DYNAMIC POSITIONING CONFERENCE
October 17 – 18, 2000

SENSORS

Marine Benefits from NASA's Global Differential System: Sub-Meter Positioning, Anywhere, Anytime

Yoaz E. Bar-Sever

Jet Propulsion Laboratory
California Institute of Technology

Overview

Precise real-time, onboard knowledge of a platform's state (position and velocity) is a critical component in many marine applications. This article describes a recent technology development that provides a breakthrough in this capability for platforms carrying a dual-frequency GPS receiver – seamless global coverage and roughly an order of magnitude improvement in accuracy compared to state-of-the-art.

Our reference network is a subset of NASA's Global GPS Network (GGN), consisting of geodetic quality dual-frequency receivers. Using novel internet-based technology for editing and real-time streaming of data from the GGN as input to a real-time orbit determination software, JPL's new global differential system has demonstrated ~10 cm horizontal and ~20 cm vertical real time positioning accuracy for a ground-based dual-frequency GPS receiver [Muellerschoen et al., 2000]. This performance is roughly an order of magnitude better than any differential service currently available. Although a number of private and government organizations provide localized real-time positioning services to users on or near the ground, a global system such as demonstrated here, capable of supporting global users far away from any ground reference site, has never been achieved nor attempted due to the perceived technical and cost challenges.

This technology will enable NASA to provide cm level onboard, real-time orbit determination for Earth orbiting satellites, and 10 cm level real-time positioning accuracy for air-borne, ground, and marine platforms anywhere in the world. The system provides seamless global coverage, with uniformly valid GPS correction messages. The technology carries broad benefits to society in general as it revolutionizes our ability to sense and respond in a timely manner to natural hazards such as earthquakes and volcanic eruptions.

The dissemination of the differential corrections to authorized users is currently enabled with specially developed internet tools. An effective global communications systems that will relay the differential corrections to a users anywhere on the ground and in space is currently under development.

System description

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 by SATLOC (a commercial company) primarily for the agricultural market [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 system has been installed in the FAA's National Satellite Testbed (NSTB), and is scheduled to become operational in 2001. WAAS provides GPS differential corrections for users in the continental United States (CONUS). The WAAS and SATLOC systems, as well as every other existing differential system are optimized for users carrying 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 produce maps of the total electron content (TEC), which are transmitted to the users. Residual ionospheric errors, and a variety of other error sources yield an overall user positioning accuracy not better than 1 m RMS and sometimes much larger than that. There are no differential services that cover the entire globe, and there are no differential services capable of supporting spaceborne users.

Our new system is geared toward users carrying dual-frequency receivers, such as are flown on a wide variety of remote sensing, low Earth orbiter missions, and are prevalent in the high-end marine market. These high-end users typically require high-accuracy positioning. Having eliminated the ionosphere as an error source using dual-band receivers, these users are still susceptible to errors in the GPS ephemerides and clocks. Ground-based users and aircraft must also deal with errors due to the troposphere. Accurate correction for the GPS ephemeris and clock errors requires a network of GPS reference sites. Zumberge et al. [1997] demonstrated that a well-distributed global network of about a dozen sites is sufficient for continuously providing GPS ephemeris and clock corrections for GPS satellites. We have taken advantage of the NASA Global GPS Network (GGN), which is operated and maintained by JPL. The GGN consists of approximately 60 sites which have traditionally been operated in batch mode [*http://igscb.jpl.nasa.gov*].

The breakthrough in our capability came in the form of a new software set, Real-Time Net Transfer (RTNT), designed to return GPS data in real time from remote receivers. RTNT collects, edits, and compresses the raw GPS observables at the remote site. It then transmits the packetized data over the open Internet to the processing center. At the processing center the global data is analyzed by the real time orbit determination software, RTG, to produce precise GPS orbits and clocks. These are formatted as corrections to the GPS broadcast ephemerides, encoded, and are provided over the internet to authorized users. The combined software set was named IGDG (Internet-based Global Differential GPS). IGDG has won the NASA Software of the Year 2000 Award [http://www.hq.nasa.gov/office/codei/swy2000win.html]. A detailed description of the two major software modules of IGDG now follows:

RTNT (Real-Time Net Transfer)

The remote sites minimally have a dual-frequency GPS receiver, a PC running linux operating system, and connectivity to the open Internet. A receiver-specific data daemon running on a PC at the remote site establishes communications with the receiver through its serial port, and places the raw GPS data (phase and range) in a revolving buffer of shared memory. A second process that is independent of receiver type, reads this shared memory and opens a socket connection to the central data daemon. The data is checked and edited, and then sent out the socket. This is a critical step because certain percentage of the data is lost in the transmission over the Internet (see below), which makes data editing at the processing center impossible. A remote site tracking 10 GPS satellites transmits over the open Internet 227 bytes/sec to a central data daemon. At the central processing site, the transmitted 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.

