AVIATION APPLICATIONS OF NASA'S GLOBAL DIFFERENTIAL GPS SYSTEM

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Abstract- The NASA Global Differential GPS (GDGPS) system provides an unparalleled combination of real time positioning accuracy and availability. Developed and operated by the Jet Propulsion Laboratory (JPL) for NASA's terrestrial, airborne, and spaceborne applications, the GDGPS system processes real time GPS data from a global network of more than 40 dual frequency GPS ground sites. It is the only network providing global, multiply-redundant, real time coverage of all GPS satellites, all the time. The system has demonstrated real time positioning accuracy of 10 cm horizontally, and 20 cm vertically for users anywhere in the world, on the ground and in the air. Real time orbit determination of low Earth satellites carrying precise GPS receivers was demonstrated to achieve accuracy of 10 – 30 cm 3D RMS (depending primarily on altitude). A track record of 99.99% availability extends from January 2000 to the present. In this article we describe the aviation applications of the system, and describe the extensive flight tests and the performance validation methodology.

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. While for many it is not needed in real time, the ability to achieve high positioning 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.

We have developed and demonstrated a GPS-based technology that enables Earth-orbit satellites, airplanes, and terrestrial systems to achieve unprecedented levels of real-time positional accuracy, anywhere and at any time. For kinematic applications, such as airplanes and terrestrial vehicles, the system delivers 10 - 20 cm accuracy.

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 GPS 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 latency is 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.

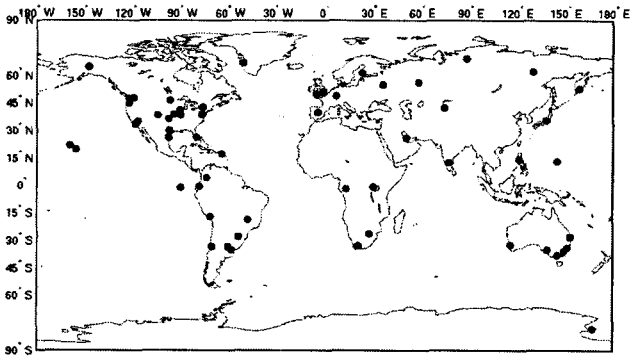

Fig. 1. the network of dual-frequency GPS receivers returning data to JPL in real-time as of June 2003.

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. (An earlier version of RTG is functioning as the core GPS orbit determination software for the FAA's Wide Area Augmentation System.)

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 dissemination 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, and they provide global coverage from latitude –75° to +75°. To receive the Inmarsat signal users must have special Navcom hardware.

AIRBORNE APPLICATIONS AND DEMONSTRATIONS

We have developed a special navigation payload for aviation applications (Fig. 2). It consists of a rack-mount chassis with dual-redundant GPS receivers, a Linux laptop running the RTG software, an aircraft GPS antenna, a connection to the aircraft barometer, an L-band Inmarsat receiver, and an Iridium modem. The payload also features a massive rechargeable battery, electronics for automatic power switching ensuring continuous operations during loss of external power, and various controls. The GPS receivers used are the Ashtech Z-12 and Navcom's NCT-2000. Both are dual-frequency, 12-channel receivers.

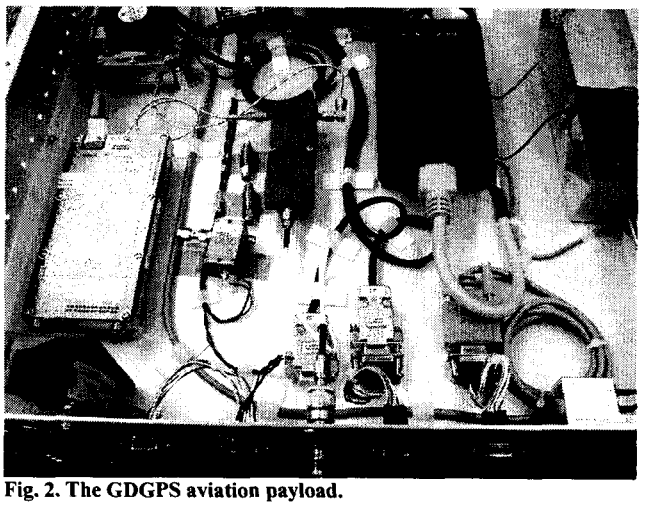

Fig. 2. The GDGPS aviation payload.

