Orbit and Troposphere Results of a Real-Time Prototype WADGPS System

Ronald J. Muellerschoen, Winy 1. Bertiger, Larry J. Remans

Jet Propulsion Laboratory, California Institute of 1 *'echnology*

Biographies

Ronald J. Muellerschoen 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. A member of the Earth Orbiter Systems Group at JPL, hc special izes in efficient filtering and smoothing software for precise orbit determination and geodesy with GPS and development of wide area differential systems.

Winy I, Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. 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, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Larry J. Romans received his Ph.D. in Theoretical Physics from the California Institute of Technology in 1985. Since 1993, he has been a Member of the Technical Staff at J PL in the Satellite Geodesy and Geodynamics Systems Group, where his work has focused on applications of GPS, including geodesy, remote sensing, and wide area differential systems.

Abstract

Implementation and results of a real-tire GPS orbit correction process for WADGPS is presented. The current processing utilizes data from SATLOC's North American reference net work. It has been in operation since November 13, 1996. Every 15 minutes it processes the accumulated data from the previous 15 minutes. The GPS horizontal orbit accuracy over this network is 1.2 m rms. The horizontal orbit accuracy over the north latitudes of the Western hemisphere 2.0 m rms. Augmenting this network with 6 IGS sites including Hawaii, Alaska, and Bermuda, reduces the horizontal orbit accuracy over the north latitudes of the Western hemisphere to 1 meter rms. The zenith troposphere errors from this processing arc 1-2 cm rms.

Introduction

A Wide Area Differential GPS (WADGPS) system, of which the Federal Aviation Administration's Wide Area Augmentation System (WAAS) is a particular example, consists of three components: a fast (l-second) pseudorange correction to account primarily for the -25 meter GPS clock errors induced by selective availability, an ionosphere correction to account for typical 4 meter ionosphere delays at L-band, and a GPS orbit correction to account for an imprecise 5 meter (3D) broadcast ephemeris. A brief summary 01 each component follows:

The fast pseudorange correction is similar to real-time correctors used in local area DGPS. In addition to removing the GPS clock errors, this correction also reduces the GPS orbit error, particularly the radial component. For local networks, nearly all of the GPS orbit error can be absorbed into the clock corrections. For an extended network like WAAS, the contribution to the user's UDRE (User Differential Range Error) of the down-track and cross-track error components of the broadcast orbit can be reduced at least by a factor of 8 by the fast clock corrector, but otherwise contributes to the user's

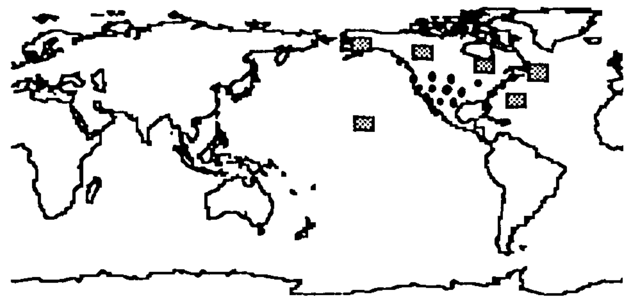
UDRE [1][2]. To improve performance of an extended DGPS network, the orbits used by the fast corrector should originate from a more precise source such as an orbit correction process. An additional benefit of such a process is that it also isolates and identifies errors in a WADGPS system by separating orbit error from clock error.

The ionosphere correction solves for an ionosphere shell in a solar-magnetic frame which is fixed with respect to the sun-Earth line [3][4][5]. Gridding this shell and using local support, solved for vertex values can be hi-linearly interpreted to any desired point. The accuracy of this process is determined by the proximity 01 the observer to the reference sites. That is, the further a user is from a reference site where data is being collected, the greater will be the ionosphere contribution to a user's UDRE. For users requiring several decimeter accuracy regardless of their locality, dual frequency receivers can be utilized to eliminate these errors.

The orbit correction process makes comprehensive use of dynamics to relate a time sequence of measurements to the solved for spacecraft states. Precise modeling of the forces acting on the GPS spacecraft (gravity, solar radiation, thermal emissions) and precise modeling of the receiver's position (phase center variations, Earth rotation and wobble, solid tides, ocean loading, crustal plate motion, carrier phase windup) makes possible sub-centimeter representation of the GPS phase data with respect to the GPS spacecraft's epoch state. This external information minimizes the number of parameters adjusted and maximizes the solution strength [6]. The dynamic orbit model also allows the GPS spacecraft positions to be predictable with little loss of accuracy for several hours.

Without any of these components, a single frequency user's accuracy is typically 50 meters in horizontal, and 100 meters in 3D. With these corrections, a WAAS user's accuracy is stipulated to be 7.6 meters in horizontal, and 10.7 meters in 3D [7]. Wc note however that current implementation and testing of a real-time WADGPS system at JPL suggests that sub-meter, and potentially several decimeter accuracy is attainable [8].

The purpose of this paper is to present the implementation and results of a real-time GPS orbit correction process that has been developed at JPL over the past year. Since November 1996, the process has been continuous y ingesting data from SATLOCS's North American reference network in real-time. Figures 1 and 2 show the configuration of this network, This is similar to the WAAS reference network except without the proposed sites in Hawaii and Alaska, and possibly the Caribbean. To simulate the results of a WAAS-type network, 6 sites arc additionally added to the orbit process in a like manner. These sites, as indicated in figure 1, are stations in the IGS's (International GPS Service) global network in which data dots not arrive in real-time but packaged in 24-hour files [9]. These files, along with the archived S ATLOC data tiles tor the same period, arc divided up and conveyed to the orbit **correction** process as it' the data were arriving in real-time.



● **SATLOC** *network* ▩ additional peripheral sites

Figure 1.) Current 14 station SATLOC network configuration. Also shown is the extended network with IGS sites in (clockwise from the top) Fairbanks Alaska, Yellowknife Can., Algonquin Can., St. John's Can., Bermuda, and Kokee Park Hawaii.

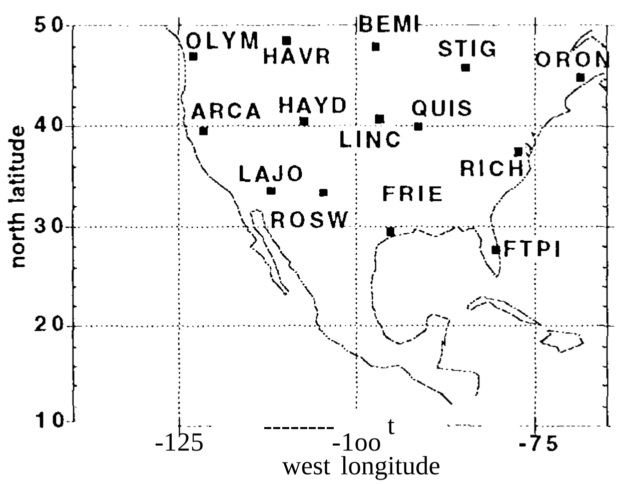


Figure 2.) Detail of SATLOC's 14 station network.

The orbit results of the SATLOC processing are compared to an exhaustively smoothed solution performed 1.5 days after real-time that utilizes a global distribution of data from the IGS. The 3D accuracy of these truth orbits is -20 cm rms. [10] Similarly, the orbit results of the extended network (SATLOC sites plus the 6 IGS sites) arc also compared to these truth orbits.

One of the error sources in the fast pseudorange process is the troposphere delay. This must either be solved for, or obtained otherwise such as tiom surface meteorological data. This same delay is also accounted for in the much slower orbit processing where it is typical 1 y treated as a solved for stochastic parameter. These ze ni th troposphere solutions, along with the solved for GPS orbits, can additionally be passed on to the fast process. In general the surface data is not as accurate as the calibration that can be obtain from orbit *correction* process [11]. Three zenith troposphere solutions from the orbit processing arc additionally compared to truth solutions obtained by point-positioning the receivers in the reference network with 24-hours of data. These truth solutions are accurate to 0.6 cm rms. [12][13][14]

Finally, to assess the impact of the orbit correction process on a user's position, the SATLOC receivers are positioned with the fast clock corrections as computed with various orbit solutions: 1.) the broadcast orbit, 2.) orbits generated from the S ATLOC net work, 3.) orbits from the extended network, and 4.) orbits from a global network.

Current Implementation

The orbit correction process currently utilizes J PL's GIPSY OASIS 11 (GOA II) [15][16], which has a long history in precise orbit determination for both GPS and other spacecraft [17][18][19][20], and in precise GPS geodetic applications [21][22]. GOA 11 primarily consists of a set of FORTRAN programs, encapsulated by C shell or perl scripts. These individual scripts are unit functional in that their purpose is to perform a unique computation. What makes these scripts and programs effective is the way they communicate with each other through a variety of input and output files. The orbit correction process currently implemented and running consists of over 3000 lines 01" perl code that 1.) intelligently processes the incoming data stream, 2.) effectively strings together the various GOA II scripts, 3.) performs quality checks on the data fit, 4.) maps the GPS orbits and outputs suitable orbit and troposphere files, and 5.) automatical ly diagnoses and determines a course of action for prospective problems.

