The Development and Demonstration of NASA's Global Differential System

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Abstract- **We will describe the evolution of the NASA Global Differential GPS (GDGPS) system, an effort that is funded under the Advanced Information Systems Technology (AIST) Program. NASA's GDGPS system is intended to provide end-to-end capabilities for autonomous, real-time orbit determination and positioning with an unprecedented level of accuracy and availability. In the second year of development the work has focused on the development of user equipment, on enhancing the operational robustness of the system, and on a series of ground, air-borne and space-borne experiments designed to test the system and demonstrate its utility to a variety of NASA missions. Moreover, we will describe how the system is already proving useful for some of these missions.**

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 - 12 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. Although a number of private and government organizations provide real-time positioning services in localized regions to users on or near the ground, a global system such as described here, capable of supporting global space users, has never been achieved nor attempted due to the perceived technical and cost challenges.

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 30 GGN sites (Fig. 1) with an average latency of 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.

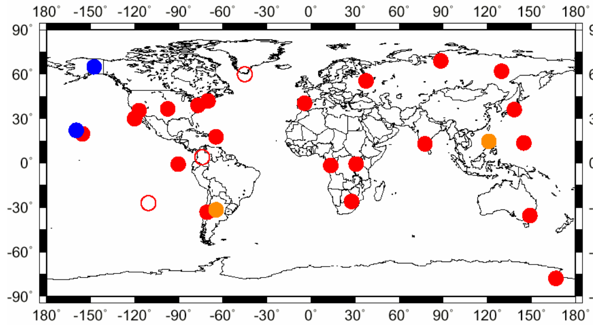

Fig. 1. Network of dual-frequency GPS receivers returning data to JPL in real-time as of August 2001. (red: Ashtech Z12 receivers, blue: AOA Benchmark ACT receivers, orange: AOA TurboRogue receivers, open circle: future sites).

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 two communication channels. The first is the open internet, where a user can connect to a TCP 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, to address the need for global availability of the signal. 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

Recent technology development and demonstration have concentrated in two areas: operational reliability and user applications. In the area of operational reliability we have focused on efficient implementation of a multiply redundant architecture. Under this architecture each reference site streams its raw GPS data over the internet simultaneously to at least two processing hubs that operate in parallel. One is designated as primary, and the other as secondary. At present, these two hubs are located thousands of kilometers apart to minimize the impact of any natural disaster on the operation of the system. Each of the two hubs can echo the GPS data to any number of additional processing centers with negligible additional latency, resulting in a highly reliable operation with no single point of failure (Fig. 2).

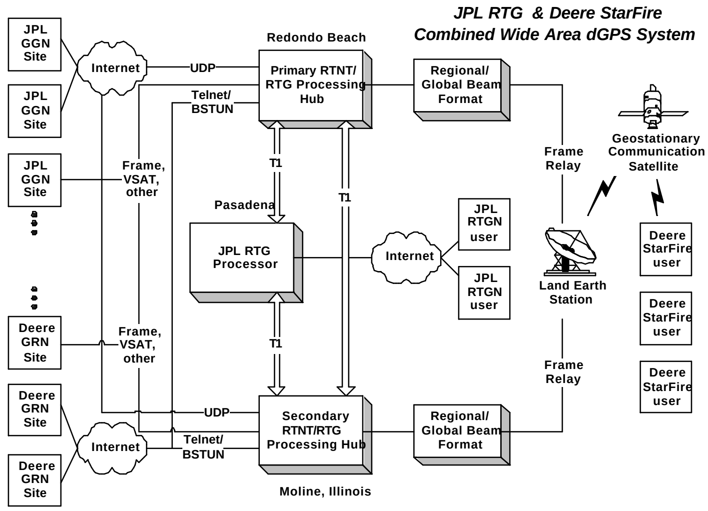

Fig.2. Network architecture for the NASA GDGPS system

While extensive testing has demonstrated 10 – 20 cm RMS real time positioning accuracy for a mobile land user of our system, many Earth science applications require accurate positioning of air borne or space borne platforms. One such application is synthetic aperture radar (SAR), which can be carried out from space or from the air. To this end we have used the NASA AirSAR (Fig. 3) to test the aircraft positioning capabilities of our system.

Fig. 3. The NASA DC8 carrying the AirSAR payload.

The equipment configuration for the AirSAR flight experiment is depicted in Fig. 4. It consists of a Navcom dual frequency GPS receiver, and a Navcom L-Band receiver, which is used to receive the correction data stream relayed by the Inmarsat geostationary communications satellites. The data is then fed into a Linux PC running the RTG software, which forms the position solutions at 1 Hz. Flight experiments were carried out during February and March, 2002, over portions of California, Colorado, and the Great Lakes. Truth positions were generated after the fact with the GIPSY-OASIS software using precise GPS orbits and clocks and a local ground network to provide for high rate clock reference and ambiguity resolution. By applying this positioning technique to stationary receivers we confirmed that the 'truth' positions are accurate to a few centimeters. Fig. 5 depicts the AirSAR real time positioning errors with the NASA GDGPS system relative to the 'truth' during a typical flight. Upon cold start it takes about 30 minutes for the real time solution to converge, and the occasional airplane banking may cause interruptions in signal receptions.