The GPS receivers output P1, P2, L1, and L2 data to the laptop at 1-Hz over a serial connection. The GDGPS corrections are received at 1-Hz with bandwidths of 28 and 44 bytes/second over the Inmarsat satellite link and Iridium phone connection, respectively. 1-Hz pressure measurements from the plane's barometer are used to compute the dry tropospheric delay.

Commercial geostationary communications satellites, such as Inmarsat 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 mobile users in the high latitudes is to relay the correction data stream through the Iridium system (Fig. 3), where the modem phone is used to dial into the GDGPS Operations Center. During flights we typically receive the correction data in parallel from the two channels, Inmarsat and Iridium, for a smooth transition during loss of the Inmarsat coverage. This approach increases the overall reliability of the system by eliminating the susceptibility to failure in any one communications channel.

The onboard RTG software produces real-time solutions at 1 Hz. This state space position solution contains the aircraft position in Earth Centered, Earth Fixed (ECEF) X, Y, Z coordinates and estimates of the wet component of the tropospheric delay.

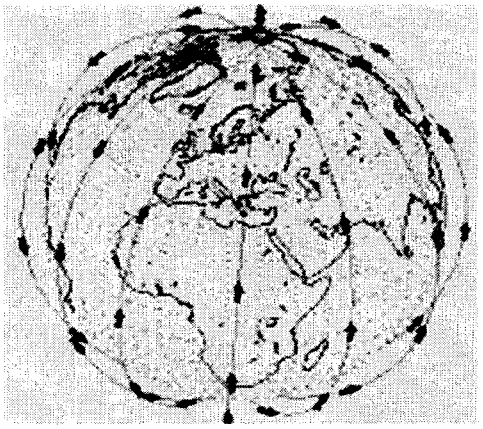

Fig. 3. The Iridium constellation

Extensive flight tests were carried out to validate the performance of the end-to-end system. The GDGPS payload flew on the NASA DC-8 (Fig. 4) in support of JPL's AirSAR flights over the United States from February through September of 2002. In the spring of 2002, the system also flew as part of the NASA P3 (Fig. 5) Ice-Mapping mission over Greenland, where Iridium was the only available means to receive the GDGPS differential corrections. In December 2002 through February 2003, the system was deployed on the NASA DC-8 for the SOLVE III flights over Scandinavia and the north polar region to profile ozone. On the way from California to the mission base in Sweden (Fig. 6) the system automatically switched between Inmarsat satellites, and then to Iridium as the Inmarsat signal dropped off. During the mission iridium was the sole means to receive the GDGPS differential corrections. The SOLVE III flights were the first without an operator onboard tending to the equipment, demonstrating the operational reliability of the system and payload.

Fig. 4. The NASA DC8 carrying the AirSAR payload.

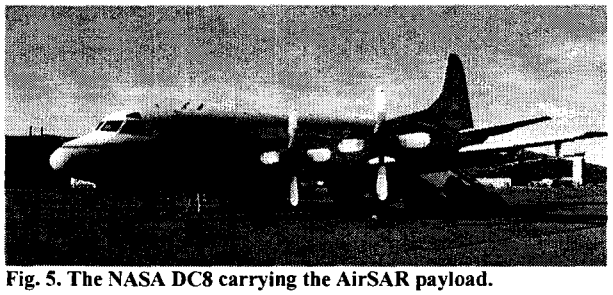

Fig. 5. The NASA DC8 carrying the AirSAR payload.

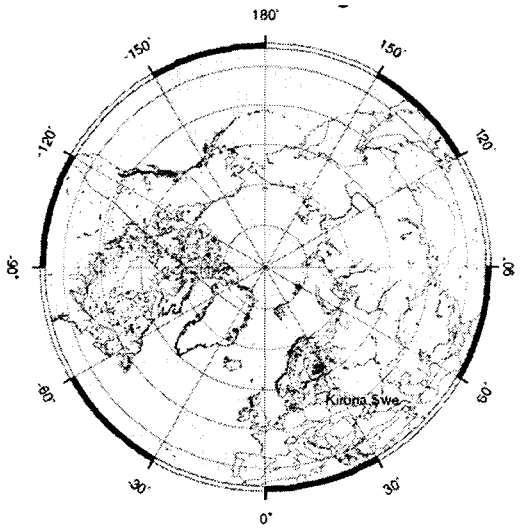

Fig. 6. A SOLVE DC-8 flight path from California to Sweden. GDGPS maintained continuous operations throughout the flight

The key challenge in validating decimeter level positioning accuracy in flight is the availability of 'truth'. Truth positions were generated after the fact with JPL's 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. The P3 mission over Greenland provided a rare opportunity to compare JPL solutions an independent GPS solution. On these flights, a team of researchers from NASA's Wallops Flight Facility computed post-processed, carrier-phase based local area differential GPS solutions using a specially deployed ground network of reference receivers.

