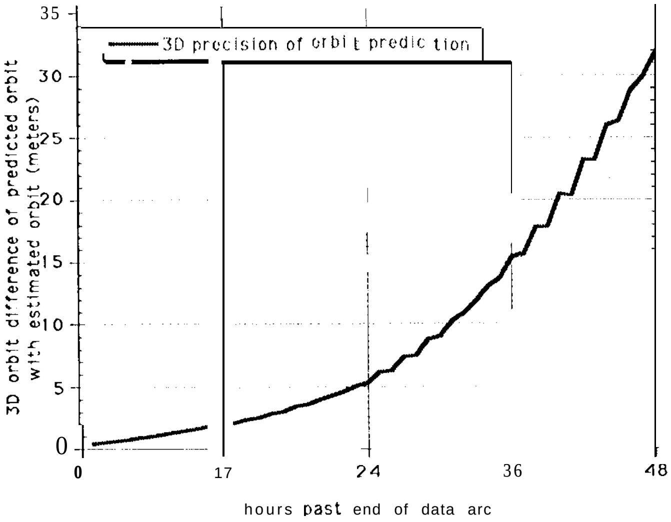

Figure 9) 3D difference of T/P's predicted orbit and the estimated orbit within the data arc.

GPSMET PROCESSING RESULTS

The same technique of using fixed orbits and solving for GPS clocks has also been applied to the GPSMet data to determine the precise orbit ephemeris of the MicroLab 11 satellite. Precision orbit determination is necessary for proper calibration and processing of tbc GPS radio occultation data. It is the accuracy of the velocity that is most critical to the experiment. Since the occultation experiment is looking at GPS signals at low elevation angles relative to the spacecraft zenith, the GPS antenna is pointed perpendicular to the spacecraft zenith. This is not an ideal orientation for orbit determination. Although Anti-Spoofing (AS) dots not effect orbit determination, it dots have a significant effect on the occultation experiment. Data processing has thus concentrated on the 2 three-week periods in 1995 when AS was off. Here wc examine a onc week period from June 23, 1995 through June 30, 1995. Currently, orbit determination is not the limiting error source for the occultation experiment and little effort has gone into tuning tbc dynamic or reduced-dynamic orbits. Wc believe there is substantial room for improving the orbits which arc currently at the decimeter level.

Reduced-dynamic phase and range residuals arc 2.4 cm and 76 cm respectively; the dynamic phase and range residuals arc 3.4 cm and 79 cm. Typically wc do not recover continuous tracking data from the GPSMet flight receiver. These data gaps arc not duc to the receiver operation but other spacecraft and ground systems. '1'able 8 shows a list of data gaps larger than a one-half hour duration for the period of June 23-30. Note the large gaps in data around midnight June 25/June 26 and around midnight June 27/June 28. There is also little data on June 24.

start of gap	end of gap	hours
95jun23 16:26	95jun23 18:04	1.6
95jun24 06:52	95jun24 23:54	17
95jun25 06:07	95jun25 10:17	4.2
95jun25 16:36	95jun26 00:32	7.9
95jun26 07:03	95jun26 09:21	2.3
95jun26 15:15	95jun26 15:45	0.5
95jun26 15:52	95jun26 17:38	1.8
95jun27 15:06	95jun28 01:45	11
95jun28 14:21	95jun28 16:01	1.7
95jun29 15:17	95jun29 15:53	0.6
95jun30 05:47	95jun30 09:43	3.9
95jun30 14:32	95jun30 16:22	1.8

I'able 8) Data gaps in the GPSMet data, June 23, 1995-June 30, 1995.

Table **9** shows the rms overlaps for this time span. The large data gaps on June 24 and between June 25/26 arc responsible for the large orbit overlaps for these days. Excluding these excessive overlaps, the average reduced-dynamic overlaps arc 6.8 cm, 4.8 cm, and 11 cm in the radial, cross, and down-track components, respectively

overlap pcried	H (cm)	c (cm)	L(cm)
95jun23/95jun24	10.4	**04.9**	**19.6**
95jun24/95jun25	39.7	16.3	226,7
95jun25/95jun26	67.9	43.5	1080.3
95jun26/95jun27	6.1	1.5	9.0
95jun28/95jun29	4.5	4.8	9.7
95jun29/95jun30	6.3	7.9	8.3

Table 9) Reduced-dynamic overlaps for MicroLab II, June 23, 1995-June 30,1995.