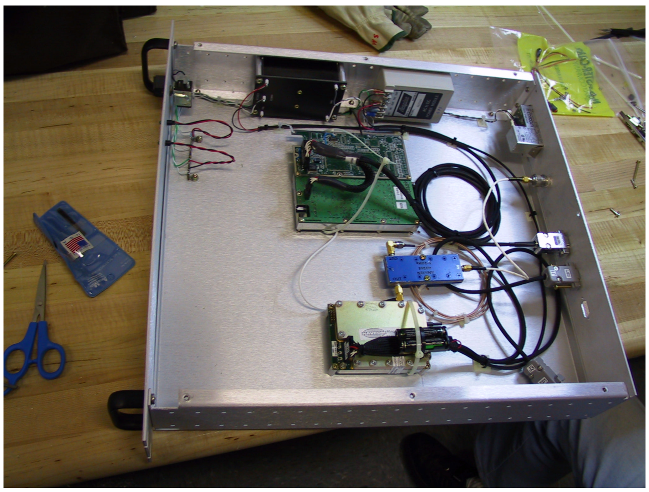

Fig. 4. The real-time positioning rack-mounted chasis and electronics.

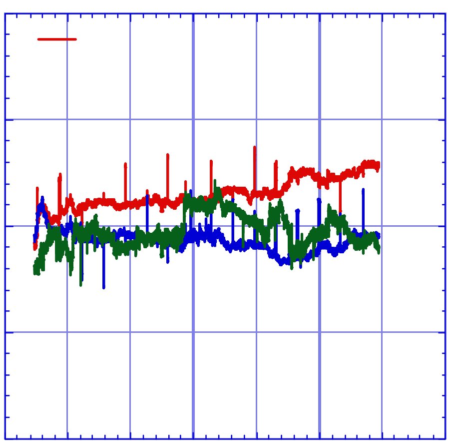

Fig. 5. Real time positioning errors for AirSAR flight over southern California on February 11, 2002. The first 30 minutes time after cold start are not shown.

The real time positions generated by our system are used to help calibrate the radar, as they are far more accurate than the operational GPS-based positioning system employed on the plane.

Geostationary communications satellites cannot provide coverage with their global beams beyond latitude 75°. That means, for example, that most of Greenland and Antarctica cannot receive the Inmarsat correction signal. The only viable solution for users in the high latitudes is to relay the correction data stream through the Iridium system. We have conducted extensive tests of internet connectivity with Iridium and found it to be fairly reliable. In fact, because of the polar orbit of the Iridium satellites the system is expected to have a better coverage at high latitudes (Fig. 6). We plan to put the Iridium system to the ultimate test in June, with flight experiments over Greenland, using Iridium as the sole conduit for the correction data stream.

The implementation of a space borne real-time orbit determination capability has focused on both hardware and software. On the hardware side we are qualifying a design of a multi-function receiver, combing GPS and L-Band (Inmarsat) capability. On the software side we plan to upload the RTG software to the SAC-C satellite (Fig. 5) and demonstrate autonomous onboard orbit determination. SAC-C is an Argentinean satellite carrying JPL's Blackjack GPS receiver. While SAC-C does not have the capability to receive the Inmarsat corrections, this experiment will increase the technology readiness level (TRL) of RTG from 5 to 7. At present we have completed the port of the RTG software to the Blackjack platform, and have begun to upload the code.

Fig. 6. The SAC-C satellite

We assess the expected orbit determination performance of our system using actual GPS data from the BlackJack receiver onboard the Jason-1 spacecraft (1300 km altitude), processed on the ground with RTG in real-time mode, and using real time GPS orbits and clocks. The real time orbit determination errors (relative to the post processed orbits that are sub-10 cm 3D RMS accurate) were:

7 cm RMS in the radial direction

5 cm RMS in the cross track direction

17 cm RMS in the along track direction

Orbit determination requirements for altimetric satellites such as Jason-1 and Topex focus on the radial component. The performance reported above is sufficient to support a large variety of tactical oceanography applications. Of course, satellites at lower altitude should expect somewhat degraded performance due to the increased difficulty in modeling the dynamics of the satellite. Similar simulations conducted last year with data from the CHAMP satellite (450 km altitude) demonstrated 30 cm 3D RMS real time orbit determination accuracy. The Jason performance, and the CHAMP performance provide reasonable bounds for the expected performance of our system in orbit.

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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