In summary, the orbit correction process currently processes 3 minute smoothed pseudorange and decimated phase ionosphere-free observable and solves for the GPS spacecrafts' states and clocks, the receivers' clocks (excluding a reference clock) and zenith troposphere delays, and phase bias parameters t'or each phase arc. A more comprehensive synopsis of the processing follows:

The data tiles are accumulated by a data management procedure that reads from shred memory the real-time SATLOC data stream transmitted over dedicated frame-relay phone lines. The fast pseudorange process also reads from the same shared memory segment to compute the real-time clock corrections. This data management procedure compresses the L1 and L2 phase and pseudorange data to 30 seconds and outputs N minute data files in rinex format. The noisier L2 phase due to Anti-Spoofing (AS) is smoothed with a fit to L1-L2 since the ionosphere is smoother than L2 over short intervals. Carrier-aided smoothing or Hatch smoothing is applied to the pseudorange data. The L 1 phase data is simply decimated to 30 seconds. Phase breaks are detected by looking at the continuity of L 1 and L2 phase at the 1-Hertz data rate. During this compression, the nav solution is used to steer the receiver's clock, while millisecond jumps in the pseudorange data are detected and the appropriate correction is applied to the integrated phase data. These jumps occur because the receivers, which run off internal crystal oscillators, reset their clock values with millisecond increments whenever the clock drifts more than a millisecond from GPS time.

The orbit correction process itself is initiated by a cron every N minutes. After the current N minute data files are completed and closed, a new' directory is established. Both the current and previous N minute data files are then merged for common stations, edited to determine additional phase breaks, corrected for frrst-order ionosphere effects with a linear combination of data at L1 and L2 frequencies, and compressed to 3 minute points. The 3-minute compression is smaller than that typically used for post-processed GPS orbit determination since it reduces the potential of data breaks that inevitability occur in the transmission of a real-time data stream. This final compression smooths the 30 second pseudorange observables with the phase (mm Hatch smoothing), while the phase observables are decimated and aligned to within a narrowlane wavelength (-10.7 cm) 01 the first corresponding pseudorange point on the merged file.

In order to make phase continuous with the previous N minute orbit correction solution, a re-alignment of the phase observables is required. This is the primary reason that the previous N minute data tiles are additionally used in the current editing. By looking at the difference between common phase observables between the previous N minute orbit correction process and the current N minute process, consistent adjustment of narrowlane wavelengths is obtained. After this re-alignment of the phase observables, only the current N minute data arc is retained for the orbit correction process.

Other information that is passed from the previous N minute orbit correction process that must be accounted for is the carrier phase windup. Due to the right-hand circular polarization of the GPS signal, a complete rotation of one participant, either the transmitter or receiver, adds a wavelength to the accumulated phase measurement, GOA II accounts for this internally in the modeling of the phase data. To make the phase continuous for successive data i-its, the previous phase windup correction of the last N minute orbit correction initializes the phase windup of the current N minute orbit correction.

Additionally, the state partials of the GPS spacecraft and their dynamic parameters for the previous data fit and the current data fit have a common epoch. After 24 hours, a new nominal orbit based on the last orbit correction process is created. This update changes only the epoch of the partials and dynamic parameters and not the nominal orbit, At the same time, the solved for Earth wobble parameters (x and y polar motion parameters) are updated (white-noise updates), and the solved for Earth rotation rate (length-of-day) is integrated and also updated. These corrections arc then added to the nominal Earth I rotation and polar motion series (UTPM series). Furthermore, the GPS spacecrafts' covariances, estimates, and nominals are mapped to the current epoch, rotated to an Earth-fixed system with the old UTPM series, then rotated back to an inertial system with the updated UTPM series.

Finally, the current data fit is initialized with the covariance and confections from the previous data fit, or from one of the 24-hour GPS epoch updates as described above it' appropriate. No information is ever lost in going from one data fit to the next, The processing is seamless as if the data were processed in one continuous arc,

Quality checks on the data fit include searches for 1.) piece-wise jumps in the smoothed postfit residual so the phase greater than 5 cm and 2.) smoothed postfit residual pseudorange points greater than 2 meters. In the first case, additional phase breaks arc inserted and the data is re-fitted. In the second case, a fast downdating algorithm [23] is used to remove the outlying pseodorange points. It proves that the longer the N minute data arc being fitted, the more comprehensive and successful these anomaly searches become.

Each orbit solution delivers to the fast pseudorange process smoothed GPS orbit solutions within the data arc and predicted GPS orbit solutions mapped 2 hours after the end of the data arc. The orbit solutions are rotated m an Earth-fixed system with the solved for UTPM parameters and expressed with respect to the GPS's phase center. Additionally, a polynomial fit is made to the solved for zenith troposphere delays and the predicted values are also made available to the fast process.

Should a station or spacecraft consistently have large outliers or anomalous number of phase breaks after several data fits, it is automatically flagged as suspicious and removed from successive orbit correction solutions, This occurs particularly whenever a GPS spacecraft is being repositioned. All scheduled and unscheduled maneuvers are easily detected this way. After 1.5 days has passed and a good solution for the repositioned GPS has been obtained by other means [10], manual intervention allows the repositioned GPS back into the orbit correction process. Should a station experience repeated problems over successive data tits, it is also taken off line automatically. Again only alter manual intervention is it allowed back into the orbit correction process.

The software is capable of running in a filtering only mode every 5 minutes with 5 minute points. This would generate an overwhelming 288 orbit solutions per day. Since the GPS orbits arc very predictable and the troposphere solution does not change more than a few cm in tens 0! minutes, the current operation wakes up every 1S minutes to process the previous 1S minutes of accumulated data. This results in a more manageable 96 orbit solutions per day. Each data fit uses 3 minute data points to minimize data outages from transmission loses. Additionally, the orbit correction process smooths the data to better analyze postfit data residuals,

Future Implementation

When we developed GOA II, since all the anticipated processing was to be performed after the data had been collected and archived in large history tiles, it was reasonable to build unit functional scripts that communicated among themselves with a multitude of file interfaces. This however is not optimal for a real-time orbit correction process. New code, called RTG (Real-Time Gipsy), currently being developed by the authors and others at JPL, is more attuned to real-time processing. RTG is written entirely in ANS 1 c. It includes all the precise models of GOA 11 but not yet all of it's flexibility.

The flexibility that GOA II provides has proven invaluable in tuning and experimenting with the orbit correction process. The lessons learned from the described orbit correction process are being applied to the RTG orbit correction process under development. A brief comparison of the RTG implementation of the orbit correction process with the GOA II implementation follows:

RTG will not operate in a smoothing mode. After each interval (or batch) of data is filtered, the predicted orbit and troposphere products wil I be made available to the fast pseudorange corrections. This will diminish the effectiveness of the current quality checks. To minimize this impact, postfit residuals are re-computed after all the data from a batch has been processed bawd on the current estimate. These single-batch-smoothed postfit residuals arc then used in the quality checks.

RTG will retain the ability to add or remove spacecraft or ground receivers on the fly. That is, when data from a new GPS becomes available, and it' nominals are available, the orbit process will automatically insert into the fil ter's covariance and estimate the necessary states. The same is true if a new receiver comes on line.

Furthermore, only a minimal number of phase bias parameters will be retained in the processing. When a bias parameter is no longer needed, a rank-one update is used to remove it from the filter's states. When a new phase arc is acquired, a new phase bias parameter will bc inserted into the filter's state.

Updated nominal Earth rotation and polar motion series, along with other new nominals for GPS states, receiver configurations, or stochastic attributes of the filter's states, are also incorporated on the fly by sending a user defined signal to the orbit correction process. In the case 01 new UTPM nominals, the filter's covariance, estimates, and nominals are rotated to an Earth-fixed system with the old UTPM series, then rotated back to an inertial system with the new UTPM series. Other nominals will either update the modeling of the participants or be used to append the existing list of participants.

Unlike GOA 11 which uscs a pseudo-epoch state to incorporate piece-wise dynamic process noise, the RTG implementation uses an "almost" current state formulation. "Almost" here refers the necessity of accounting for the light-time in computation of the satellite state partials. The RTG orbit implementation will function much like an extended Kalman filter.

Finally, the RTG implementation will be somewhat simplified since besides from user namelist type inputs, there will be no complex t-he interfaces to maintain. For instance, the previous phase windup and falter's covariance and estimates will remain in memory until the next interval of data is available.

