An Internet-Based Global Differential GPS System, Initial Results

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Biography

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 Orbiter and Radio Metric 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 development of wide area differential systems.

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 Orbiter and Radio Metric Earth 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.

Michael Lough obtained a Ph.D. in Applied Mathematics from the California Institute of Technology in 1995. Since 1997, he has worked in JPL's Orbiter and Radio Metric Systems Group. His current interests include the development of techniques for improving GPS-based precise orbit determination (POD) strategies for low-Earth orbiters as well as the development of real-time tools for GPS analysis.

David A. Stowers obtained his B.S. in Electrical and Computer Engineering from California State Polytechnic University, Pomona in 1985. Mr. Stowers is a member of the Satellite Geodesy and Geodynamics Systems group at the Jet Propulsion Laboratory (JPL). The group's responsibilities include the operation of NASA's stations in the Global GPS Network. Recent activities include development of applications for handling high-rate GPS ground station data.

Danan Dong received Ph.D degree in geophysics at the Massachusetts Institute of Technology. He is currently a Member of the Technical Staff in the Satellite Geodesy and Geodynamics Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL is focused on the development of global GPS network operation software, and the application of GPS on tectonics.

Abstract

Using a network of 15 global GPS receivers, GPS data is returning to JPL via the open Internet to determine the orbits and clocks of the GPS constellation in real-time. Corrections to the broadcast orbits and clocks are currently communicated in real-time to the user over the open Internet via a TCP server. Tests of user positioning show real-time RMS accuracy of ~10 cms RMS in horizontal and < 20 cms RMS in the vertical.

Introduction

The JPL architecture for a GPS global real-time differential system was first put forward by Yunck et al. [*1995, 1996*]. A commercial North American Wide Area Differential GPS (WADGPS) system based on the JPL architecture and software was implemented in 1997 [*Whitehead et al. 1998; Bertiger et al. 1998*]. In 1996 the Federal Aviation Administration (FAA) selected the JPL architecture and software for their prototype Wide Area Augmentation System (WAAS). The core GPS corrections are computed with the Real-Time Gipsy (RTG) software licensed from JPL. WAAS as well as all other existing differential systems are optimized for users with a single-frequency GPS receiver. These receivers are susceptible to large, unmodeled ionospheric delays. In order to compensate for this error source, these differential systems employ a dense network of reference stations over their service area (for example, WAAS uses 24 reference stations over the continental US), and produces maps of the total electron content (TEC) which are transmitted to the users. In contrast, many of NASA's projects are global in nature and demand the highest possible accuracy. This system addresses the issues of accuracy and global coverage.

To address the issue of global coverage, we took advantage of the NASA Global GPS Network (GGN), which is operated and maintained by JPL. The GGN consists of approximately 50 sites which are already operated in batch mode over the Internet [*http://igscb.jpl.nasa.gov*]. To return data in real-time a new software set, Real-Time Net Transfer (RTNT), was developed. Data at a 1 Hz sample rate is currently returned with a latency of < 1.5 seconds using the open Internet. Better than 95% of the data is returned in less than 3 seconds from a network of 15 global receivers. We expect to expand the network to 30 real-time sites over the next 6 months. This will increase accuracy and reliability through redundancy.

The system has been optimized for dual-frequencyusers. Tests of user positions currently show 10 cms RMS accuracy in the horizontal and 20 cms RMS accuracy in the vertical.

The global differential corrections are packaged into a 560 bit/sec message, and can be made available on the open Internet via a TCP server running at JPL.

Enabling Software

RTG (Real-Time GIPSY)

RTG provides real-time estimates of the dynamic GPS orbits, and one-second GPS clocks [*Bertiger et al. 1998]*. Orbit estimates are needed less frequently than the clocks due to their slower varying physical behavior. RTG contains many of the precise models contained in JPL's GIPSY OASIS II (GOA II) software. GOA II has a long history in precise orbit determination of GPS and other spacecraft equipped with GPS receivers [*Muellerschoen, 1994,1995*; *Bertiger,1994*; *Gold,1994*; *Haines,1994*], and in precise GPS geodetic applications [*Heflin,1994*; *Argus,1995*]. Post-processing of global GPS data with GOA II routinely yields better than 10 cms GPS orbits.

Additionally, RTG has been embedded in real-time user equipment for flight on the X33 sub-orbital vehicle, and has flown on the NASA DC-8 SAR flights [*Muellerschoen and Bertiger, 1999*].

