# A Prototype Real-Time Wide Area Differential GPS System

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*SATLOC*

## Biography

*Willy 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.

*Yoaz Bar-Sever* has a Ph.D. in Applied Mathematics from the Technion - Israel Institute of Technology and a M.S. in Electrical Engineering from the University of Southern California. Since 1989 he has been a member of the Earth Orbiter System Group at JPL where his current focus is on high precision orbit determination with GPS and its applications in Earth sciences.

*Bruce Haines* received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon Science Working Team, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

*Byron Iijima* is a member of the GPS Networks and Operations Group at the Jet Propulsion Laboratory in Pasadena CA. For the last 8 years he has been developing technology for deep-space and GPS tracking applications. He is currently focused on GPS-based ionospheric maps, especially in real-time applications. He holds a Ph.D. in physics from MIT.

*Stephen Lichten* has worked at the Jet Propulsion Laboratory since 1983, where he presently is the Earth Orbiter Systems Group Supervisor and Radio Metrics manager in NASA's Deep Space Network Technology Program. He received a Ph.D. in astrophysics from Caltech in 1983. His group specializes in technology development for high-precision navigation, geodetic and atmospheric applications, emphasizing automated GPS tracking techniques and software. Recently, Dr. Lichten's group has developed high-precision real-time software which has been licensed for operational use in the FAA's GPS Wide Area Augmentation System (WAAS).

*Ulf Lindqwister* received his Ph.D. in physics from Princeton University, Princeton, in 1988. He has been working in the Tracking Systems and Applications section since he began at JPL in 1988 and is currently supervisor of the GPS Networks and Ionospheric Systems Development group. In recent years his work has been focused on the development of NASA's permanent GPS ground tracking network and on developing research and development applications of the global ionospheric mapping technique.

*Angelyn Moore* received her Ph.D. in Physics from the University of California, Riverside, in 1995. She began working at JPL in 1987, performing her undergraduateand graduate research in the area of ultrastable trapped-ion frequency standards. Since 1995 she has been a member of the GPS Networks and Ionospheric Systems Development Group, primarily developing near real-time systems for global ionospheric determination using a global network of GPS ground stations.

*Ronald 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. 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 delevopment of 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 JPL 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.

*Brian Wilson*, a member of the GPS Networks and Ionospheric Systems Development Group at JPL, has been studying the ionosphere using GPS for six years and is a co-developer of the GPS-based global ionospheric mapping (GIM) technique. His current work is focused on improving and validating GIM, global ionospheric calibration of single-frequency ocean altimetry missions, real-time global WADGPS, and other remote sensing applications of GPS. He received a M.S. in physics from Caltech in 1982.

*Sien-Chong Wu* is currently a Technical Group Leader in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep-space as well as near-Earthspace vehicles, and their applications to precision geodesy. His current interest is in the area of real-time wide-area differential GPS and special applications of GPS technologies. Sien received his Ph.D. from the University of Waterloo, Ontario, Canada.

*Thomas P. Yunck* is Deputy Manager of the Tracking Systems & Applications Section at JPL, where for the past 15 years he has been active in developing GPS technology for precision applications in Earth science. He has a BSEE degree from Princeton University and a Ph.D. from Yale University.

*Greg Piesinger* received his MSEE in 1968 from the University of Nebraska. Piesinger has primarily worked in the areas of communication and radar systems. Most of his career was spent at Bell Telephone Labs, Motorola, and Honeywell. In 1995, he joined Satloc where he is currently project leader for the L-band network.

*Mike Whitehead* received his Ph.D. in Electrical Engineering from the University of Florida in 1986. He developed the software which serves as the backbone for SATLOC's Wide Area Differential System. This includes communications, integrity, control, and user interfaces. Most of Mike's work experience has involved a combination of software, signal processing and control.

## Abstract

In this paper we describe the system architecture, algorithms, and preliminary results from an operating prototype Wide Area Differential GPS (WADGPS) system spanning the continental US (CONUS). With dual-frequency GPS user equipment and improved positioning algorithms, real-time 3-D RMS user position accuracy is better than 50 cm. Single-frequency users can obtain comparable accuracy with the current ionospheric intensity. There may be some degradation in single-frequency positioning during solar maximum or during ionopheric storms.

The system consists of 14 codeless dual-frequency geodetic quality receivers distributed over the CONUS returning real-time data at a 1-Hz rate, and a central processing facility where WADGPS products are computed. These products include: real-time GPS satellite positions with a 3-D RMS accuracy of 1.3 meters; real-time zenith tropospheric delays (at each site) estimated from GPS measurements (surface meteorological data are not needed or used) to an RMS accuracy of about 1.5 cm; GPS fast range corrections (1-Hz rate) which are optimally extrapolated to the time of use using information from the phase data; and a grid of real-time ionospheric corrections for measurements at L1 produced every 5 minutes with a current vertical RMS accuracy of 20 cm

The software for GPS data processing and computation of real-time WADGPS corrections is easily hosted on a single UNIX workstation. The full computation adds only about 3 msec latency for users of the corrections.

Commercial availability of the single frequency system is scheduled for the 2nd quarter of 1997. The software for estimation of the WADGPS corrections is also being adapted for use in the Federal Aviation Administration's (FAA) Wide Area Augmentation System (WAAS).

## Introduction

The formal requirements established by the FAA for the Wide Area Augmentation System (WAAS), to be completed by 2001, stipulate that aircraft real time position should be determined to an accuracy of 7.6 m in both the vertical and horizontal components with 95% probability (two sigma) throughout the North American service volume. This assumes a conventional single-frequency user applying WAAS-supplied corrections to broadcast GPS orbits and clocks and to the ionospheric delay model.

An expansion of WADGPS to global use would have far-reaching impact. A reliable real-time precision global positioning capability can, for instance, provide autonomous spacecraft navigation, reducing operations costs for NASA and commercial space missions.

There are some applications for which higher accuracies, from the 1-meter to sub-decimeter level, are desired. These include real time docking and proximity operations in space. Other high precision applications will come from NASA-supported science activities and from commercial efforts around the world, examples of which include: satellite remote sensing, in situ Earth science on land and water, synthetic aperture radar (SAR) imaging, topographic mapping, ocean and land altimetry, precision surveying applications, and gravimetry. Measurement platforms requiring precise real-time positioning may include satellites, balloons, aircraft, ships and bouys. For interferometric mapping applications, the high-accuracy global WADGPS capability would enable significant operational cost savings and major enhancements in areas such as natural hazard monitoring. While for many, these accuracies are not necessarily needed in real time, the ability to achieve such accuracy autonomously onboard would save considerable time and expense on the ground. A real-time onboard capability for autonomous navigation and production of precision science products is a key element in NASA's New Millennium Program.