Orbit Results

The GPS orbital parameters along with the 6 clement Cartesian state include a solar-radiation scale (solar-scale) estimate and a y-axis acceleration (y-bias) estimate. The Cartesian state parameters are estimated as bias parameters with 1 meter position and .05 mm/sec velocity apriori, while the solar-scale and y-bias parameters are modeled as random-walks with stochastic increments of 0.01 (unitless) and 0.02 nanometers/sec/sec pcr update which occurs every 15 minutes, respectively. Tuning these stochastic dynamics proves particularly important since only when the GPS are in view of a WADGPS network arc observables available for processing. The individual GPS covariances must be adjusted so that when they reappear to the network on successive passes, the covariances are not unduly restrained. That is, new data is allowed to readjust the estimates. On the other hand, the adjustment to the covariance must not be so great as to lose integrity in the orbit. Figure 3 shows the 3D formal sigmas from a typical 1 5-minute orbit solution. The GPS satellites in view have. a 3D sigma of less than 1 meter, while others may be as large as 4 meters when they arc out of view. For the case of the extended network, the 3D formal sigmas are moderately smaller.

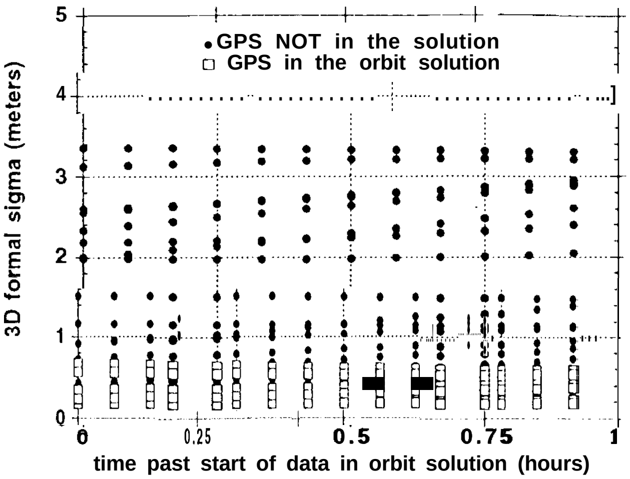


Figure 3.) Formal sigmas for a typical 15-minute orbit solution. The orbit solution includes data only in the first 1/4 hour from the SATLOC network. The GPS s/c are mapped every 5 minutes. The phase data is weighted at 1 cm and the pseudorange data is weighted at 1 meter.

To assess the accuracy of these orbits, the GPS orbit solutions are compared every 5 minutes within the data arc to post-processed solutions generated from a global network. These truth orbits are accurate, to -20 cm 3D rms. [1 O] The orbit comparison is performed over two sizes of latitude/longitude boxes that enclose the SATLOC and extended networks (see figure 4). The first box encloses the area north-south from Anchorage Alaska to Cuba, and west-east from Hawaii to Newfoundland, Canada. The second box coc1oscs the north latitudes of the Western hemisphere, or 1/4 of al I the GPS ground tracks.

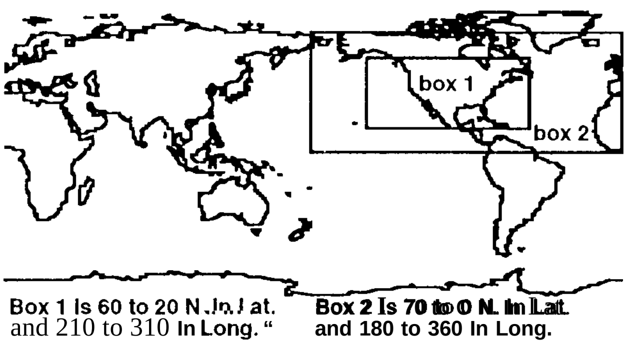


Figure 4.) The GPS orbit solutions are compared to -20 cm 3D rms. post-processed orbits generated from a global network over boxes 1 and 2 to ascertain the orhit accuracy.

Figure 5 shows the quadrature sum of the cross-track and down-track errors of the GPS spacecraft over box 1 for the period 96nov14 to 96dec1 7. The average horizontal GPS orbit error is 1.24 while the average vertical GPS orbit error (not shown) is 0.42 meters over this period, The maximum latency for each 15-minute solution is 20 minutes (15 minutes of data collection plus 5 minutes 01 processing). However, as figure 6 shows, latency is not really an issue since the GPS orbits are very predictable over these short intervals. In the anticipated RTG implementation, the maximum latency is reduced to just the processing time.

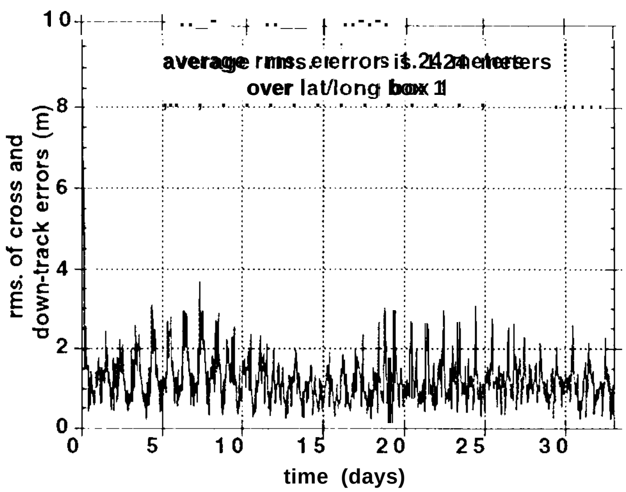


Figure 5.) Horizontal GPS orbit error for the period 96nov14 to 96dec17 over box 1. A GPS orhit solution was computed every 15-minotes with the real-time data stream from the SATLOC network.

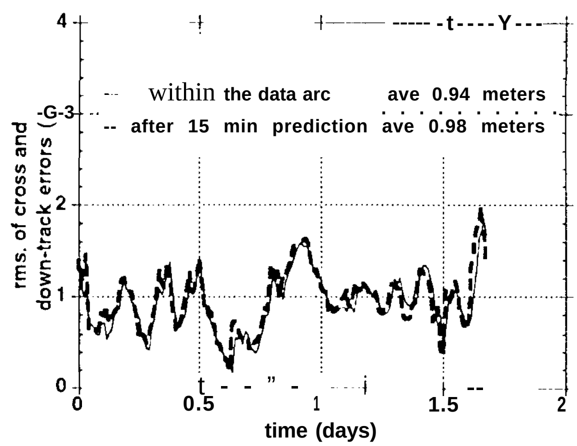


Figure 6.) Horizontal GPS orbit error for the period 96sep20 to 96sep21. The 15-minute predicted orbit solution from a previous

solution is only marginally greater than the orhit solution within the 15-minute data arc.

Figure 7 shows **the quadrature sum** of **the** cross-track and down-track errors of the GPS spacecraft over box 2 for the period 96nov14 to 96dec17. The average horizontal rms orbit error is 2.05 while the average vertical rms error (not shown) is **0.72** meters over this period. The large error "spikes" are due [o the GPS spacecraft drifting into view of the network either from west to east or from south to north. Some GPS spacecraft are not so predictable alter several hours due to anomalous or un-modeled forces on the spacecraft, **or in particular angular momentum dumps** which may impart to the spacecraft smal i accelerations. Usually after a 15-minute data **solution the** newly **acquired** GPS spacecraft's accuracy drops to the 2 meter level.

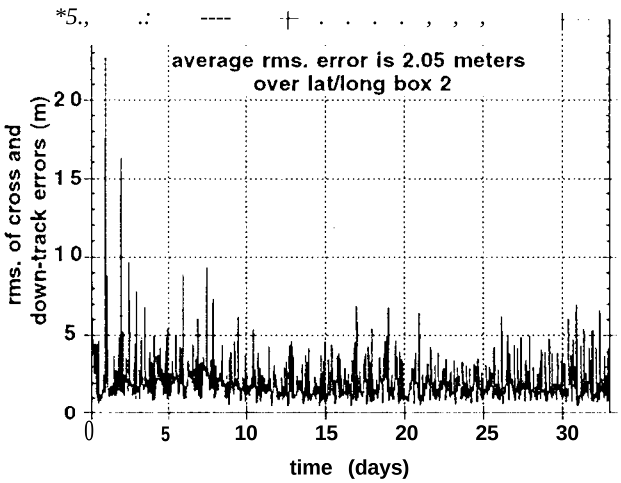


Figure 7.) Horizontal GPS orhit error for the period 96nov14 to 96dec17 over box 2. A G 1'S or-hit solution was computed every 15 minutes with the real-time data stream from the SATLOC network.