RTNT (Real-Time Net Transfer)

RTNT returns 5 of the 6 GPS data types: CA range, P1 and P2 ranges, and P2 phase, and either the P1 or CA phase, plus signal to noise ratios. The data is edited, smoothed, phase breaks detected, andcompressed down to 21 bytes/GPS, with 17 bytes of overhead needed for time-tag, site id, nav solution, sequence number, and status flags. A remote site tracking 10 GPS satellites would then transmit over the open Internet 227 bytes/sec to a central data daemon. Additionally,the broadcast ephemeris is included in this transmission when new iode/iodc numbers are observed.

For improved reliability, the central data daemon keeps track of the sequence number of these packets from each remote site, and may request up to 3 retransmissions of missed data epochs. The central data daemon may have a twin data daemon running on another computer. The central data daemon relays all of its incoming GPS data to its twin also via socket communications. Should the twin no longer see any data flow, it will send out a request to the entire global network to request re-routing of the real-time data to itself. It would then serve as the central data daemon until the primary daemon is brought back on-line. It is also possible to chain these data daemons, in order to export the real-time GPS data to any other computer on the open Internet, and even merge streams from various data daemons or additional receivers.

The remote sites minimally have a dual-frequency GPS receiver, a PC running linux operating system, and connectivity to the open Internet. RTNT currently supports the data streams from Ashtech Z-12, Turbo-Rogue, and AOA-ACT Benchmark GPS receivers. A particular data daemon running on a PC at the remote site establishes communications with the receiver through its serial port, and places the data in a revolving buffer of shared memory. A second process that is independent of receiver type, reads this shared memory and opensa socket connection to the central data daemon. The data is checked and flagged for phase breaks, and thensent out the socket. In addition, "soc" files are constructed which contains the socket packets, and can be saved for later batch retrieval. Conversion routines are available from "soc" files to standard rinex files or turbo-binary format. Turbo-binary can then be converted to rinex files with for example TEQC [*Estley, Meertens 1999*].

System Overview

Data Collection

Fig. 1, shows a map of the current real-time receiver network. The coverage is clearly not very well distributed but is expected to improve in the near future. Data returned includes dual-frequencyphase measurements with a resolution of 0.02 mm, and dual-frequency range measurements with a resolution of 1 mm, the receivers solution for its time, and broadcast ephemeris information. At the central processing site, these data are collected by another RTNT process which monitors the state of the whole system. This central data daemon sorts the data according to timetag, rejects duplicate transmissions, and at a specified drop dead time, outputs all the data at a common epoch into a circular buffer of shared memory.

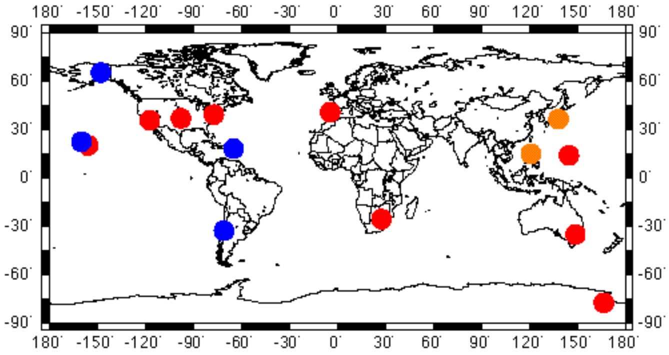

Figure 1.) Network of dual-frequency GPS receivers returning data to JPL in real-time. Current network consists of 4 AOA-ACT Benchmarks, 2 Turbo-Rogues, and 9 Ashtech Z-12s.

Data Latencies

Fig. 2, shows a plot of typical latencies from the turbo-rogue site in the Philippines, and from the Ashtech site in Tidbinbilla, Australia. The spikes in the Philippines graph are requests for retransmission of missed data epochs. The 0.1 second scatter in the floor of these plots is a consequence of an imposed sleep state at the remote sites so as to minimize CPU usage on the PCs.