CONCLUSION

A highly automated GPS **data** processing system has been developed around JPL's GIPSY/OASIS 11 software. The process determines when there is a sufficient distribution of ground stations from the IGS network. When such a configuration is achieved, a GPS orbit solution is computed. At completion, the GPS orbit and GPS clock solutions arc placed in a data base and an e-mail message is sent out reporting residuals and orbit overlaps with tbc previous day's solution. The 3D precision of these GPS orbits within the data arc is < 25 crn (rms). In addition, the GPS orbits arc predicted such that the 3D precision of these real-time orbits is < 2 meters (rms).

A second automated process makes usc of the predicted GPS orbits for orbit determination of the Earth orbiter Topcx/Poseidon. When a sufficient distribution of ground stations is available, a T/P orbit solution is computed. At completion, the orbit solution is placed on the sponsor's computer and an c-mail message reports T/P's orbit overlaps, residuals, and data outliers. The 3D precision of these T/P orbits within the data arc is 18 cm (rms). These orbits arc generally available within 12 hours after the end of the data arc.

Both these processes arc completely automated and require no human intervention. Problems arc automatically detected and corrected by the expert system.

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REFERENCES

[1] Muellerschoen, R. J., Bertiger, W. 1., Wu, S. C., Munson, T. N., Zumberge, J. F., Haines, B. J., Accuracy of GPS Determined Topcx/Poseidon Orbits During Anti-Spoof Periods, Institute of Navigation Conference, 1994 National Technical Meeting, San Diego, CA, January, 1994.

[2] Srinivasan, J. M., Meehan, T. K., Young, L. E., **Code** and Codeless ionospheric Measurements with **NASA's Rogue** GPS Receiver, Institute of Navigation Conference, Colorado Springs, Colorado, September 1989.

[3 Cangahuala, L., Muellerschoen, R. J., Yuan, D., Graat, E., Guinn, J. R., Topcx/Poseidon Precise Orbit Determination: Quick-look Operations with SLR and GPS Data, AAS/AIAA Astrodynamics Conference, Halifax, Nova Scotia, Canada, August 1995.

[4] Hajj, G., Bertiger, W. 1., Kursinski, E., Leroy, S., Remans, L., Schofield, J., Initial Verification of the GPS-LEO Occultation Technique of Mapping the Neutral Atmosphere with the GPSMet Experiment, Institute of Navigation Conference, Palm Springs, CA, September 1995.

[5] Zumberge, J. F., Webb, F. H., An Introduction to GIPSY/OASIS 11, JPL Course Notes, Boulder Colorado, July 1993.

[6] Bar-Sever, Y. E., A New GPS Yaw Attitude Model - Design and Performance, Institute of Navigation Conference, Palm Springs, CA, September 1995.

[7: Zumberge, J. F., Jefferson, D. C., Blewitt, G., Heflin, M. B. , Webb, F. H., Jet Propulsion laboratory IGS Analysis Center Report, 1992, *Proceedings of the* 1993 *IGS Workshop,* edited by G. Beutler and E. Brockmann, pp. 154-163, Astronomical Institute, University of Bernc, 1993.

[8: Zumberge, J. F., Neilan, R. E., Mueller, I. I., Densification of the IGS Global Network, IGS Workshop, Pasadena, CA, December 1994.

[9] Muellerschoen, R. J., Dowdating a Time-Varying Square-Root information Filter, Flight Mechanics/Estin~ation Theory Symposium, Greenbelt, Maryland, May 1990.

[10] Ceva, J. C., Bertiger, W. I., Muellerschoen, R. J., Parkinson, B., Incorporation of Orbit Dynamics to Improve Wide Area Differential GPS, Institute of Navigation Conference, Palm Springs, CA, September 1995.

[11] Boucher, C. Z., Altamimi, Duhem, L., ITRF 91 and Its Associated Velocity Field, *IERS Technical* Note 12, Central Bureau of IERS, Observatoire de Paris, October 1992.