To simulate a WAAS-type scenario, 6 additional IGS stations are added to the SATLOC network. Figure 8 shows the quadrature sum of' the cross-track and down-track errors of the GPS spacecraft over box 1 for the period 96dec04 to 96dec17. The last 13 days of the SATLOC network solution from figure 5 are added for comparison. For this period, the addition of the peripheral sites reduces the average horizontal GPS orbit error from 1.18 meters to 0.73 meters. 'I'he average vertical GPS orbit error (not shown) reduces **from 0.40 meters 10 0.33 meters.**

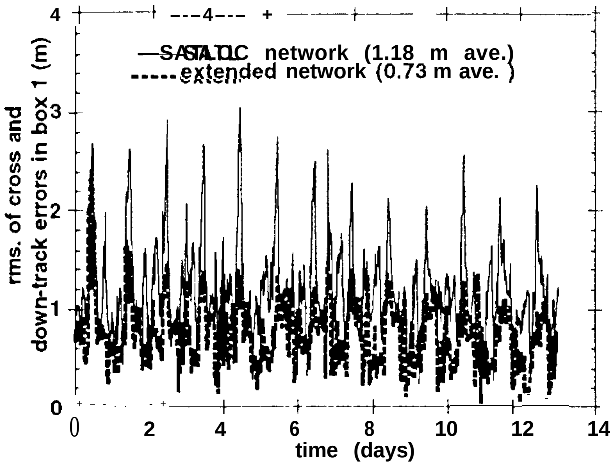


Figure 8.) Horizontal GPS orbit error for the period 96dec04 to 96dec17 over box 1 for both the SATLOC network and the extended network.

Finally, figure 9 **shows** the quadrature **sum of the** cross-**track and down-track errors** of **the** GPS spacecraft **over box 2** for the period 96dec04 to 96dec 17. For this period, the addition of the peripheral sites reduces the average horizontal GPS orbit error from 1.88 meters to 1.08 meters. The average vertical GPS orbit error (not shown) reduces from 0.67 meters to 0.43 meters.

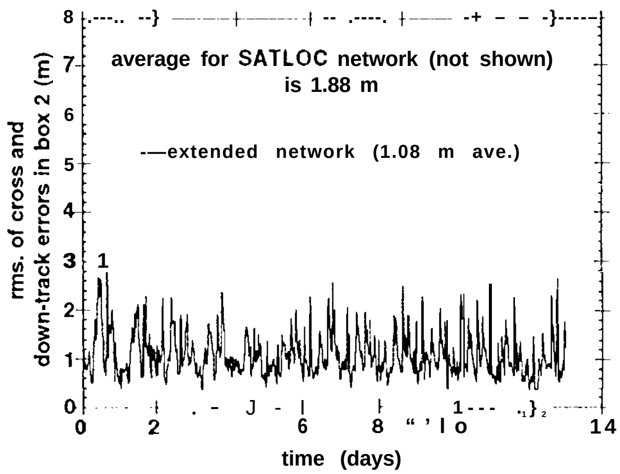


Figure 9.) Horizontal GPS orbit error for the period 96dec04 to 96dec17 over box 2 for both the SATLOC network and the extended network.

Figure **6** addresses **the** problem of added latency **to the** GPS **orbit** solution. Removing the latency associated with the data collection and hence omitting smoothing in the RTG implementation will inevitability increase the orbit errors within the data arc. Figure 10 tries to address this: The filtered only solution computes the GPS orbits immediately after each data batch. The previously discussed 1 S-minute processing computes smoothed orbits over the 15-minute data arc. Only at the end of each 15-minute solution does the filtered orbit solution agree with the smoothed orbit solution given the same data and apriori information. This is not evident in figure 10 since the smoothed and filtered errors are computed over the entire 1 S-minute solution, not just after the data batches. Furthermore, no data editing of the solutions was performed for the filtered only solution. There is a difference of nearly 700 outlying (> 2 meters) pseudorange points between the two graphed solutions. It is evident that going to this scenario, the errors should be no more than 10-20%, and more likely only a few percent greater if the outlying data points are taken into account

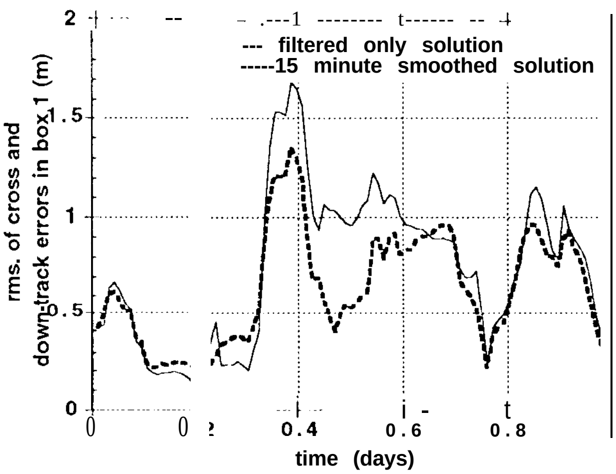


Figure 10.) Horizontal GPS filtered and 15-minute smoothed orbit error for the period 96dec17 to 96dec18 over box 1 the for the extended network.

Troposphere Results

The zenith troposphere delay is modeled as a random-walk with stochastic increments of 2.3 mm per 3-minute update. To obtain a troth estimate of the delay, each archived 24-hour data file is point-positioned with a precise GPS solution which is computed from a global network. Point-positioning refers to processing a single station with fixed GPS orbits and clocks. only the station's coordinates, clock, phase biases, and troposphere parameters are estimated. These truth troposphere estimates are accurate to 0.6 cm rms. [12][13][14] Figure 11 shows the troposphere solution and the truth solution for Olympia, Washington on 97jan06. The rms. difference between the solutions is 1.22 cm; the maximum difference is 3.0 cm,

Note that shifting the graph of the computed delay in figure 11 by 20 minutes would represent the error due to latency in the current processing. The rms. difference of this shifted version of' the delay with the truth yields nearly the same results. This is because the troposphere delay typically varies on a time scale of several tens of minutes. Again in the anticipated RTG implementation, this latency is reduced to just the processing time.

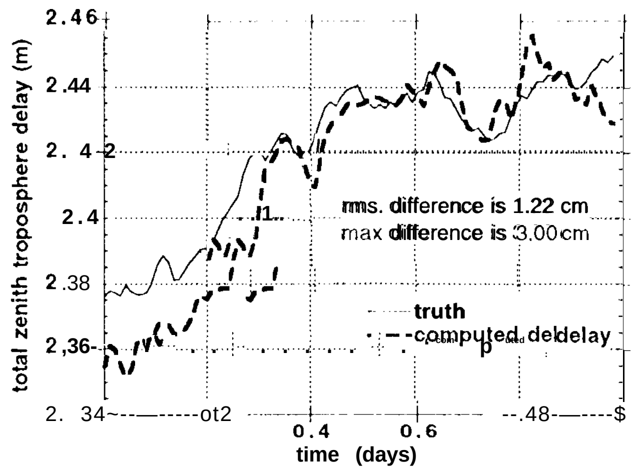


Figure 11.) Comparison of computed troposphere delay from SATLOC orbit processing and truth delay for Olympia, Washington on 97jan06.

Table 1 presents the rms. difference for al I the stations with respect to truth solutions for the period 96dec04 to 96dec17. Both the S ATLOC network processing and the extended network processing results are presented. For common stations during this period, the addition of' the peripheral sites reduces the rms. difference from an average of 1.56 cm to 1.30 cm

station	SATLOC network (cm)	extended network (cm)
ARCA (Oroville CA)	1.66	1.46
BEM1 (Grand Forks ND)	1.25	1.15
FRIE (Friendswood TX)	2.18	1.92
FTPI (Vero Beach FL)	1.86	1.4(I
HAVR (Havre Montana)	1.27	1.21
HAYD (Hayden CO)	1.46	1.15
LAJO (Phonix AZ)	1.68	1.35
LINC (Lincoln NB)	1.51	1.28
OLYM (Olympia WA)	1.32	1.17
ORON (Orono Maine)	1.74	1.34
QUIS (Quincy Illinois)	1.53	1,27
RICH (Richmond VA)	1.48	1.11
ROSW (Roswell NM)	1.64	1.24
STIG (St. Ignace MI)	1.26	1.09
FAIR (Fairbanks, Alaska)		1.15
YELL (Yellowknife Can.)		0.91
ALGO (Algonquin Can.)		1.09
STJO (St. John's Can.)		1.93
BRMU (Bermuda)		1.64
KOKB (Kokee Hawaii)		1.80

Table I.) 13 day rms. difference of zenith troposphere delay with truth delay as computed from independent point-positioned solutions for the period 96dec04 to 96dec17. The average rms. difference of the SATLOC orbit processing is 1.56 cm while the average rms. for the same stations in the extended network processing is 1.30 cm

Results of Stochastic Positioning

Ultimately it is not the accuracy of the orbit but of the user"s position that is of interest. To directly evaluate the effect of the various orbit solutions on user positioning, 13 of SATLOC's receivers[1] arc stochastically positioned using a 1 S-minute segment of 1-second data. The fast clock corrections are computed from the same data set but with different orbit solutions. In the stochastic positioning, the troposphere delays are held fixed m previously solved for values since for short data arcs they are highly correlated with the station's vertical component. Furthermore, both ionosphere-free phase and range is used in the processing and smoothing is performed so as to allow the phase bias estimates to influence the stochastic position estimates. Additionally, outlying points are edited before the final solutions are produced. Also no delay is modeled in the transmission of the fast clock correctors to the users. Hence the results presented that follow are an optimistic realization of user positioning accuraries compared to an actual WADGPS user. An accurate assesment of user accuracy is described in the paper by W. Bertiger, *et al.* [8].