Reliability is a key consideration in an operational differential service. For improved reliability, the central data daemon keeps track of the sequence number of packets that arrive from each remote site, and may request up to 3 retransmissions of missed data epochs. A unique architecture of fully redundant processing centers guarantees continuous service even if one processing center unexpectedly goes down. The central data daemon has a twin data daemon running on another computer. The central data daemon relays all of its incoming GPS data to its twin 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 global differential corrections produced by RTG are packaged into a 560 bit/sec message, and can be made available on the open internet via a TCP server running at JPL.

RTG (Real-Time GIPSY)

RTG provides real-time estimates of the dynamic GPS orbits, and one-second GPS clocks [*Bertiger et al. 1998]*. RTG contains many of the precise models of the GIPSY OASIS II (GOA II) software. GOA II has a long history in precise orbit determination of GPS and other spacecraft, and in precise GPS geodetic applications. Post-processing of global GPS data with GOA II routinely yields better than 10 cm GPS orbits.

Orbit estimates are needed less frequently than the clocks due to their slower varying physical behavior. RTG reads the shared memory output of the central data daemon process. Orbit and troposphere estimates at the reference stations are computed once per minute 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, which produces corrections at 1 Hz.

RTG is also used for onboard, autonomous user positioning. It 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*]. In this mode RTG ingests the correction message as well as the raw GPS data from a given receiver and provides precise estimates of the user position. For users with known dynamics (such as spacecraft), it performs orbit determination. For users with unknown dynamics (vehicles, airplanes), it provides kinematic positioning.

Results

Currently real time data is returned to JPL from 18 out of the 60 GGN sites (Figure 1). GPS data at 1 Hz are returned with a latency of < 1.5 seconds using the open Internet. Better than 95% of the data are returned in less than 3 seconds (Figure 2). The GPS orbit and clock are estimated, and then differenced with the broadcast ephemeris and clock. The corrections, which are being produced routinely at JPL since November 1999, can be automatically distributed via the Internet to authorized users.

To test the accuracy of these global differential GPS correctors, we point-position stationary GPS receivers at known locations. The point-positioning is carried out at 1 Hz, and is completely insensitive to the dynamics of the user. Here RTG is used with the global differential GPS correctors obtained through a socket connection from the TCP server. Comparing the kinematic positioning of a static user with its post-processed location shows 19 cm RMS vertical error and less than 10 cm horizontal error (Figure 3). Most of the positioning error is believed to be due to GPS orbits error caused by sub-optimal network coverage. GPS orbit errors are expected to improve as more GGN sites are upgraded to provide data in real time. Indeed, this performance constitutes a significant improvement over the 40 cm RMS error in AirSAR positioning using differential corrections based on SATLOC's CONUS-only network [*Muellerschoen and Bertiger 1999*]. Consequently, we anticipate 10 cm positioning accuracy with a network of 20 sites. A continuous real time demonstration of the positioning performance of IGDG, and other relevant information, is available at [http://gipsy.jpl.nasa.gov/igdg].

Any additional constraints that can be imposed on the point-positioning due to known dynamics will tend to improve the accuracy. In particular, marine applications with its relatively benign dynamics could realize sub-10 cm accuracy in all components with properly optimized estimation strategy.

Because our differential system is based on state-space, the performance of the system is not depended on the geographic location of the user. This is of particular importance in Marine applications where often the user is far from land-masses. Alternative differential systems, which are optimized for single-frequency users penalize the user for being far away from the reference network, which is typically localized on the nearest land mass.

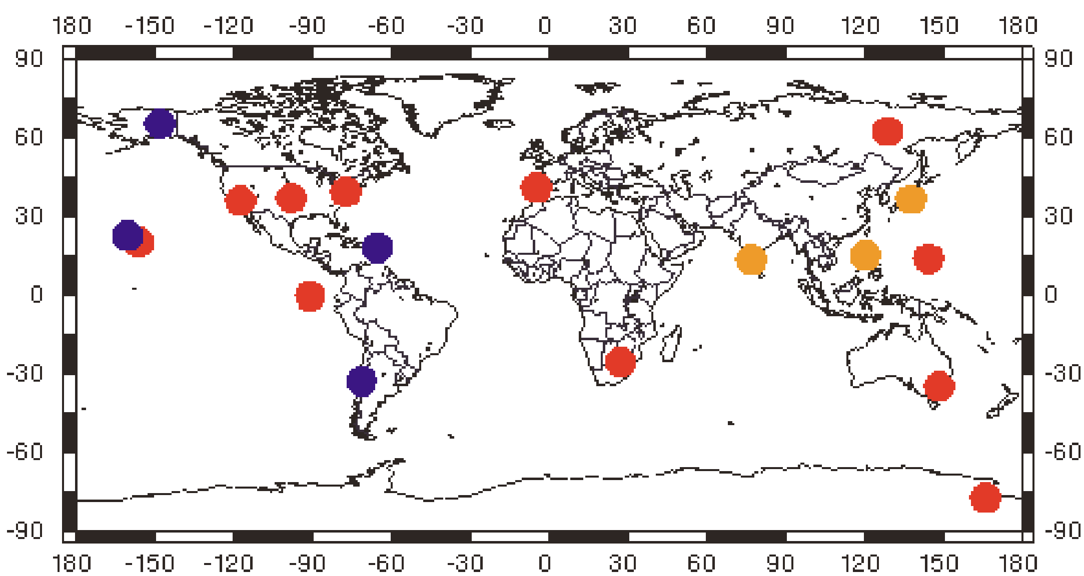

Fig. 1. Network of dual-frequency GPS receivers returning data to JPL in real-time.

