The NASA's Global Differential GPS System – Present and Future

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Abstract-After three years in development, the NASA Global Differential GPS (GDGPS) system has accomplished and surpassed all its stated goals. Funded under NASA's Advanced Information Systems Technology (AIST) Program, the system combines innovative software and hardware components with advance internet technology to provide end-to-end capabilities for autonomous, real-time orbit determination, time transfer, and positioning, with an unprecedented level of accuracy and availability. The developed system has matured into a highly reliable operational prototype, and has repeatedly demonstrated 10 cm level accuracy for real-time positioning, orbit determination and time transfer on the ground, in the air, and in space. The profound benefits from these new capabilities extend well beyond NASA, into the civil, commercial and defense sectors.

In this article we describe the developments in the third and last year of this effort, and discuss the current status of the system and its potential future evolution.

INTRODUCTION

Precise real-time, onboard knowledge of a platform's position and velocity is a critical component for a variety of Earth observing applications. Examples of such applications include ground, airborne and spaceborne monitoring of natural hazards where accuracy as well as latency are of the essence, as in the case of the determination of the spatial distribution of motions before, during, and after major earthquakes. The benefits extend to any mission that currently requires any kind of post-processing for positional accuracy. These missions range from satellite remote sensing to aerogeophysics, to in situ Earth science on land and water. A variety of free-flyers – ocean altimeters, laser and synthetic aperture radar (SAR) mappers, multispectral imagers – seek orbit accuracies from centimeters to decimeters. While for many it is not needed in real time, the ability to achieve such accuracy autonomously on-board would allow mobile science instruments worldwide to generate finished products in real time, ready for interpretation, with enormous savings in analysis cost and toil. Many Earth observing platforms will also benefit from intelligent autonomous control enabled by precise real time positioning. Possibly the most stringent positioning requirements come from the airborne SAR group at JPL, which would like to control aircraft flight path in real time to at least a meter, and ultimately to a few centimeters. The scientific appeal of seamless worldwide positioning offering post-processing performance in real time can hardly be overstated. Countless other navigation, commercial, and safety services, such as aircraft navigation, geolocation, fleet management, excavation, search and rescue, to name just a few, that are currently available only in infrastructure-rich regions could readily be extended to any part of the world, with no performance degradation and little to no marginal cost.

Funded by the Earth Science Technology Office under the Advanced Information Systems Technology Program, we have set out to develop and demonstrate a GPS-based technology that will enable Earth-orbit satellites, airplanes, and terrestrial systems to achieve unprecedented levels of real-time positional accuracy, anywhere and at any time. The system promises a few centimeters-level accuracy for applications with largely predictable dynamics, such as some satellites in Earth orbit. For kinematic applications, such as airplanes and terrestrial vehicles, the system delivers 10 - 20 cm accuracy. In developing such a breakthrough capability we are leveraging the significant investment NASA has made in its Global GPS Network (GGN), as well as the government investment in the Wide Area Augmentation System (WAAS) technology developed at JPL.

SYSTEM DESCRIPTION

The fundamental tenet of NASA's Global Differential GPS System architecture is a *state-space* approach, where the orbits of the GPS satellites are precisely modeled, and the primary estimated parameters are the satellite epoch states. This approach guarantees that the corrections will be globally and uniformly valid. The system is geared toward users carrying dual-frequency receivers. The promise of a second and possibility third civilian GPS frequency will make dual frequency operation a common feature within a few years. Having eliminated the ionosphere as an error source, these users are still susceptible to errors in the GPS ephemerides and clocks. Ground-based users and aircraft must also cope with tropospheric delay effects. Accurate corrections for the GPS ephemeris and clock errors require a network of GPS reference sites. Our reference network is a subset of the NASA Global GPS Network, which has been converted to provide streaming GPS data over the open internet. At present, GPS data at 1 Hz are returned from 35 GGN sites, with 25 additional sites contributed by several Government and commercial partners (Fig. 1). The average latencyis less than 1.5 seconds. Multiple operation centers can process the data in parallel to provide redundant capability for generation of precise orbit and clock solution.