In the first case, the GPS broadcast orbits are fixed in the fast clock correction process to obtain the GPS clock solutions. The clock solutions are then used to solve for the receiver locations which are modeled as a white-noise processes. Table 2 presents the results. The 3D position accuracy is 74.2 cm rms., which can be explained as follows: The average distance of the sites to the centroid of the SATLOC network is 1355 km. This results in a factor of -1 5 reduction of the broadcast orbit error induced by the fast corrections. Since the horizontal broadcast orbit error is 400 cm, the contribution to the UDRE is then on average 27 cm. The contribution to the UDRE from the fast correction process is about 9 cm with 15-minutes of data. This can be inferred in the paper by T. Yunck, et *al.* [2] in which a considered-cov:wiance analysis is performed. in [2], it was assumed that a phase bias error of 20 cm resulted after smoothing the pseudorange for 5 minutes and that the resulting fast clock correction error is 15 cm. With 15 minutes of 1-second data, the phase bias error is reduced by a factor of $\sqrt{3}$, and hence the fast clock correction is reduced to about 9 cm. Summing in quadrature these two quantities (27 and 9), and multiplying this by a PDOP of 2.5 yields an expected position error of -70 cm.

Similarly Tables 3, 4, and 5 present the results of stochastically positioning the network receivers with the orbits computed from the SATLOC network, from the extended network, and from a global network, respectively. If we assume that the horizontal orbit errors are 120, 70, and 20 cm, respectively, and applying the same arguments as above yields expected position errors of 30, 25, and 23 cm, respectively. The actual rms. values arc 24.5, 22.5, and 22.0 cm.

[1] Data from HAVR (Havre, Montana) was not available for the data segment selected.

station	East (cm)	North (cm)	vertical (cm)	3D (cm)
HAYD	6.7	3.7	9.5	12.2
RICH	20.3	4.5	14.9	25.5
LINC	15.5	11.6	21.2	28.7
FTPI	24.7	10.2	24.8	36.4
STIG	*27.9*	*5.7*	*27.6*	39.6
FRIE	12.6	5.5	38.5	40.9
ORON	*29.6*	*12.7*	*42.3*	*53.1*
QUIS	33.1	24.6	57.0	70.4
ARCA	44.5	15.8	62.3	78.2
ROSW	7.2	24.2	88.9	92.4
LAJO	15.9	21.2	92.0	95.7
OLYM	5.0	49.8	97.0	109.2
BEMI	28.1	69.6	127.2	147.7
rms .	23.7	27.3	64.7	74.2

Table 2.) Error components for stochastically positioning the SATLOC network with clock corrections derived from the broadcast ephemeris obits.

station	East (cm)	North (Cm)	Vertical (cm)	3D (cm)
HAYD	**4.4**	**2.2**	1.4	**5.2**
LINC	**6.5**	0.9	**3.6**	**7.5**
OUIS	7.8	2.0	1.0	8.1
BEMI	11.9	**8.6**	**2.5**	**14.9**
ORON	15.1	1.8	4.1	15.7
ROSW	4.0	1.3	15.6	16.1
STIG	18.2	0.4	1.9	18.4
FRIE	3.0	1.1	21.3	21.5
FTPI	**7.9**	**9.2**	**19.1**	**22.6**
LAJO	**8.0**	**22.1**	**17.6**	**29.4**
OLYM	29.9	0.6	11.3	32.0
RICH	15.X	7.7	29.1	34.0
ARCA	10.7	11.5	33.2	36.7
rms .	13.1	8.1	16.4	22.5

I'able 4.) Error components for stochastically positioning the SATLOC network with clock corrections derived from the extended network orbits.

station	East (cm)	North (an)	Vertical (cm)	3D (an)
ROSW	0.6	2.9	1.9	3.6
HAYD	3.8	1.6	2.6	4.9
LINC	8.2	3.6	9.9	13.4
STIG	15.8	1.3	5.4	16.7
BEMI	16.1	10.4	3.5	19.5
ORON	16.7	1.1	10.7	19.9
FTPI	8.6	9.1	15.9	20.2
FRIE	5.0	1.2	20.2	20.8
QUIS	11.8	6.8	18.7	23.1
RICH	17.7	7.1	26.5	32.6
LAJO	7.5	22.6	22.8	33.0
OLYM	32.0	10.1	11.1	35.3
ARCA	*11.4*	11.1	*39.1*	*42.2*
rms .	*14.2*	9.0	*17.9*	*24.5*

Table 3.) Error components for stochastically positioning the SATLOC network with clock corrections derived from the SATLOC network orbits.

station	East (cm)	North (cm)	vertical (cm)	3D (cm)
LINC	4.1	0.8	3.8	5.6
QUIS	6.3	0.8	3.1	7.0
ROSW	1.5	0.7	8.1	8.3
HAYD	10.1	2.1	5.4	11.7
STIG	12.8	1.1	1.7	12.9
ORON	12.9	1.5	9.1	15.9
FRIE	13.1	1.4	14.5	19.5
FTPI	**7.3**	**10.0**	15.4	19.8
BEMI	21.8	6.5	2.0	22.8
ARCA	10.1	11.2	25.9	30.0
RICH	**14.2**	**5.4**	**27.8**	**31.7**
LAJO	7.4	22.3	21.4	31.8
OLYM	**31.4**	**2.7**	**19.6**	**37.1**
rms .	14.0	7.9	15.0	22.0

Table 5.) Error components for stochastically positioning the SATLOC network with clock corrections derived from the global network orhits.

Problems

There have been several failures of the orbit processing since it was initiated On November 13, 1996. The first such failure occurred on December 17, 1996 and was caused by anomalous time-tags in the data stream. Since the process is continuously running in an automated mode this failure was undetectable for several hours. During the period 96dec1 7 to 96dec25 there were several failures due to computer and data transmission problems. However from 96dec25 to now (97jan09), the orbit processing has been running continuously. Figure 12 shows the results of the cold start which occurred on 96dec25. It typically takes about 24-hours until there is sufficiant data strength to reduce the orbit erorrs to steady-state. in the future, this will be eliminated by initializing the apriori covariance with a full covariance from a previously solved for global orbit solution [10].

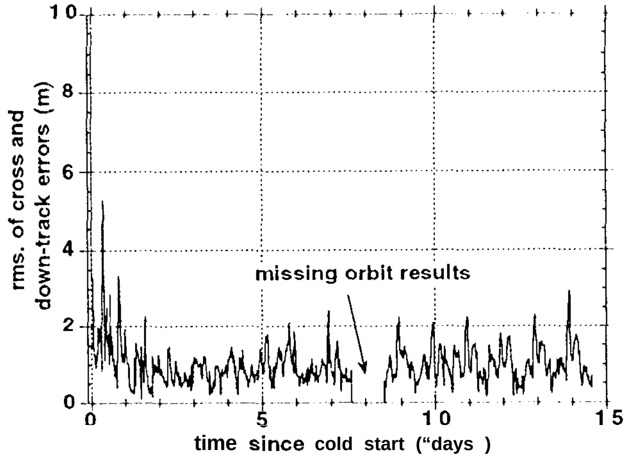


Figure 12.) Horizontal GPS orbit error for the period 96dec25 to 97jan09 over box 1. A cold start refers to initializing the apriori covariance with diagonal values.

A second problem involves the inability to synchronize the user's orbit and clock corrections due to limited bandwiihh when transmitting the corrections. It the solved for orbits are smooth and continuous this is not a be problem. However there may be several meter jumps in the 1 S-minute orbit solutions as compared to previously predicted solutions, particularly when new satellites come into view. In the RTG implementation, the magnitude of these jumps will be mitigated due to the immediate orbit updates after each data batch. However further means of smoothing the orbits over data batches may needed.

Summary

WADGPS UDRE is mostly composed of residual orbit error and fast clock correction error. For a well distributed network over the continental United States such as SATLOC's North American reference network, a dual-frequency user's 3D position accuracy with just DGPS is limited by the imprecise broadcast orbits to on average 70 cm. If the DGPS process is aided by an orbit correction process, the user's 3D position accuracy then becomes limited by the fast clock correction error. For dual-frequenc y WADGPS users, several decimeter accuracies arc attainable.

Acknowledgement

The work described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We arc grateful to Greg Piesinger and Mike Whitehead of SATLOC, Inc. for their assistance in providing real-time data from SATLOC's North American reference network.

References

[1] Yunck, T. P., Bar-Sever, Y. E., Bertiger, W. I., Iijima, B. A., Lichten, S. L., Lindqwister, U. J., Mannucci, A. J., Muellerschoen, R. J., Munson, T. N., Remans, L. R., Wu, S. C., A Prototype WADGPS System for Rc:il-Time Sub-Meter Positioning Worldwide, Proceedings of 10N GPS-96, Kansas City, MI, September 1996.