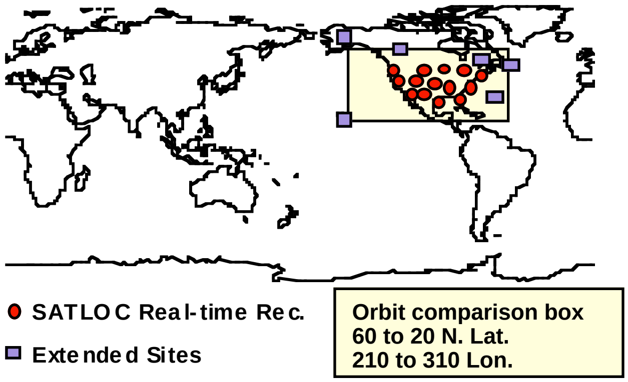
The system described in this paper could be broadened into a global system capable of supporting high precision real-time user positioning anywhere in the world or in the low-Earth space regime. With the current software, ground user accuracies at the several decimeter level have been demonstrated. A long-term objective is to develop a capability for seamless global real-time accuracy at the sub-10 cm level, through algorithm enhancements and modified operations, effectively equalling localarea DGPS performance worldwide

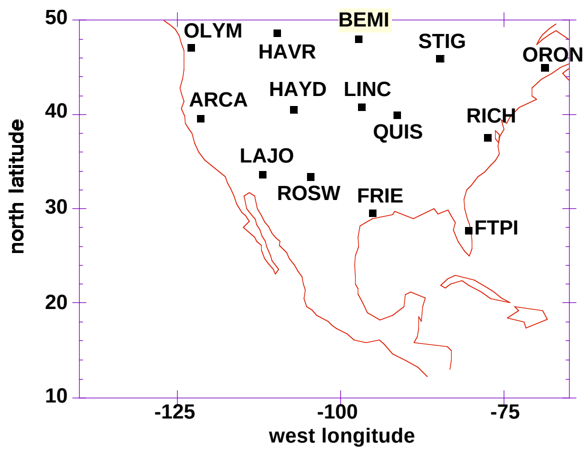
The agriculture industry, in particular, has developed a need for highly accurate positioning to support the emerging field of precision farming. Precision farming concepts are being applied to two main areas: yield mapping and soil sampling. Soil fertility mapping has been a natural extension of attempts to understand and manage crop yield variations. The potential to target herbicide application to specific weeds and weed patches offers an opportunity to improve management, reduce herbicide application and save money. Because applying chemical fertilizers is expensive, farmers can reduce costs through accurate application in areas where soil sampling shows a specific need.

The results in this paper were achieved using GPS tracking data from a ground network recently implemented by SATLOC, a company active in the use of precision DGPS for agriculture.

## System Overview

Figure 1 with detail in Fig. 2, shows the SATLOC network of 14 fixed Ashtech Z12 ground receivers (circles) which return data to a SATLOC central processing facility in Arizona at a 1-Hz rate. These data are then reformatted and sent to the Jet Propulsion Laboratory (JPL) in California for processing, arriving with a latency from time of reception at the receiver of about 1.6 seconds. After the initial engineering checkout, the processing facility will be moved from JPL to SATLOC's facility. Figure 3 shows a block diagram of the processing performed at JPL. GPS orbits and troposphere delays at the receiver are determined at a 15-min update interval using precise dynamic models with dual frequency data smoothed to 3 minutes. Ionosphere calibrations for single frequency users are updated every 15 minutes using data smoothed to 5 minutes. Slowly varying inter-frequency biases at all the receivers and the GPS satellite transmitters are determined once and monitored every 2 weeks. Range corrections to the GPS constellation, dominated by SA clock dither, are determined every second and projected a few seconds into the future to account for system latency (dominated by network communications).


SATLOC Real-time Rec.
Extended Sites
Orbit comparison box
60 to 20 N. Lat.
210 to 310 Lon.


OLYM
HAVR
BEMI
STIG
ORON
ARCA
HAYD
LINC
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RICH
LAJO
ROSW
FRIE
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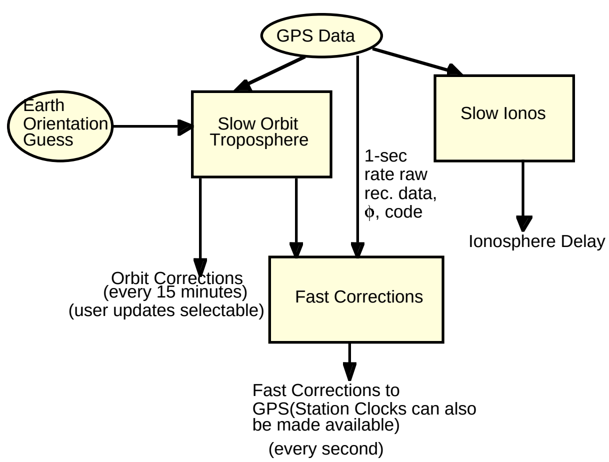
-100
-75
north latitude
west longitude


GPS Data
Earth Orientation Guess
Slow Orbit Troposphere
Slow Ionos
1-sec rate raw rec. data, φ, code
Ionosphere Delay
Orbit Corrections (every 15 minutes) (user updates selectable)
Fast Corrections
Fast Corrections to GPS(Station Clocks can also be made available)
(every second)

described below. The FAA is also utilizing the RTG software as the basis for the system which will eventually produce the slow orbit corrections in the operational WAAS.

Every 15 minutes the orbit determination and troposphere process wakes up and processes the previous 15 minutes of data smoothed to 3 minute data points. Parameters solved for include GPS epoch state (position and velocity), GPS solar pressure parameters, earth orientation parameters (UT1, polar motion), GPS clocks and station clocks. Once each day the epoch of the GPS state is updated keeping the full covariance information. The GPS orbits are predicted with precise dynamic models 2 hrs ahead to be used in the 1-Hz range correction process. Typically, only the next 20 minutes are used. In a 15 minute prediction the 3-D RMS GPS orbit accuracy as measured against precise post-processed truth orbits is 1.3 m using the 14 SATLOC ground receivers in the large rectangle including North America from 20° to 60° North latitude and 210° to 310° longitude, Fig. 1, with a 2-D (horizontal) RMS accuracy of 1.2 m. Note that it is the 2-D RMS that is the most significant figure of merit in a wide area differential GPS system. If the network is augmented with 6 receivers in Alaska, Hawaii, Western Canada, and the Caribbean (squares in Fig. 1), the 3-D RMS accuracy falls to 80 cm with a corresponding 2-D RMS of 75 cm. With a global ground network, initial tests indicate that real-time accuracies better than 40 cm for GPS orbits can be achieved.