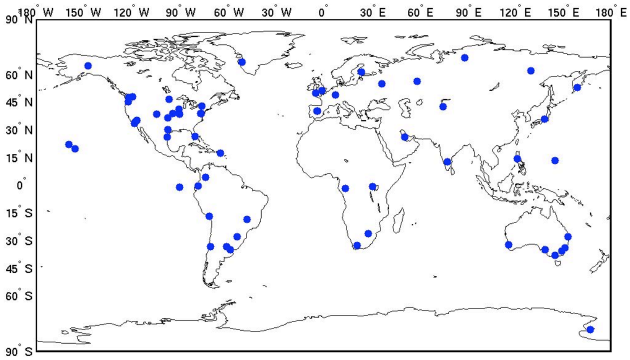

Fig. 1. the network of dual-frequency GPS receivers returning data to JPL in real-time as of May 2003.

At the heart of the operations center is the GPS orbit determination process, where the Real Time GIPSY (RTG) software ingests the streaming GPS data and generates real-time estimates of the dynamic GPS orbits, one-second GPS clocks, and tropospheric delay estimates for each reference site [1]. The estimated GPS orbits and clocks are differenced with the GPS broadcast ephemerides to form the global differential corrections. The differential corrections are then optimally packed to allow for efficient relay to the users.

The correction data stream is made available to authorized users via several communication channels. The first is the open internet, where a user can connect to a TCP or UDP server running at the processing center. Remote users can establish such a connection through a broadband hookup (e.g. Ethernet), or through telephony, including wireless telephones such as provided by the Iridium system. An additional disseminations system was developed together with a commercial partner, Navcom Technology Inc., a Division of John Deere. The system uses three Inmarsat geosynchronous communications satellites to relay the correction messages on their L-band global beams. The three satellites (at 100˚ W (Americas), 25˚ E (Africa), and 100˚ E (Asia Pacific)) provide global coverage from latitude –75˚ to +75˚. To receive the Inmarsat signal users must have special Navcom hardware.

New Developments and Results

The technology development and demonstrations in the third year of this effort have concentrated in two areas: user hardware and new applications. In the area of user hardware we have pursued parallel development of GDGPS receiver payloads for aviation applications and for space applications.

Aviation payload and flight demonstrations. The aviation rack-mount chassis that was cobbled together to support the early AirSAR flight demonstrations was redesigned in an effort to provide robust performance, enable easy reproduction, and comply with aviation safety standards. The new chassis is depicted in Fig. 2. In addition to the Navcom GPS and L-band receivers, it contains a massive rechargeable battery, electronics for automatic power switching ensuring continuous operations during loss of external power, input for a pressure transducer, antenna feeds, and various controls.

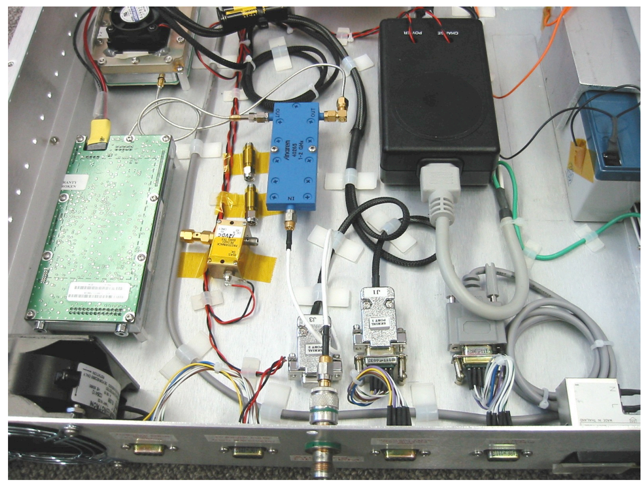

Fig. 2. The GDGPS aviation payload.

The aviation user module of the RTG software was enhanced to improve overall performance, and in particular the cold start convergence time. The control scripts were significantly enhanced to support autonomous operations. These improvements were refined and validated on many AirSAR flights over the continental U.S., and during the January-February 2003 DC8 flights of the SOLVE science experiment over Scandinavia and the north pole, for which GDGPS provided operational support (Fig. 3). The SOLVE flights have demonstrated many firsts:

- The first time GDGPS provided real time airplane positioning without operator on board.
- The first time a GDGPS user has traversed coverage area of the Inmarsat global beam. This enabled us to verify that coverage extends to roughly 75˚ latitude.
- The first time a GDGPS user demonstrated automatic switching from one Inmarsat global beam to the another.
- The first multi-week experiment with continuous streaming of the GDGPS differential correction through an Iridium modem phone.
- The first flight experiment to pay for GDGPS support.