[2] Yunck, T. P., Bertiger, W. I., Mannucci, A. J., Muellerschoen, R. J., WU, S. C., A Robust and Efficient New Approach to Real-Time Wide Area Differential GPS Navigation for Civil Aviation, JPL Report D-12584, 1 April 1995.

[3] Mannucci, A. J., B. A. Iijima, B. D. Wilson, S. R. Peck, R. Ahmadi, M. Hagen, "Wide Area Ionospheric Delay Corrections Under Ionospheric Storm Conditions", to be published in proceedings of" ION National Technical Meeting, Santa Monica, CA, January 1997.

[4] Mannucci, A. J., B.D. Wilson, and C. D. Edwards, "A New Method for Monitoring the Earth's Ionospheric Total Electron Content using the GPS Global Network", Proceedings of ION GPS-93, Salt Lake City, UT, September 1993.

[5] Mannucci, A. J., B.D. Wilson, and D.N. Yuan, "An Improved Ionospheric Correction Method for Wide-Area Augmentation Systems", Proceedings of ION GPS-95, Palm Springs, CA, September 1995.

[6] Ceva, J. C., Bertiger, W. 1., Muellerschoen, R. J., Parkinson, B., Incorporation of Orbit Dynamics to Improve Wide Area Differential GPS, proceedings of 10N GPS-95, Palm Springs, CA, September 1995.

[7] Federal Aviation Administration, *Wide Area Augmentation System (WAAS) Specification,* Document FAA-E-2892, U.S. Department of Transportation, 9 May 1004.

[8] W. 1. Bertiger, 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, A Prototype Real-Time Wide Area Differential GPS System, to be published in Proceedings of ION National Technical Meeting, Santa Monica, CA, January 1997.

[9] 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 Berne, 1993.

[10] Muellerschoen, R. J., Lichten, S., Lindqwister, U. J., Bertiger, W. 1., Results of an Automated G PS Tracking System in Support of Topex/Poseidon and GPSMet, Proceedings of ION GPS-95, Palm Springs, CA, September, 1995.

[11] Griffith, C., Peck, S. R., Malla, R. P., Ceva, J. C., Should WAAS Get Rid of the MET Instruments, to be published in proceedings of ION National Technical Meeting, Santa Monica, CA, January 1997.

[12] Bar-Sever, Y.E., Kroger, P. M., Strategies for GPS - Based Estimates of Troposphere Delay, proceedings of ION GPS-96, Kansas City, MI, September 1996.

[13] Tralli, D. M., Lichten, S. M., Stochastic Estimation of Tropospheric Path Delays in Global Positioning System Geodetic Measurements, *Bulletin Geodesique*, Vol. 64, pp. 127-159 (1990).

[14] Tralli, D. M., Lichten, S. M., Herring, T. A., Comparison of Kalman Filter Estimates of Zenith Atmospheric Path Delays using the Global positioning System and Very Long Baseline Interferometry, Radio Science, Vol. 27, pp. 999-1007(1992).

[15] Webb. F. H., and J. F. Zumberge (Eds.), *An Introduction to GIPSY/OASIS [I , JPL Internal Document D- 110M',* Jet Propuls. Lab., Pasadena, Calif., July, 1993.

[16] Wu, S. C., Y. Bar-Sever, S. Bassiri, W. 1. Bertiger, G. A. Hajj, S. M. Lichten, R. P. Malla, B. K. Trinkle and J. T. Wu, *Topex/Poseidon Project: Global Positioning System (GPS) Precision Orbit Determination (POD) Software Design,* JPL D-7275, Mar 1990.

[17] Bertiger, W. 1., Y. E. Bar-Sever, E. J. Christensen, E. S. Davis, J. R. Guinn, B. J. Haines, R. w. Ibanez-Meier, J. R. Jet, S. M. Lichten, W. G. Melbourne, R. J. Muellerschoen, T. N. Munson, Y. Vigue, S. C. Wu, and T. P. Yunck, B. E. Schutz, P. A. M. Abusali, H. J. Rim, M. M. Watkins, and P. Willis, GPS Precise Tracking 01 Topex/Poseidon: Results and Implications, *JGR Oceans Topex/Poseidon Special Issue*, vol. 99, no. C12, pg. 24,449-24,464 Dec. 15, 1994.

[18] Gold, K., Bertiger W. 1., Wu, S. C., Yunck, T. P., GPS Orbit Determination for the Extreme Ultraviolet Explorer, *Navigation: Journal of the Institute of Navigation*, Vol. 41, No. 3, Fall 1994, pp. 337-351

[19] Haines, B. J., S.M. Lichten, J.M. Srinivasan, T.M. Kelecy, and J.W. LaMance, GPS-like Tracking (GLT) of Geosynchronous Satellites: Orbit Determination Results for TDRS and INMARSAT, AAS/AI AA Astrodynamics Conference, Halifax, Nova Scotia, Aug. 14-17, 1995 (AI AA, 370 L'Enfant Promenade, SW, Washington DC 20024).

[20] Muellerschoen, R. J., Bertiger, W. I., Wu, S. C., Munson, T. N., Zumberge, J. F., Haines, B. J., Accuracy of GPS Determined Topex/Poseidon Orbits During Anti-Spoof Periods, Proceedings of ION National Technical, San Diego, California, January 1994.

[21] Heflin, M. D., Jefferson, D., Vigue, Y., Webb, F., Zumberge, J. F., and G. Blewitt, Site Coordinates and Velocities from the Jet Propulsion Laboratory Using GPS, SSC(JPL) 94 P 01, IERS Tech. Note 17, 49, 1994.

[22] Argus, D., Heflin, M., plate Motion and Crustal Deformation Estimated with Geodetic Data from the Global Positioning System, Geophys. Res. Lett., Vol. 22, No. 15, 1973-1976, 1995.

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

Orbit and Troposphere Results of a Real-Time Prototype WADGPS System

Ronald J. Muellerschoen

Winy I. Bertiger

Larry R. Remans

Orbit Correction Process

Current process wakes up every 15 minutes and processes the previously accumulated 15 minutes of data.

- operating since November 13,1996.
- 3-minute decimated phase and smoothed pseudorange data points.
- solves for:
  - GPS orbits and clocks
  - receiver zenith troposphere delays and clocks
  - phase bias parameter for each phase arc

Makes comprehensive use of dynamics.

- precise dynamic orbit model allows GPS satellite prediction with little lose of accuracy.
- some process noise added to deweight older solutions.

Orbit Correction Process

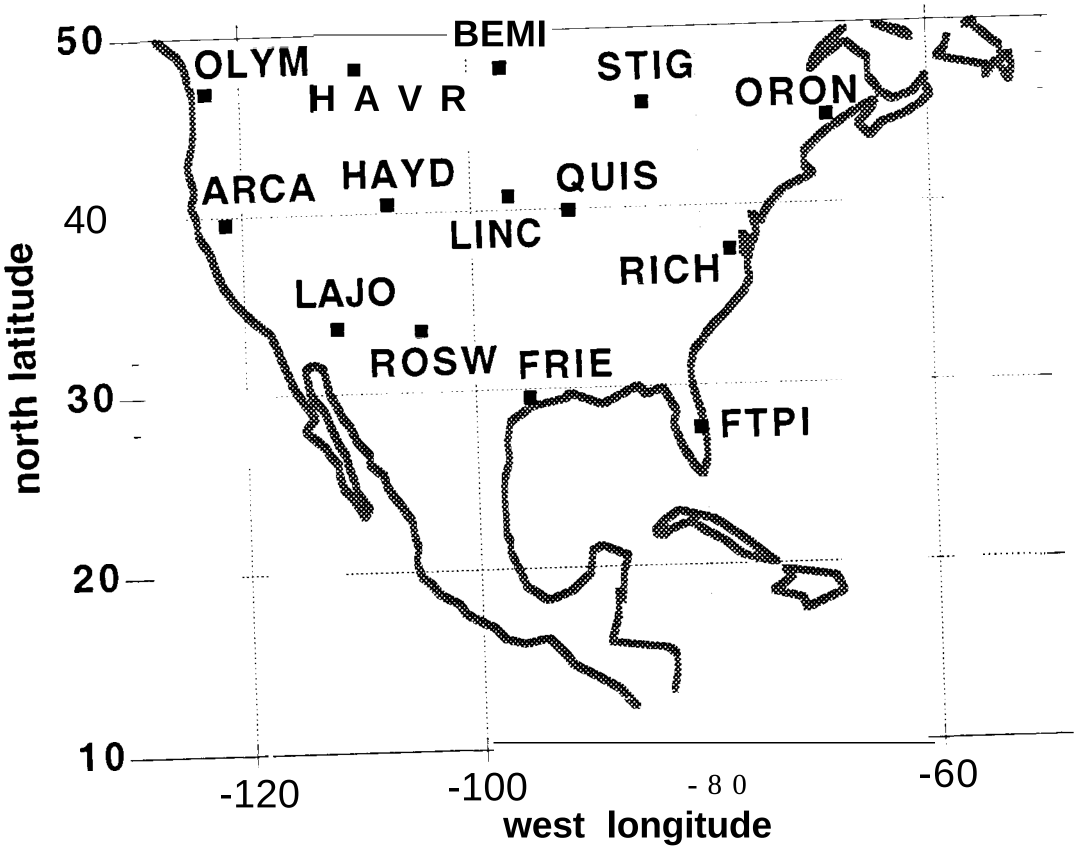
Current solution initialized by the previous data fit.