Table 1 shows the RMS difference between the GIPSY-OASIS post-processed 'truth', and the local area differential technique produced at Wallops, during the three flights with the P3 over Greenland. The agreement is at the few centimeter level in all coordinates, consistent with the assumption of a few centimeter accurate 'truth'. The remaining comparisons are carried between the GDGPS real-time solutions and the GIPS-OASIS post-processed 'truth' solutions.

Table 1: Real-time point solution vs. GIPSY-OASIS solution. Errors are in RMS cm.

Date	East	North	Vert
31May02	1.4	1.9	5.0
01Jun02	1.7	3.1	7.4
04Jun02	5.0	4.9	8.6

Table 2 shows the RMS errors of the GDGPS real-time solution relative to truth for the three P3 flights.

Table 2: GDGPS Real-time point solution vs. GIPSY-OASIS solution. Errors are in RMS cm.

Date	East	North	Vert
31May02	17.3	6.6	11.4
01Jun02	4.4	4.0	7.5
04Jun02	6.8	4.0	9.0

The error level indicated in Table 2 is typical. The RMS error of the GDGPS real-time solutions as measured over the many hundreds of flight hours is 10 cm in the horizontal component, and 20 cm in the vertical component.

A typical time profile of the position error is depicted in Fig. 7. It clearly features a filter settling time of roughly 60 minutes. Note that the solution attains sub-meter accuracy within minutes. In principle, filter convergence can be achieved well before takeoff, if the GPS measurements are not obstructed while on the ground. Actual converge time depends on the GPS observing geometry and on local multipath conditions.

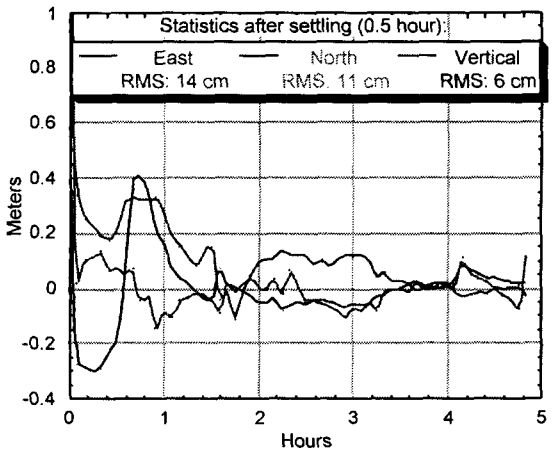

Fig. 7. Real-time positioning accuracy during a typical flight of the SOLVE flight experiment. 'Truth' is represented by post processing with the GIPSY OASIS software.

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. The GDGPS system provides time transfer relative to the U.S. Naval Observatory (USNO) Master Clock, the official keeper of the U.S. Universal Time Coordinated (UTC).

STATUS AND FUTURE PLANS

One of the main drivers for developing the GDGPS system was SAR interferometry. Repeat pass SAR interferometry is a powerful technique to effectively observe subtle changes in the Earth's surface. However, any positioning error in repeating the ground pass translate to spurious effects in the science products. The precise real-time positions of the GDGPS system remove one of the major obstacles from repeat path control. The control problem is somewhat easier for high altitude airplanes, and consequently the coupling of GDGPS and UAV is promising to enable sub-meter control of the flight pass.

The first attempt to control a plane based on GDGPS input will be carried out in the summer of 2003 on a piloted Predator UAV out of NASA Dryden Flight Center. Ultimately, autopilot will be programmed to control the plane along a predefined flight path, with a near term goal of sub-meter accuracy.

The NASA GDGPS system is fully operational with a multiply redundant architecture for high reliability. Since its inception in early 2000 it has demonstrated 99.99% reliability in delivering the differential corrections to its users. Continuous, near real time monitoring of NASA's GDGPS system and additional references and technical information is available at [http://galia.gdgps.net/igdg].

ACKNOWLEDGMENT

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[1] Muellerschoen, R. J., W. I. Bertiger, M. Lough, D. Stowers, D. Dong, "An Internet-Based Global Differential GPS System, Initial Results," Proceedings of ION NTM 2000, Anaheim, CA, January, 2000.