Return to Session Directory ►

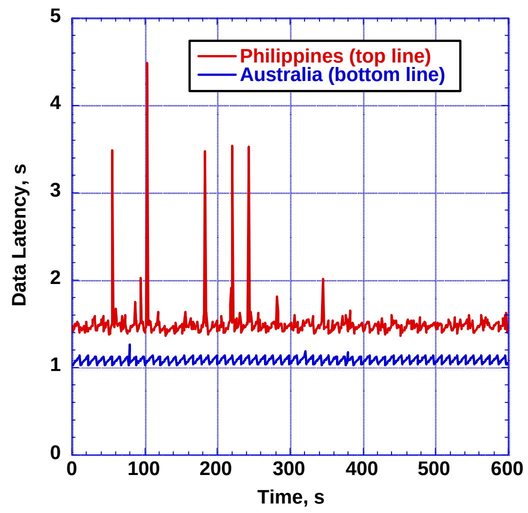

Fig. 2. Data latency is the difference between the GPS timetag of the data and the central computer's system time. The spikes in the Philippines graph are requests for retransmission of missed data epochs.

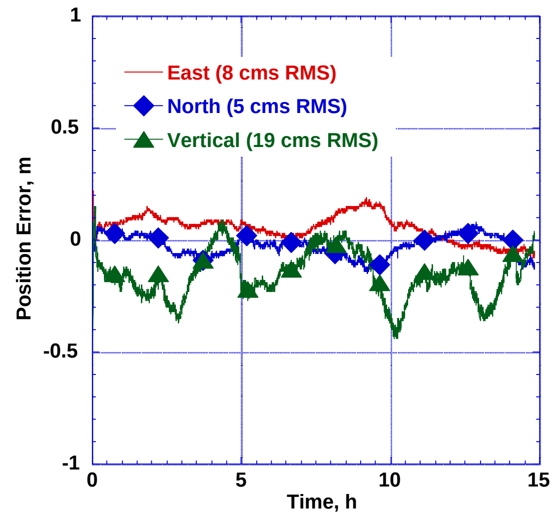

Fig. 3. Results of 15 hours of 1-Hertz positioning of a static receiver at Fort Pierce, Florida with global differential corrections.

Future plans

The accuracy and coverage of our GDGPS system is currently without parallel. However, many improvements remain to be realized. Most important is the densification of the real time network to provide the redundancy that is required by an internet-based architecture. The real time network is expected to grow to 25 sites in 2001. Various components of the system may be tuned for optimal performance in specific configurations. We are working to optimize the real time GPS orbit determination strategy as the size of the real time network grow, and to optimize the user positioning strategy for specific applications, such as orbit determination, airborne, and marine.

We are currently developing a global dissemination system and compatible end-user equipment that will complete an end-to-end global positioning system.

References

Bertiger, W.I., Y. E. Bar-Sever, B. J. Haines, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoen, T. N. Munson, A. W. Moore, L. J. Romans, B. D. Wilson, S. C. Wu, T. P. Yunck, G. Piesinger, and M. Whitehead, “A Real-Time Wide Area Differential GPS System,” *Navigation: Journal of the Institute of Navigation*, Vol. 44, No. 4, 1998, pgs. 433-447.

Muellerschoen, R.J., Bertiger, W. I., Flight Tests Demonstrate Sub 50 cms RMS. Vertical WADGPS Positioning, Proceedings of ION GPS-99, Nashville, Tenn. September 1999.

Muellerschoen, R.J., W.I. Bertiger, M.F. Lough, D. Stowers, and D. Dong, An internet-based global differential GPS system – initial results, Proceedings of the ION National Technical Meeting, Anaheim, CA, January, 2000.

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

Yunck, T.P., Y. E. Bar-Sever, W. I. Bertiger, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoen, T. N. Munson, L. Romans, and S. C. Wu, "A Prototype WADGPS System for Real Time Sub-Meter Positioning Worldwide," Proceedings of ION GPS 96, Kansas City, Kansas, September, 1996.

Zumberge, J.F., M.B. Heflin, D.C., Jefferson, M.M. Watkins, and F.H. Webb, "Precise Point Positioning for the Efficient and Robust Analysis of GPS Data From Large Networks", *J. Geophys. Res., 102* [B3], pp 5005-5017, 1997.