- epoch of spacecraft partials updated every 24-hours.
- seamless processing as if the data was processed in one continuos arc.
  - no information is lost from one data fit to the next.
  - phase and phase windup is continuos over successive data fits.

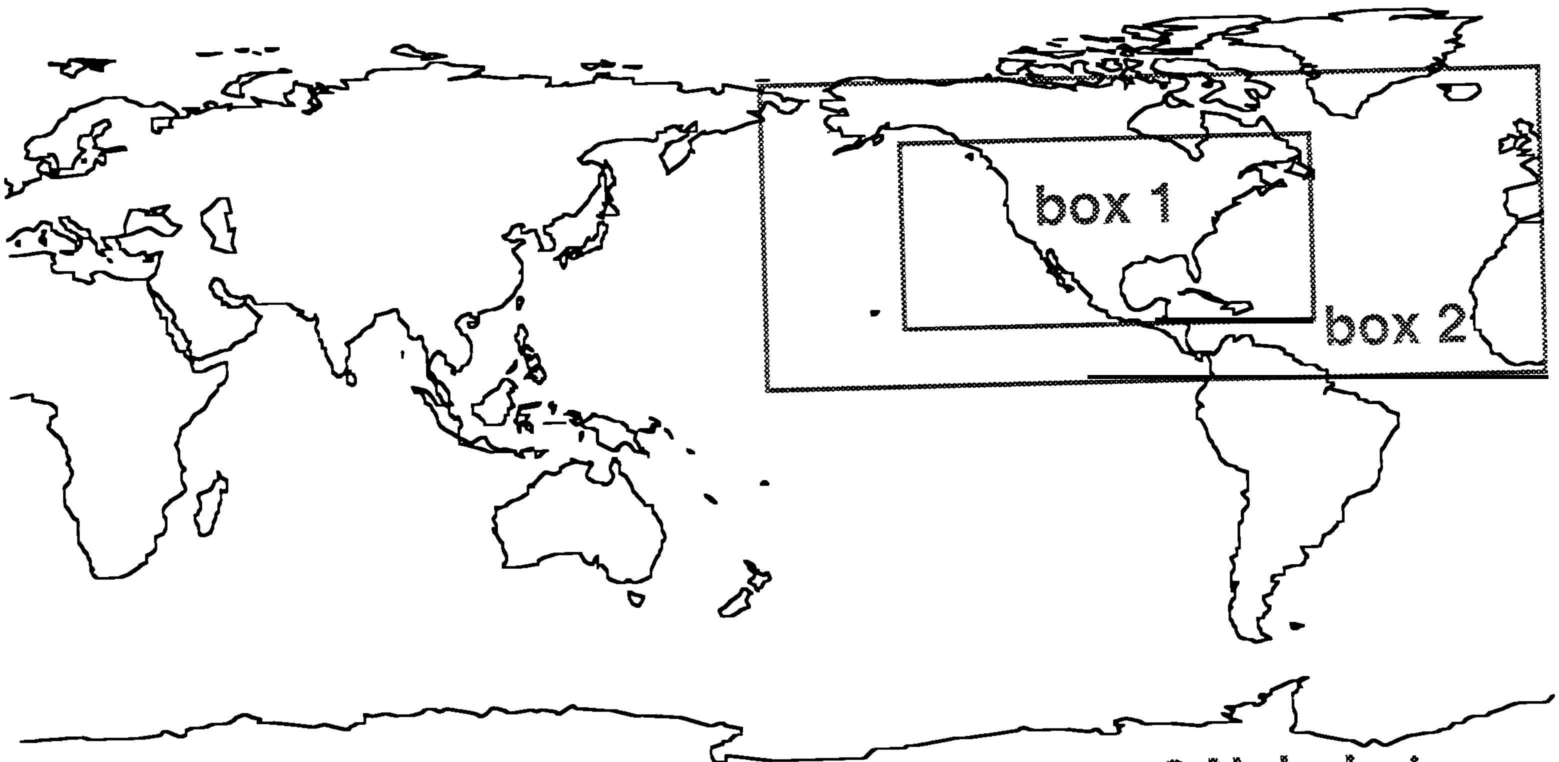
Currently uses Gipsy-Oasis II software.

- extremely flexible, useful for tuning and detecting problems.
- not optimal for real-time processing.
- future implementation will be Real-Time Gipsy (RTG)
  - coded in ANSI c.
  - no complex file interfaces.