The zenith delay troposphere at each of the 14 ground stations is treated as a random-walk process in time with a stochastic update every 3 minutes. It is mapped to GPS line of sight using the Niell mapping function [*Niell*, 1996]. The noise added at each stochastic update is 0.17 $cm/sec^{1/2}$. The value at the end of the 15 minute data batch is then used by the fast correction process as a constant value in the next 15 minutes. For a typical 24 hour period shown in Table 1(-see Fig. 2 for locations), the 15 minute predictor has an RMS difference with truth of about 1.7 cm. The truth troposphere is determined by post-processing the GPS data. The accuracy of post-processed GPS troposphere delays has been validated against water vapor radiometers and Very Long Baseline Interferometry (VLBI) techniques at the sub-centimeter level [*Bar-Sever and Kroger*, 1996; *Trali and Lichten*, 1990; *Tralli et al.*, 1976].

The accuracy of the orbit and troposphere solutions and the exploitation of precise and well-tested dynamic and measurement modeling for GPS observables enables the WADGPS system described here to strongly separate the effects of GPS orbits and clocks (including SA). Such separation of physically different effects is a key feature of this software which provides significant advantages when testing for outliers and performing integrity checks.

## Ionosphere Calibrations

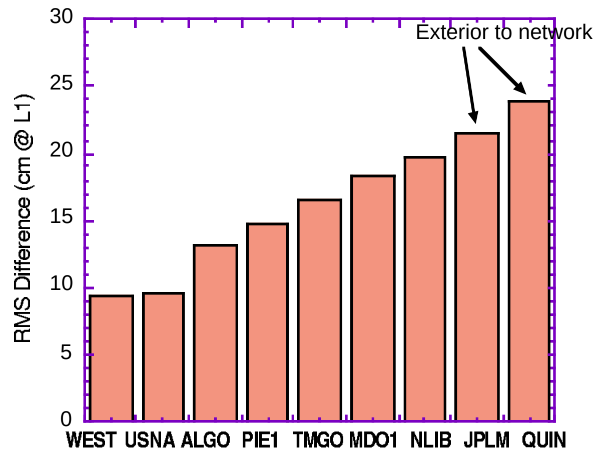
The process for generation of precise real-time ionospheric delay corrections utilizes a modified version of the Global Ionosphere Map (GIM) software developed at JPL [*Mannucci, et al.* 1993]. GIM has been extensively used and validated in non-real-time applications since 1993 [*Mannucci, et al.* 1995]. GIM takes dual-frequency GPS tracking data from a network of GPS receivers and produces maps of the electron content of the ionosphere. GIM's FORTRAN-based programs have been automated for real-time operations with a set of Unix scripts, and have been successfully processing real-time GPS data from the SATLOC WADGPS network since September 1996. Parts of the GIM software are currently being converted to ANSI c and integrated with the RTG software package, as described below, so that the process can run more efficiently. This real-time ionosphere software will also eventually be integrated into the FAA's operational WAAS software.

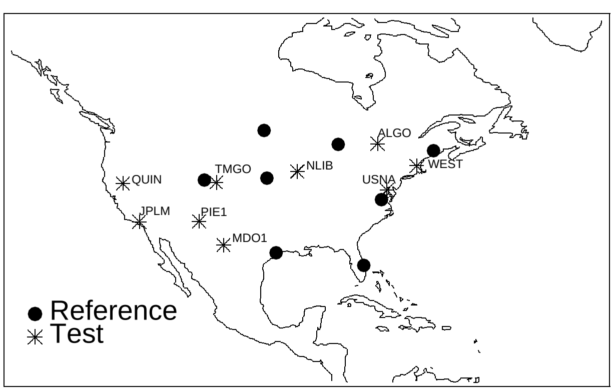
**Table 1, Troposphere Accuracy Compared to Post-processed Truth**

| Station | RMS Within Data Arc | RMS 15 Minute Prediction |
|---|---|---|
| BEMI | 1.06 cm | 1.07 cm |
| FRIE | 2.35 cm | 2.46 cm |
| FTPI | 1.82 cm | 1.92 cm |
| HAYD | 1.20 cm | 1.24 cm |
| LAJO | 1.68 cm | 1.74 cm |
| LINC | 1.17 cm | 1.22 cm |
| OLYM | 1.84 cm | 1.91 cm |
| ORON | 1.71 cm | 1.71 cm |
| RICH | 1.48 cm | 1.51 cm |
| ROSW | 1.63 cm | 1.68 cm |
| STIG | 1.07 cm | 1.20 cm |
| **Average RMS** | **1.59 cm** | **1.65 cm** |

Every 15 minutes the ionospheric correction process wakes up and processes the previous 15 minutes of dual-frequency GPS tracking data smoothed to 5 minute data points. A Kalman filter is used to produce sequentially updated maps. The ionosphere is modeled as a thin spherical shell at an altitude of 450 km. The ionosphere's electron content on this shell is parameterized by the values of electron content at the vertices of a highly uniform triangular grid on the shell. The spatial variation of the electron density between the vertices is modeled as linear. We fix the grid in the solar-magnetic frame (sun-fixed or local-time frame) since the ionospheric density is relatively stationary in that frame. (The ionosphere changes rapidly in an earth-fixed frame, with the greatest electron density appearing at ~2 pm local time.) The density at each vertex is modeled stochastically with carefully tuned time correlations between updates.