Throughout the many weeks of this flight experiment the GDGPS delivered 10-20 cm real time positioning accuracy, with a marked improvement in the time for cold start convergence (from roughly 1 hour to roughly 0.5 hour) (Fig. 4).

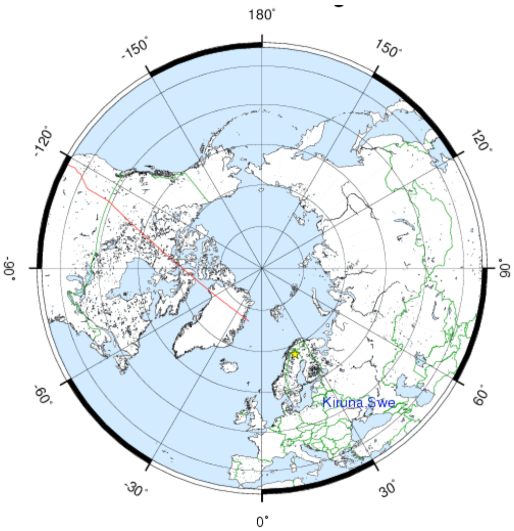

Fig. 3. A SOLVE DC8 flight path from California to Sweden. GDGPS maintained continuous operations throughout the flight.

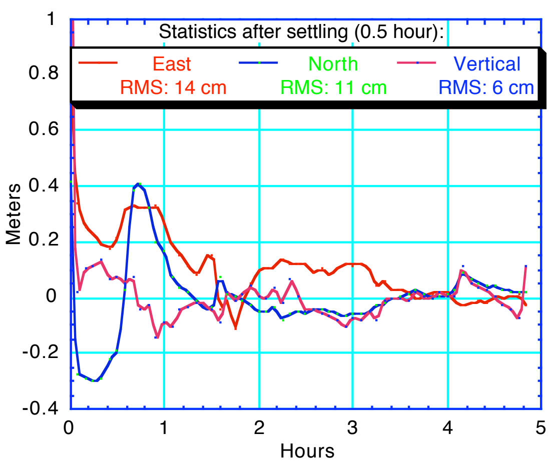

Fig. 4. Real-time positioning accuracy during a typical flight of the SOLVE flight experiment. 'Truth' is represented by post processing with the GIPSY OASIS software.

We also revisited the May 2002 NASA P3 flight experiment over Greenland (described in last year's ESTC report) to compare our GDGPS real time solutions to a real time kinematic (RTK) based solutions derived independently by Mr. Bill Krabil using a small local network of GPS receivers near the fight path of the airplane. Most of the GPS orbital and clock errors cancel out over such short baselines. The RTK solutions and our post-processing 'truth' agreed at a level of a few centimeters, RMS, in essence validating our validation approach. The agreement between our real time solution and the RTK solutions is summarized in Table 1.

Table 1. Differences between the GDGPS real time position solutions for the NASA P3, and the RTK solution, for the three flight paths in May, 2002.

Date	East	North	Vert
31 May	17.2	10.1	13.0
02 Jun	4.5	4.6	5.9
04 Jun	8.0	6.1	12.6

Spaceborne payload and orbit determination demonstrations. To enable spaceborne applications of the GDGPS system we set out to develop an integrated GDGPS receiver, comprising of a high quality GPS receiver (at least 12 dual frequency channels), and an Inmarsat L band receiver capable of receiving the GDGPS differential corrections. The embedded RTG orbit determination module will combine the raw GPS data with the correction message to provide precise orbital state estimates in real time. After analyzing various possible configurations we elected to integrate the JPL Blackjack GPS receiver with JPL's Autonomous Formation Flyer (AFF) baseband processor as the basis for the GDGPS receiver. This combination marries the unmatched GPS tracking performance of the Blackjack with the flexibility and power of the AFF, which possesses a PowerPC 750 processor, and a fully reprogrammable FPGA. The AFF board was mated with a new L band RF front end, and the tracking loops are closed in the FPGA. RTG will run on the AFF CPU, where it will process the differential corrections together with the GPS observations that are streamed from the Blackjack receiver through a serial port. The prototype GDGPS receiver will initially consist, therefore, of two 'boxes': the Blackjack receiver and the AFF/L-band receiver. The design, fabrication, and assembly of the GDGPS receiver has been completed (Fig. 5), and the unit is undergoing testing.