14 Station SATLOC Network



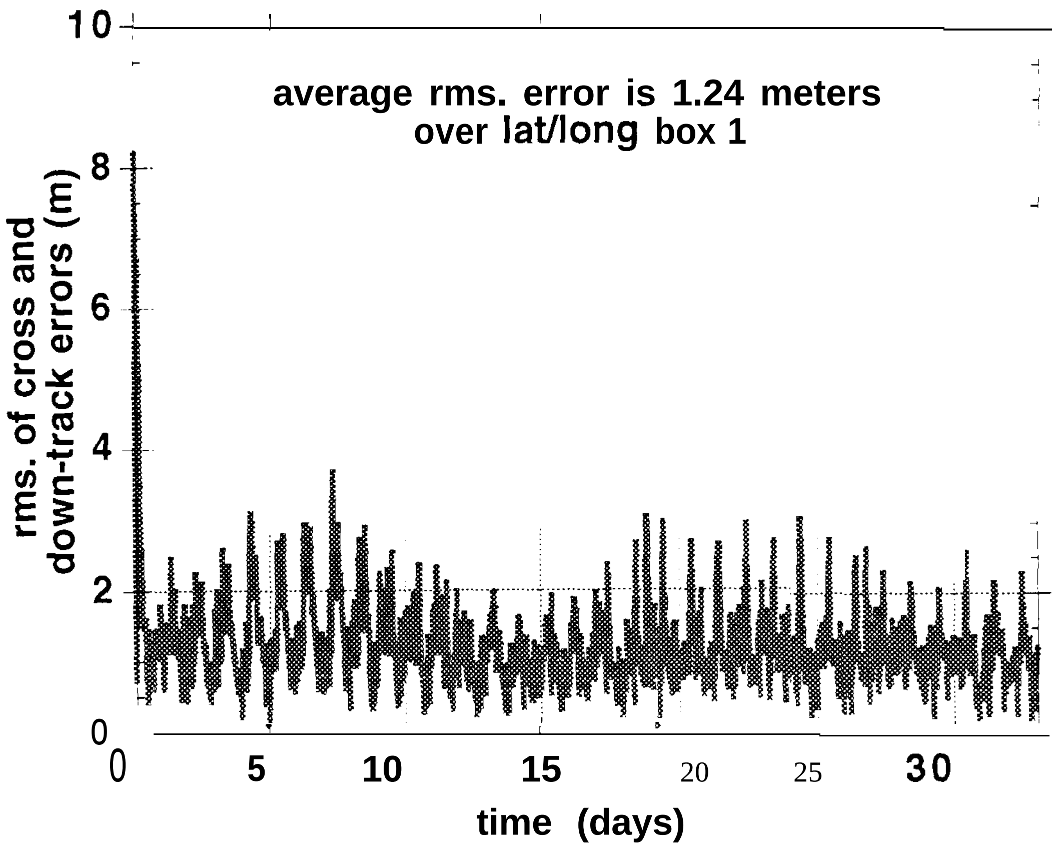
Assessment of Orbit Errors



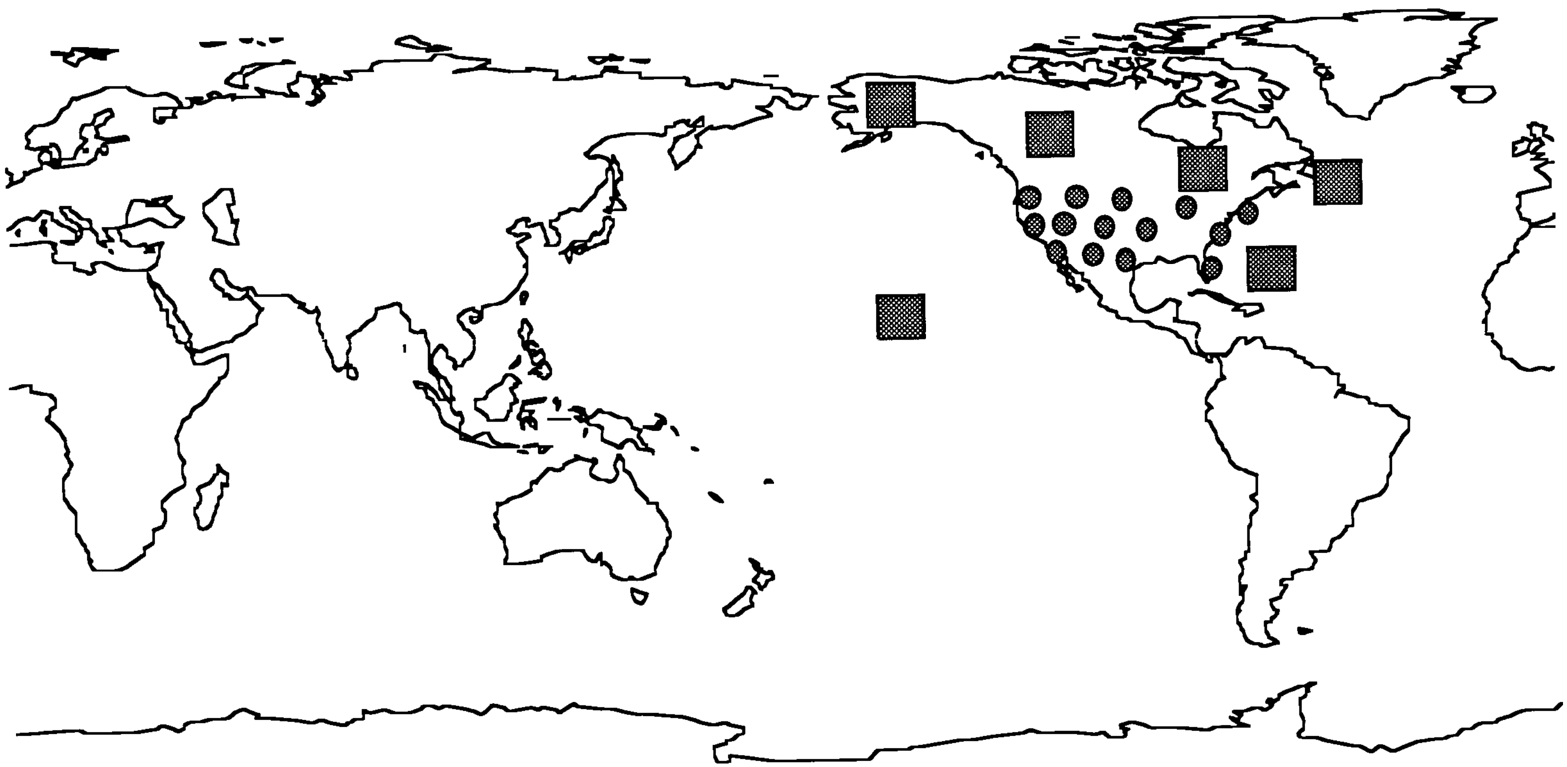
Box 1 is 60 to 20 N. in Lat. and 210 to 310 in Long.

Box 2 is 70 to 0 N. in Lat. and 180 to 360 in Long.

Orbit Results of SATLOC Network

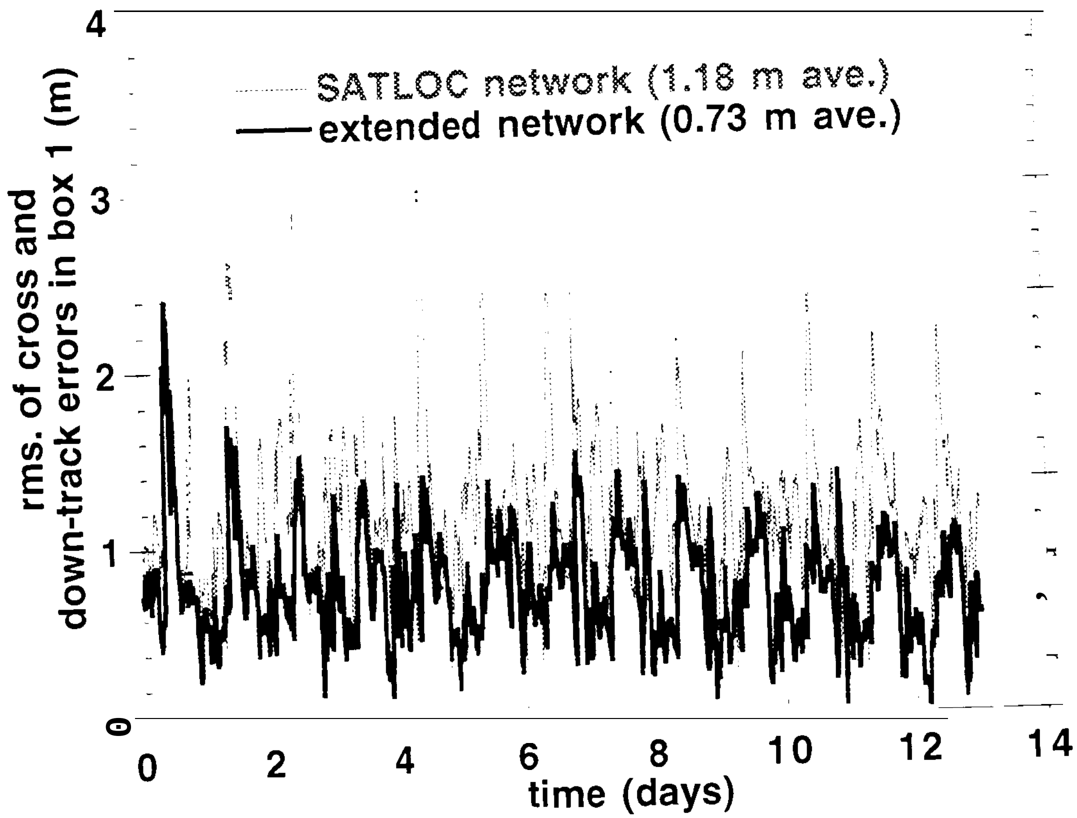


Extended Network

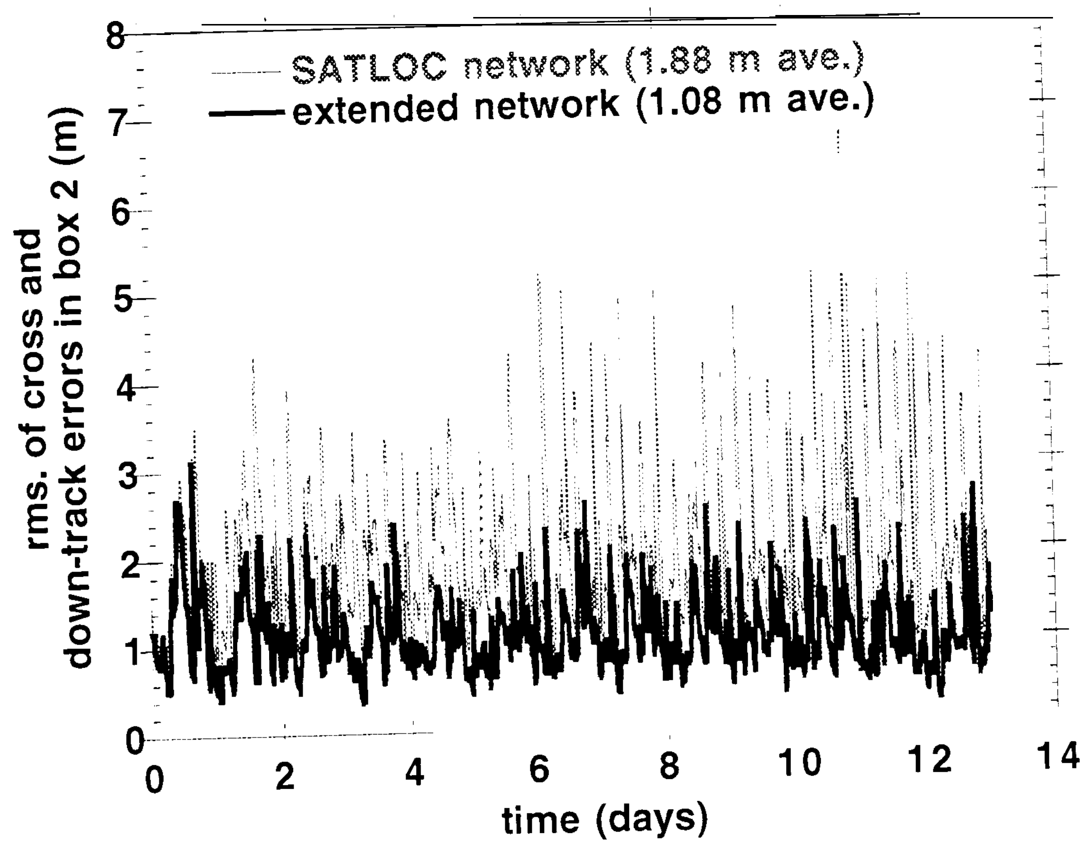


● SATLOC network ❑ additional peripheral sites

Results of Extended Network Over Box 1



Results of Extended Network Over Box 2



Troposphere Results