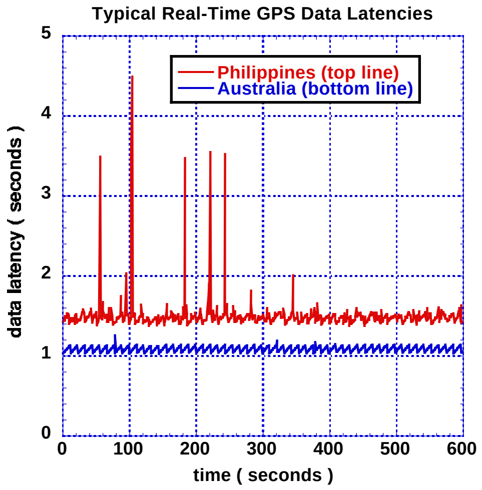

Figure 2.) Data latency is the difference between the GPS timetag of the data and the central collecting computer's system time.

Data Reliability

Table 1, shows the percentage of 1-second data obtain from the Philippines site for a 6 hour period. After 3 seconds, 97% of the data has arrived at the central data daemon. The Philippines is one of the more difficult sites since it may require at times 25 hops across gateways in order for the data to reach JPL.

X	percent of data epochs received from the Philippines in less the X seconds.
2 second	93.4 %
3 seconds	97.0 %
4 seconds	97.7 %
5 seconds	97.9 %
6 seconds	98.0 %

Table 1.) Percentage of GPS data epochs successfully returned from the Philippines site to JPL.

Orbit Determination and Clock Estimation

RTG reads the shared memory output of the central data daemon process. Orbit and troposphere estimates at the reference stations are computed once perminute by RTG's "slow" process. These corrections are then placed into another revolving buffer of shared memory so that they may be read by the clock correction process known as "fast". Clock corrections are computed every second by fast.

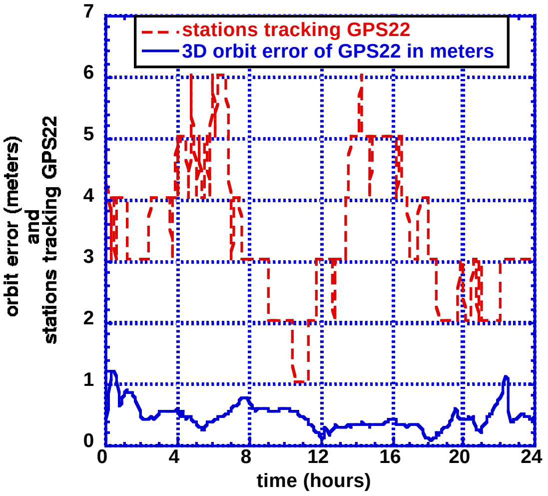

Figure 3.) RSS 3-D orbit errors for GPS22 for a 24 hour period with RTG and a 15 station global network.

Fig. 3, shows GPS 22 orbit errors for a 24 hour period. Even when the GPS s/c is poorly tracked as in the middle of the day, orbit errors are still held in check due to the dynamic/predictable nature of the orbits. The real-time orbit represented in Fig. 3 does not yet include dynamic partials for solar scale factors and y-bias parameters. These partials are in the RTG integrator and we are in the process of tuning the stochastic attributes of these parameters. Also, the orbit integrator at this time did not include the effects of solid earth tides, pole tides, or ocean tides. These models have decimeter to centimeter level effects on the orbits. These tide models have been coded and are currently undergoing testing.

Global Differential Correctors

Orbit and clock estimates are differenced with the broadcast ephemeris and broadcast clock. Corrections to these broadcast elements are packaged into a 560 bit message. Each message contains 4 orbit solutions, 4 meter level clocks, and 32 cm level clock corrections. It takes 8 seconds then to initialize all 32 prn orbit and clock estimates. The total clock correction is the sum of meter level clock and the cm level clock corrections. The resolution of the clock corrections is 1.5625 cms. This is 4 times better than the resolution of the Satloc corrections and 8 times better than the resolution of the WAAS corrections. The orbit correction resolution is 6.25 cms which is the same for Satloc and WAAS. iode/iodc ephemeris changes are held until 2 minutes has past when new iode/iodc's are observed. This gives the user sufficient time to accumulate the newest ephemeris message.

User Point Positioning Tests

To test the accuracy of these global differential GPS correctors, we point position stationary GPS receivers at known locations. The same RTG s/w used on the DC-8 flights [*Muellerschoen, Bertiger 1999*] is used with the global differential GPS correctors obtained through a socket connection from the TCP server.