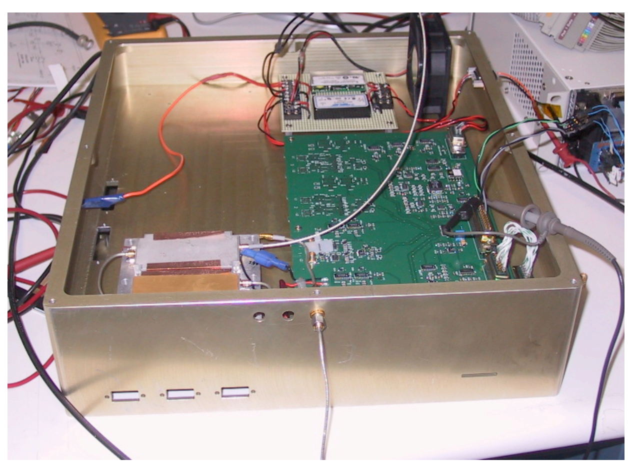

Fig. 5. The GDGPS spaceborne receiver prototype.

The TRL of the RTG software has gradually increased in preparation for embedding in the GDGPS receiver. It was first ported to the Blackjack platform, and after successful ground testing uploaded to SAC-C, an Argentinean satellite carrying JPL's Blackjack GPS receiver. While SAC-C does not have the capability to receive the Inmarsat corrections we expected to validate in this way the fundamental orbit determination capability of RTG as an embedded software, which consists of 90% of the final RTG code to reside in the GDGPS receiver. Fig. 6 depicts the autonomous real time orbit determination accuracy achieved on SAC-C by RTG using un-aided GPS. This is the first time 1 m real time GPS-based orbit determination was achieved in space for a low Earth orbiter. This performance is consistent with expectations based on ground processing of the same flight data by the GIPSY-OASIS software.

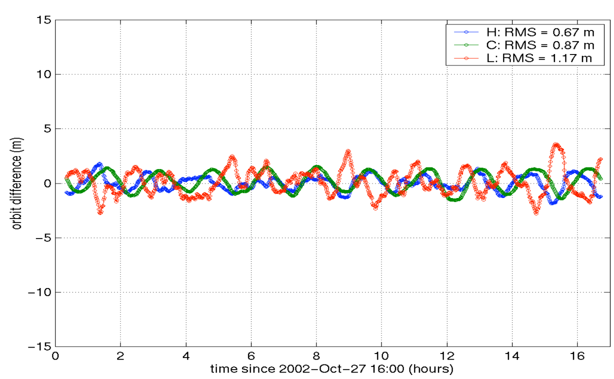

Fig. 6. The accuracy of the SAC-C onboard real time orbit determination compared to a post-processed solution.

New Applications. The potential applications of the GDGPS system are almost limitless. We have pursued the development and demonstration of a few key applications.

<u>Near real time sea surface height:</u> The GPS data from the Blackjack receiver on board Jason-1 become available 0-3 hours after real time. The Jason-1 orbit can then be estimated using the real time GPS orbit and clock solutions, which are a by product of the GDGPS system. The resulting science-quality orbits (radial accuracy better than 2.5 cm RMS) can be used together with other science data from Jason-1 and some ancillary data to derive near-real-time sea surface height measurements. The availability of science-quality near-real-time sea surface height is of great interest to meteorologist, and tactical oceanographers. After a year of beta tests, the JPL Physical Oceanography Distributed Active Archive Center (PO DAAC) has officially released this as an operational product.