To assess ionospheric calibration accuracy, data were collected from two North American networks, shown in Fig. 4. on 2 Sept 96. The solid circles indicate the locations of eight of the 14 SATLOC real time sites operating on that day, used to compute true real time ionospheric delay maps for all of the CONUS, updated every 15 minutes. Independent data were acquired simultaneously from nine test sites across the US and in Canada, represented by the crosses. The test data were used to compute the zenith ionospheric delays near the test sites using a precise post processing technique for maximum accuracy. The real time maps were then evaluated at the ionospheric pierce points of the test observations and compared directly with those observations. Fig. 5 shows the RMS difference over 24 hours between the real time maps and the direct test measurements for all nine test sites. The RMS differences range from 9.5 cm to 23.5 cm. Note that the two worst cases (JPLM and QUIN) are the two sites farthest outside the 8-site real time network. With a 14-site real time network uniformly distributed, we can expect typical zenith accuracies of 20 cm or better. Some accuracy degradation (15%) is expected during most weak to moderate ionospheric storm conditions, although a factor of 2-3 degradation is possible for particularly severe storms, which may occur a few times per year [*Mannucci, et al.* 1997]. Accuracy may also degrade around solar maximum (year 2001) when vertical delays over the CONUS may be up to 7 times larger than currently. Testing under these conditions, however, has been performed using simulated data from a realistic ionospheric model. Those simulations predict that accuracies of 25 cm (RMS) would be achieved over CONUS, assuming a ground network of 24 receivers as proposed for WAAS (*Mannucci et al.*, 1995).




| | | |
|---|---|---|
| 1 | -3.30 | 0.47 |
| 2 | -1.58 | -2.33 |
| 3 | -4.44 | 1.40 |
| 4 | -6.15 | 2.33 |
| 5 | -4.35 | 2.33 |
| 6 | -4.98 | 1.86 |
| 7 | -1.92 | -0.93 |
| 9 | -5.52 | 5.12 |
| 10 | -1.93 | -1.86 |
| 14 | -2.52 | -2.33 |
| 15 | -2.11 | -0.93 |
| 16 | -0.63 | -2.33 |
| 17 | -1.59 | -0.47 |
| 18 | -5.18 | -0.93 |
| 19 | -3.09 | -3.26 |

| | | |
|---|---|---|
| 21 | -2.13 | -0.93 |
| 22 | -3.98 | 0.93 |
| 23 | -2.65 | -0.47 |
| 24 | -0.96 | -0.93 |
| 25 | -7.66 | 1.86 |
| 26 | -6.64 | 0.00 |
| 27 | -4.36 | 0.47 |
| 29 | -7.84 | 2.33 |
| 30 | -7.51 | 3.26 |
| 31 | -6.20 | 1.40 |

Accurate computation of ionospheric electron content from GPS data requires calibration of the L1/L2 interfrequency delay of each of the GPS satellite transmitters and ground GPS receivers. The GIM software is also used to extract each of these L1/L2 delays (relative to one receiver whose hardware should be calibrated for absolute determination) from the GPS tracking data as described in *Mannucci, et al.* 1995. In addition to the ionosphere calibration, the interfrequency biases are necessary for calibration of the GPS clocks ($T_{GD}$) by a single-frequency user[*Van Dierendonck, et al*, 1980].

Table 2 contains a complete set of absolute satellite biases ($T_{GD}$) obtained from GIM estimates, along with the current broadcast values. The satellite biases are expressed in nanoseconds at L1. The GIM estimates are 10-day averages of daily GIM runs using 98 GPS sites (of which ~60 contribute to improved global coverage). Repeatability of the biases is currently at the level of 0.2 ns at L1. Accuracy studies over several years (*Wilson et al.*, 1994) and comparions of GIM results to independent ionospheric measurements from the TOPEX dual-frequency altimeter (*Mannucci et al.*, 1995) indicate that the accuracy of the satellite biases is between 0.5 and 1 ns at L1. The current broadcast values are based onpre-launch measurements and differ quite markedly from the well-accepted values published by us and by other groups (*Sardon et al.*, 1993).

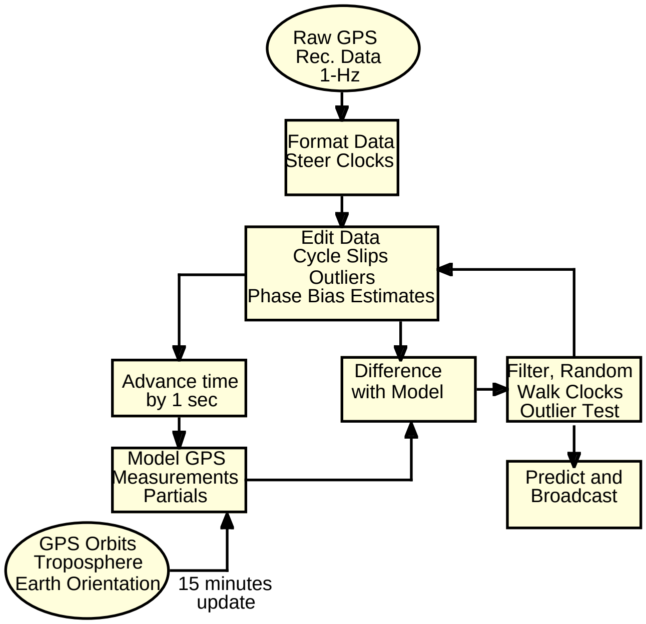
## Real- Time GIPSY (RTG)

GOA II is not a software suited to real-time processing at high data rates (1-Hz). In order to accommodate the high data rates of the 1-Hz range corrections, an enhanced software system called Real-Time Gipsy (RTG) was written in ANSI C. RTG'S original design goals included 1) incorporation of all the precise models of GOA II; 2) suitability for use in imbedded systems such as a GPS receiver (earth based or orbiting); and 3) real-time processing. For WADGPS applications, RTG is hosted on a UNIX workstation (HP, IBM, or Sun). It is also being adapted for implementation in WAAS for real-time computation of both the fast range corrections and the slow orbit and troposphere corrections. In addition, modules are also shared with the WAAS ionosphere prototype. RTG is also being used at JPL to perform real-time user positioning to validate WADGPS corrections. As discussed above, our current prototype is temporarily utilizing GOA II for the orbit and troposphere slow-rate WADGPS corrections and RTG for the fast range corrections. However, RTG is being updated for the slow orbit and troposphere corrections.

## 1-Hz Fast Range Corrections

For every satellite viewed by the network, a correction to the GPS range is computed every second. This correction is solved for as a correction to the GPS clock, which is estimated simultaneously with the receiver clocks . This allows for isolation and identification of error sources as GPS or receiver problems. Note that even over North America some orbit error is common to all the receivers viewing GPS and is absorbed by the GPS clock solution. For this reason we refer to it as a GPS range correction.

Fig. 6 is a block diagram of the process. Almost all of the computation can be carried out during the network communication process and thus the fast correction computation adds only about 2 msec to the latency of the corrections.