Fig. 4, shows a plot of kinematic positioning of a static user at JPL. The large variations at cold start indicates that the phase biases have not been well determined due to multipath. After about 10 minutes, the graphs settle down as mulitpath is averaged over time. In this particular plot, after 30 minutes, there remains a -28 cm bias in the East component. This is due to the GPS orbits at this point in time not yet being well determined by RTG. As more stations are added to the system and with the assistance of dynamic partials for solar scale and y-bias parameters, these biases are expected to be reduced to below the 10 cm level.

Table 2, shows a later result of positioning a dual-frequecy receiver in the state of Florida with the global real-time corrections. The 40 cm RMS vertical error can be attributed to troposphere error correlating with the vertical component. For slowly moving real-time users such as trucks, ships, and farm equipment a troposphere parameter can be estimated. Estimating a zenith troposphere delay as a slowly varying stochastic parameter reduces the vertical to under 20 cms RMS. This is indicated in Fig. 5.

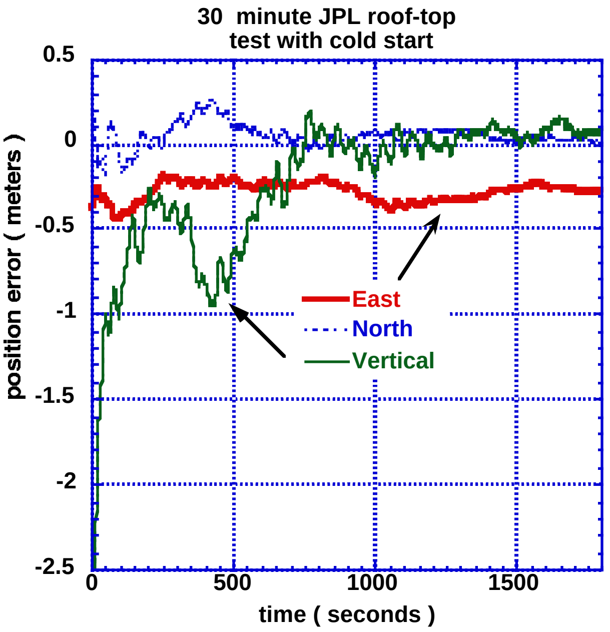

Figure 4.) 1-Hertz positioning of a static receiver at JPL with global differential corrections.

	Mean	Sigma	RMS
East	-0.04	0.12	0.13
North	0.00	0.06	0.06
Vertical	0.21	0.31	0.37

Table 2.) Results of 10 hours of 1-Hertz positioning of static receiver at Fort Pierce, Florida with global differential corrections. No zenith troposphere parameter is estimated. Units are in meters.

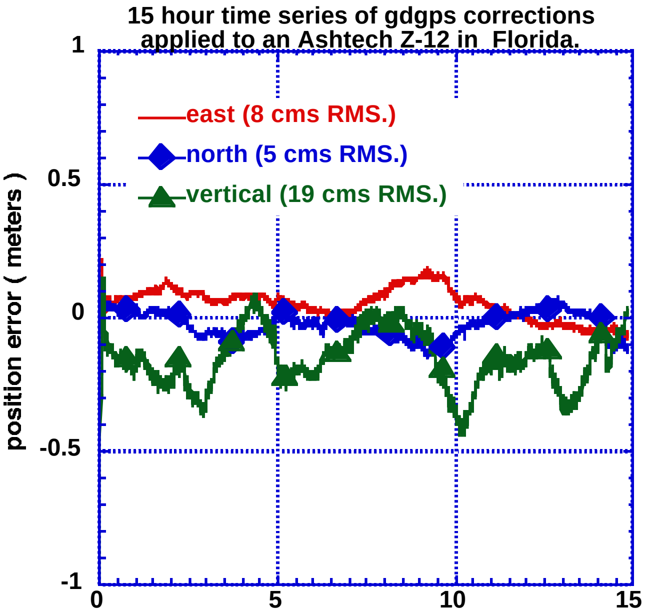

Figure 5.) Results of 15 hours of 1-Hertz positioning of a static receiver at Fort Pierce, Florida with global differential corrections. Estimating a zenith troposphere parameter reduces the vertical error to under 20 cms RMS.

Summary

The open Internet is a reliable choice to return GPS data for a state-space dual-frequency global differential system. Initial results suggest 10 cms horizontal accuracy and 20 cms vertical accuracy are achievable. As more stations come on line and with better orbit modeling, horizontal errors are expected to be further reduced.

Acknowledgments

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.

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