<u>GPS integrity monitoring:</u> The GDGPS network of reference receivers is the only real time network that tracks all GPS satellites, all the time. It has, therefore, a unique capability to monitor the performance of the GPS satellites. In contrast, the U.S. Air Force, which operates GPS, has only 5 tracking sites. For significant periods of time many satellites are not monitored by the Air Force. The critical role that GPS plays in the world's economy and security has created an urgent need to continuously monitor the integrity of the GPS constellation. In collaboration with the U.S. Air Force and the Aerospace Corporation we have developed such an integrity monitoring capability. The benefits from providing the GPS operators timely alerts of GPS failures are profound, and range from economical, to national security, to the potential saving of individual lives.

<u>Time Transfer:</u> Time transfer is a natural by-product of the JPL approach of GPS-based point positioning. Typically, the time transfer accuracy is commensurate with the positioning accuracy. 10 cm positioning accuracy thus corresponds to 0.3 nsec time transfer accuracy. This level of real-time time-transfer accuracy is unprecedented, and has many civil and national security applications. For example, this system can be used to monitor the performance of atomic clocks in real time. We have worked with the U.S. Naval Observatory (USNO) to validate the time transfer capability of the GDGPS system. Furthermore, USNO, which is the keeper of the U.S. UTC time standard, has provided the GDGS network with a specially calibrated GPS linked to the their UTC time standard. This has enabled the GDGPS system to provide U.S. UTC time standard, globally, in real time.

STATUS AND FUTURE POTENTIAL

Since the GDGPS system's inception with a 2-computer operations center, and an 18-site network in early 2000, and through its evolution to the present 18-computer operations center, 60-site network, fully redundant architecture, the system has demonstrated 99.99% reliability in delivering its core product – the GPS differential correction message. Maintaining and surpassing this record is key to the future prosperity of this unique system. Several other real time products have been developed that increase the commercial, civil, and military value of the system. These include the GPS broadcast ephemerides, the GPS navigation message (both are useful for cell-phone-based positioning), global ionospheric maps, GPS integrity monitoring, and more.

One of the main drivers for developing the GDGPS system was SAR interferometry and AirSAR. Consequently, we have put great emphasis in supporting these applications. AirSAR in particular has provided us the opportunity to demonstrate the utility of the system and it enabled cost-effective development and validation of the system. As a result, the GDGPS system provides a uniquely powerful solution for precise airborne navigation. The adoption of this system as permanent infrastructure on all of Dryden's flight platforms is now being considered.

Direct environmental monitoring is another natural by-product of the system, along with timing. The ability to provide real time tropospheric and ionospheric sensing is of great value in terrestrial weather forecasting, and space weather assessments. The latter has implications for power grid management and communication systems performance. The Deep Space Network (DSN) will benefit from the system's ability to calibrate local atmospheric conditions at the DSN sites, as well as from the real time clock monitoring capabilities to monitor the mission critical time standards at the sites.

One of the main remaining challenges is to complete the application of the system in space. The RTG flight software has cleared TRL 7 with the combination of the SAC-C flight experiments and ground testing. The prototype GDGPS receiver could fly on a shuttle with only minor enhancements. Other space flight opportunities are being sought. In parallel, NASA is evaluating the technical aspects of enabling TDRSS broadcast of the differential correction message. Several future missions will benefit from this new capability. The Ocean Surface Topography Mission (OSTM), which is the Jason-1 follow on, expressed interest in providing sea surface height measurements with at least the same latency and accuracy as Jason-1 currently provides. SAR interferometry missions, either formation flying or repeat path, were identified as high priority by the NASA Solid Earth Science Working Group (SESWG) Report, as well as interdisciplinary programs such as EarthScope. The SESWG calls for "InSAR everywhere all the time" to measure Earth deformation at a multiplicity of time scales. GDGPS enables repeat path interferometry, and obviates the need for costly and complex inter-spacecraft link for relative positioning and time transfer between formation flyers. In addition, any spacecraft with onboard GPS processing at any level will benefit from timely integrity alerts that the GDGPS is uniquely capable of providing.

Continuous, near real time monitoring of NASA's GDGPS system is available in the public domain [http://gipsy.jpl.nasa.gov/igdg/demo]. This site also provides additional references and technical information.

ACKNOWLEDGMENT

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REFERENCES

[1] 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, , pgs. 433-447, 1998.