Raw GPS
Rec. Data
1-Hz
Format Data
Steer Clocks
Edit Data
Cycle Slips
Outliers
Phase Bias Estimates
Advance time
by 1 sec
Difference
with Model
Filter, Random
Walk Clocks
Outlier Test
Model GPS
Measurements
Partials
Predict and
Broadcast
GPS Orbits
Troposphere
Earth Orientation
15 minutes
update

one clock used as reference) are passed to the filter along with the appropriate data weight which was computed in the editor.

The mechanization of the Kalman filter uses a factored form (analagous to a square-root) of the covariance for numerical stability and is referred to as a UD filter [*Bierman, 1970*; *Thornton, 1976*]. The UD term comes from the factorization of the covariance matrix as $UDU^T$, where U is an upper triangular matrix and D is a diagonal matrix. The filter is a general purpose filter in which any parameter may be treated as a first order Markov process, including the limiting cases of white noise and random walks. For the fast correction process, the clocks are treated as random walks. Some tuning of the process noise characteristics was performed to enhance outlier detection in the filter (see dual-frequency point positioning discussion below). The final tuning used 1 $m/sec^{1/2}$ for the clock process noise on both the GPS satellite clocks and the receiver clocks.

Part of the UD filter mechanization is outlier detection through use of an innovations test. The innovations test merely compares the predicted residual based on the full covariance of the parameters and the data noise with the observed residual. A scaling factor in this comparison is also part of the filter input. The measurement is accepted if

$$r \le s \times \sqrt{p^2 + v^2}$$

$v$ is the data noise. A larger residual is rejected and not processed by the filter. In the fast correction process, if a measurement is rejected by the filter a cycle break will be inserted at that time in the data editor. An innovations scaling factor of 5 was used in the fast correction process. Table 3 shows a typical set of statistics accumulated after 5 hours of processing on Dec. 16, 1996.

**Table 3, Outlier detection by Receiver and GPS.**

| Receiver/ GPS | Number of Outliers Detected by Innovations Test | Number of Data Points | Percentage of Bad Points |
|---|---|---|---|
| LAJO: | 6051 | 85382 | 7.1 |
| RICH: | 3003 | 100183 | 3.0 |
| ORON: | 2498 | 96998 | 2.6 |
| HAVR: | 2597 | 99338 | 2.6 |
| ARCA: | 2650 | 101208 | 2.6 |
| STIG: | 2114 | 107089 | 2.0 |
| BEMI: | 1864 | 104072 | 1.8 |
| LINC: | 1440 | 98633 | 1.5 |
| ROSW: | 1364 | 111647 | 1.2 |
| FTPI: | 550 | 112108 | 0.5 |
| QUIS: | 388 | 109730 | 0.4 |
| GPS31 | 2604 | 22097 | 11.8 |
| GPS16 | 8403 | 121791 | 6.9 |
| GPS27 | 455 | 6696 | 6.8 |
| GPS22 | 6625 | 175692 | 3.8 |
| GPS33 | 2095 | 66396 | 3.2 |
| GPS40 | 37 | 1435 | 2.6 |
| GPS18 | 1446 | 111922 | 1.3 |
| GPS19 | 713 | 66956 | 1.1 |
| GPS29 | 2100 | 225854 | 0.9 |

Fig. 7 shows a typical set of corrections for all the PRN's in view by the network for 5 minutes. The values are typical of SA except for PRN15 which has SA off. During this period PRN15 was only observed by a few stations at the edge of the SATLOC network, resulting in slightly noisier corrections. The best observed GPS have formal errors on the corrections of around 10 cm whereas PRN15 had a formal error of about 50 cm.

### *Correction Broadcast and Prediction*

Due to the difference in time between the reception of the GPS data at the ground receivers and the arrival of the corrections based on those data at the user equipment, the corrections are predicted several seconds into the future.

Table 4 compares the results of two extrapolation strategies using phase data with pseudorange-fixedbiases. In each case, the extrapolated value of the GPS SA clock is compared to the truth case obtained with the filter/smoothed clock solution. The data were taken on May 21, 1993 at a 1-sec rate by a TurboRogue receiver using an ovenized crystal oscillator.

Quadratic extrapolation from six 1-sec solutions reduces the error by a factor of two compared to a linear fit. Therefore, the fast correction prediction with a quadratic extrapolation from six 1-sec solutions up to current time was adopted. Constant phase biases (determined by pseudoranges) are used over all six time points to maintain continuity and thus extrapolation accuracy.

**Table 4. Extrapolated SA Clock Errors**

| Extrapolation | No. of Points | Mean (cm) | Std. Dev. (cm) |
|---|---|---|---|
| Linear | 21396 | 0.01 | 8.7 |
| Quadratic | 21396 | 0.01 | 4.3 |

The degradation of accuracy for fast correction prediction can be estimated by comparing the results of user point positioning using direct and predicted fast corrections, as shown in Fig. 8. The 3-D RSS differerenceof 0.4±13 cm is well within the expected point positioning accuracy, indicating that the prediction process does not contribute significantly to the total user position error. Additional user positioning results are presented below.

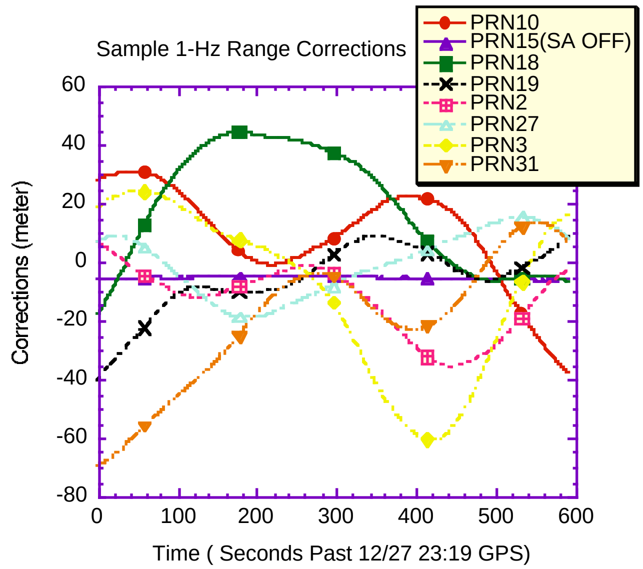
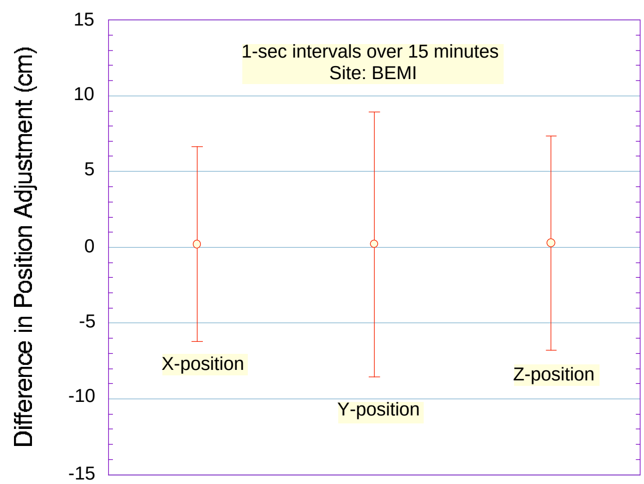



**Fig. 7, Ten minute sample of range corrections produced every second.**



m/sec$^{1/2}$ and an innovations scale factor of 5) and some results from the tuning process. Following the dual-frequency positioning results, we present single-frequency results, which test not only the accuracy of the fast correctors and orbits, but the accuracy of the ionospheric corrections and the calibration of the interfrequency biases on the GPS transmitters ($T_{GD}$). For both single and dual-frequency users, few decimeter accuracy is obtained.

Note that although we are positioning user receivers with the same data used to produce the fast corrections, the results are not overly optimistic due to the large size of the network. To demonstrate, a separate test run was made for the fast corrections eliminating BEMI, a station on the northern edge of the network, from the data stream. Both the single and dual-frequency user position solutions were compared with the solutions that used fast correctors that contained the BEMI data. The mean difference in each case was 5 cm with standard deviation of 4 cm.

## *Dual-Frequency Point Positioning*

Point positioning is performed with RTG. Corrected GPS orbits and GPS range corrections are read in and edited. Carrier phase data with the bias adjusted as in the fast corrections above is used. The model now computes the receiver clock partials and the partial derivatives of the receiver's position. These parameters are solved for as an unconstrained white-noise process in the filter at a 1-Hz rate. A nominal model is used for the troposphere zenith delay based only on the receiver's approximate height above the geoid. Since the position and clock are treated as a white-noise process, no innovations test is possible in the filter to detect outliers that pass through the data editor. We are currently developing improvements in the data editor to detect outliers that are now passing the editor. In these user positioning tests, the "users" were actually receivers in the ground network; since these "user" data must first pass through the entire communications network before being analyzed, they included data dropouts that would not be experienced in an actual user receiver. The point positioning is much more sensitive to these data dropouts than the fast corrections process; when the data drops out at a receiver for point positioning, the carrier phase bias must be re-estimated, with short-term impact on the solution, while for fast corrections a single-station dropout has little effect since many other stations' data are contributing to the computation. With an actual user where such dropouts are not experienced, somewhat better positioning results would be expected than are shown here.

In Fig. 9, we show the point positioning results from six of the stations where the range corrections were computed with our best filter strategy, 1 m/sec$^{1/2}$ process noise (random walk) and an innovations scale factor of 5. The point positioning is initialized at 3 min and 36 sec after the plot epoch. A few minutes are necessary for convergence of the carrier phase biases. The initial positioning thus has meter level accuracy; after convergence, accuracy is generally at the few decimeter level. Since most users would typically operate continuously, they would not be affected by the initial errors in positioning. The departure of positioning accuracy from the few decimeter level at points after initialization may be explained by two factors: 1) data gaps (arising in the communications network), and 2) pseudorange outliers (probably P2, see single-frequency results below). Data gaps should not be a factor for a user set, as noted above Pseudorange outliers could be a problem for a user, but should be detectable with an improved editor in the user equipment. . Note that in the fast correction process these outliers are straightforwardly detected and eliminated with an innovations test which is not possible with user point positioning treated as a white noise process. Fig. 10 (compare with Fig. 9) shows the poor positioning results when the innovations test for outliers in the fast correction process is too loose.

## *Single-Frequency User Position*

The single-frequency algorithm is essentially the same as the dual-frequency algorithm except that only single-frequency range and phase are used. The main change is in the data editor and its adjustment of the phase biases based on the range data. Before this adjustment is made, the data must be corrected for the ionosphere delay and the interfrequency bias in the GPS transmitters, eliminating the code carrier divergence. Since the ionosphere is smooth over several minutes, we may expect some improvement due to the lower data noise at the L1 frequency. Our current data editor merely does the ionosphere free combination for dual-frequency data at the 1-Hz rate resulting in noisier dual-frequency range used to perform the carrier phase bias determination. Some smoothing in time will be implemented in the future for dual-frequency data.

Fig. 11, shows the plot of single-frequency user positioning for comparison to Fig. 9. One can see the effects of decreased data noise on some of the plots. A close look at the single-frequency plots reveals a few small discontinuities which are not in the dual-frequency results. At least some of these are probably due to the discontinuous changes in the ionosphere nodal values in the sun-fixed frame occurring at the 15-minute updates. Overall one sees similar accuracy in the single and dual-frequency results, with few decimeter accuracy achieved most of the time.

## Summary, Conclusions

A prototype WADGPS capability has been developed and demonstrated. The system has shown user positioning accuracies for both single-frequency and dual-frequency receivers at the level of a few tens of centimeters in the continental United States, where real-time data have been available. The data processing software is being developed at the Jet Propulsion Laboratory and will soon be available in a compact software package written exclusively in ANSI c. This WADGPS software package is designed to be portable on a wide variety of workstation or PC platforms. The algorithms and system design make it ideal for applications with global networks as well as with smaller regional or continental networks.

The system will find initial commercial use in a WADGPS system developed by SATLOC for precision farming applications. The JPL WADGPS software is also being adapted for operational computation of real-time corrections to support aircraft navigation with the FAA WAAS. The implementation emphasizes the use of information in the GPS carrier phase for many aspects of the WADGPS correction computation. The high fidelity of the measurement, geodetic and dynamic models employed in the software enable the fast and slow corrections to be well separated, thus facilitating integrity monitoring. The software design will make the expansion from CONUS use to global application straightforward. Future enhancements currently being explored would improve global real-time user positioning accuracy to the sub-decimeter level.

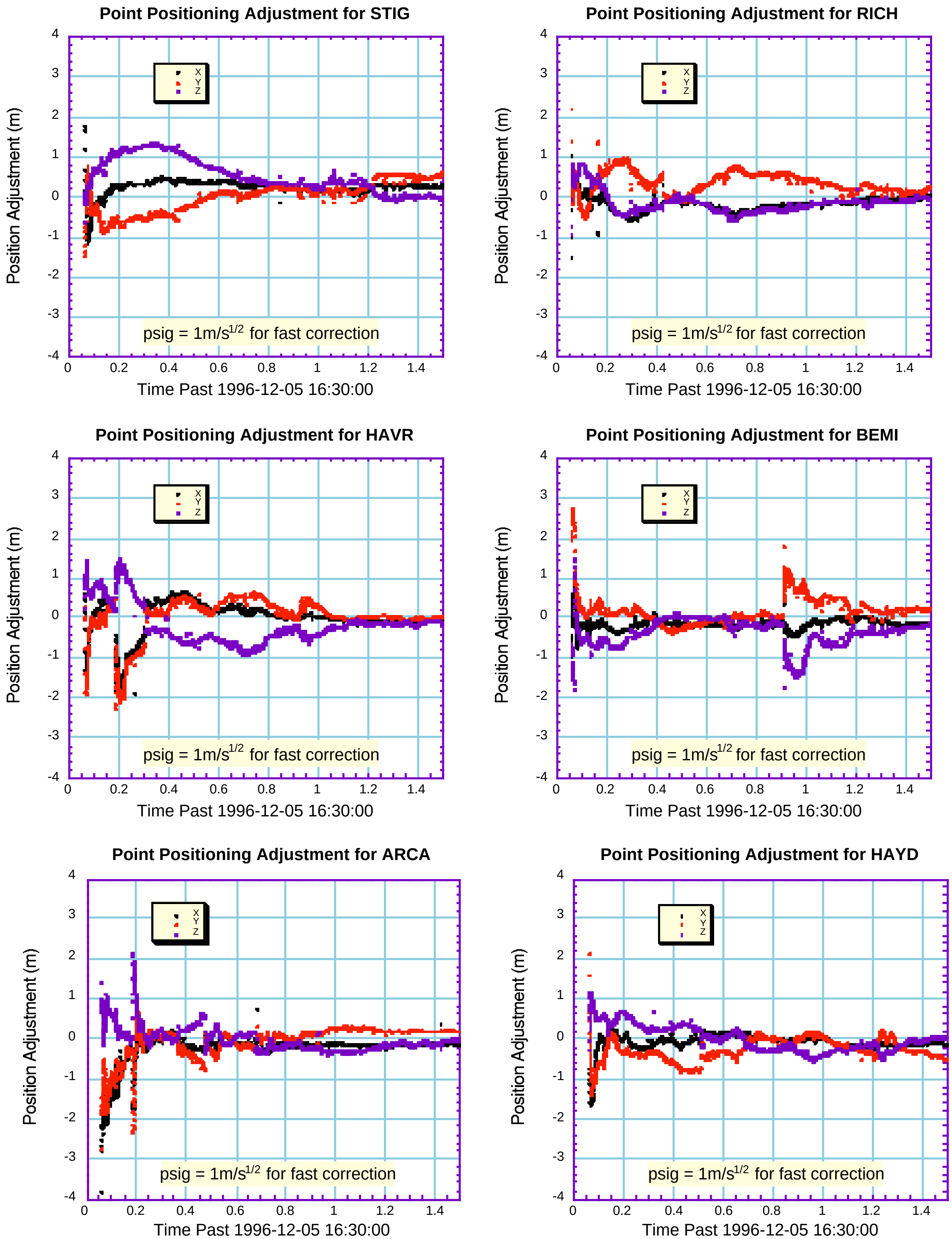



**Fig. 9, Dual frequency user positioning with a cold start 3 min and 36 sec (.06 hrs) after epoch.**

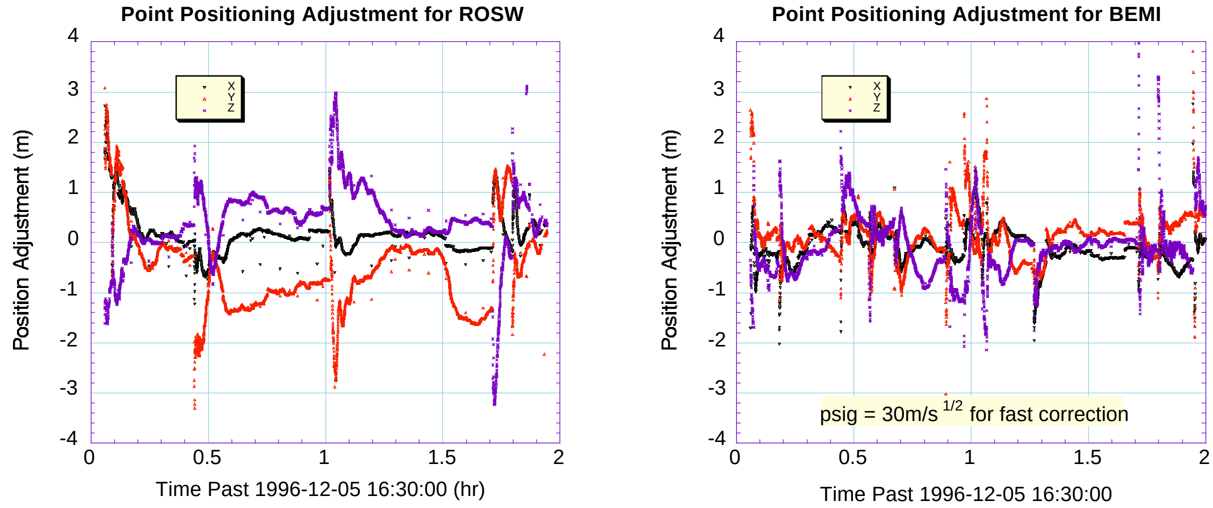
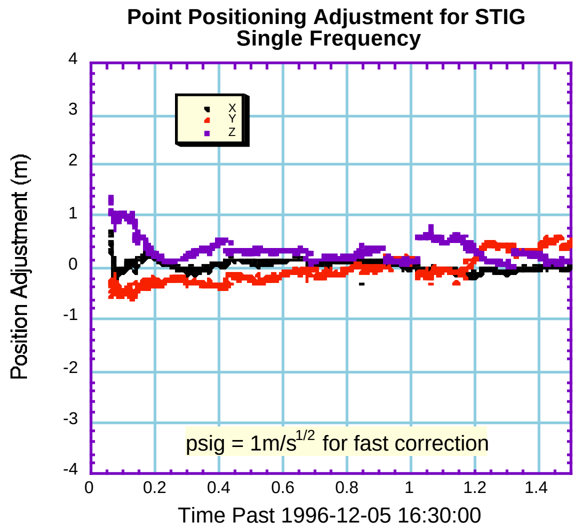
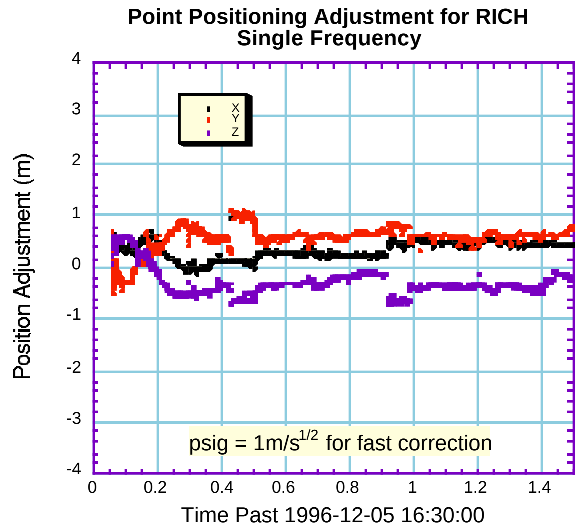
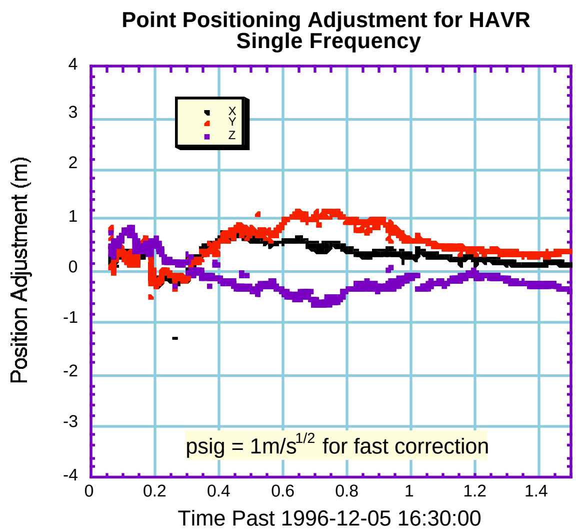
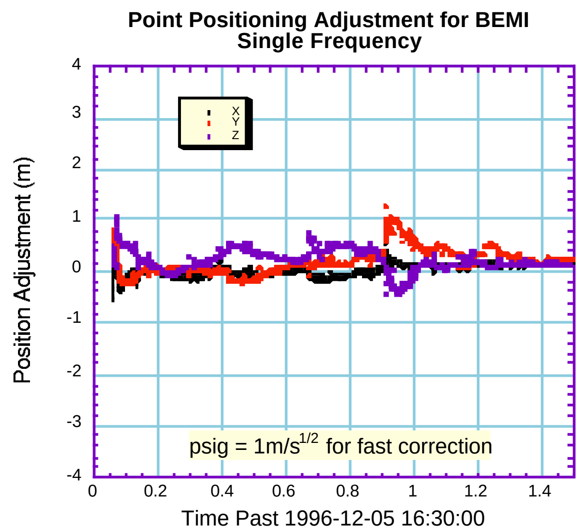


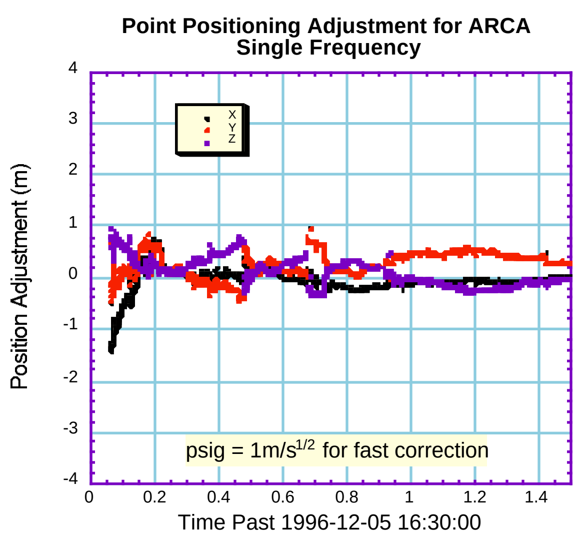

**Fig. 10 Positioning due to undetected outliers in the fast corrections. Innovations test is too loose.**

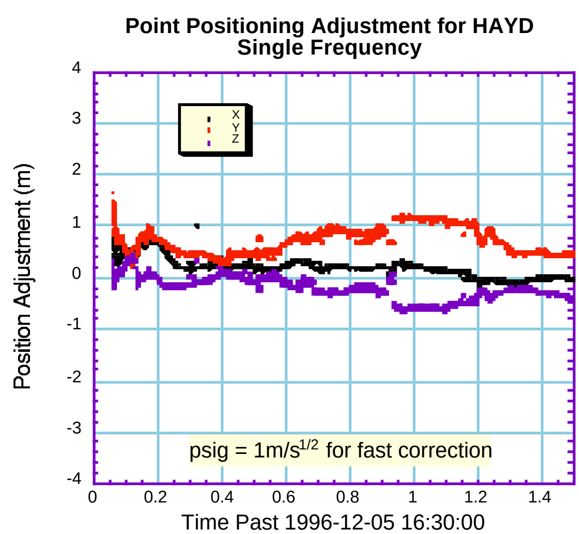

Point Positioning Adjustment for STIG
Single Frequency
X
Y
Z
psig = 1m/s1/2 for fast correction
Position Adjustment (m)
Time Past 1996-12-05 16:30:00


Point Positioning Adjustment for RICH
Single Frequency
X
Y
Z
psig = 1m/s1/2 for fast correction
Position Adjustment (m)
Time Past 1996-12-05 16:30:00


Point Positioning Adjustment for HAVR
Single Frequency
X
Y
Z
psig = 1m/s1/2 for fast correction
Position Adjustment (m)
Time Past 1996-12-05 16:30:00


Point Positioning Adjustment for BEMI
Single Frequency
X
Y
Z
psig = 1m/s1/2 for fast correction
Position Adjustment (m)
Time Past 1996-12-05 16:30:00


Point Positioning Adjustment for ARCA
Single Frequency
X
Y
Z
psig = 1m/s1/2 for fast correction
Position Adjustment (m)
Time Past 1996-12-05 16:30:00


Point Positioning Adjustment for HAYD
Single Frequency
X
Y
Z
psig = 1m/s1/2 for fast correction
Position Adjustment (m)
Time Past 1996-12-05 16:30:00

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