NASA's Global Differential GPS System and the TDRSS Augmentation Service for Satellites

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ABSTRACT

NASA is planning to launch a new service for Earth satellites providing them with precise GPS differential corrections and other ancillary information enabling decimeter level orbit determination accuracy, and nanosecond time-transfer accuracy, onboard, in real-time. The TDRSS Augmentation Service for Satellites (TASS) will broadcast its message on the S-band multiple access channel of NASA's Tracking and Data Relay Satellite System (TDRSS). The satellite's phase array antenna has been configured to provide a wide beam, extending coverage up to 1000 km altitude over the poles. Global coverage will be ensured with broadcast from three or more TDRSS satellites.

The GPS differential corrections are provided by the NASA Global Differential GPS (GDGPS) System, developed and operated by NASA's Jet Propulsion Laboratory. The GDGPS System employs a global ground network of more than 70 GPS receivers to monitor the GPS constellation in real time. The system provides real-time estimates of the GPS satellite states, as well as many other real-time products such as differential corrections, global ionospheric maps, and integrity monitoring. The unique multiply redundant architecture of the GDGPS System ensures very high reliability, with 99.999% demonstrated since the inception of the system in Early 2000. The estimated real time GPS orbit and clock states provided by the GDGPS system are accurate to better than 20 cm 3D RMS, and have been demonstrated to support sub-decimeter real time positioning and orbit determination for a variety of terrestrial, airborne, and spaceborne applications.

In addition to the GPS differential corrections, TASS will provide real-time Earth orientation and solar flux information that enable precise onboard knowledge of the Earth-fixed position of the spacecraft, and precise orbit prediction and planning capabilities. TASS will also provide 5 seconds alarms for GPS integrity failures based on the unique GPS integrity monitoring service of the GDGPS System.

INTRODUCTION

Precise real-time onboard knowledge of a platform's position and velocity is useful for a variety of Earth observing applications. Examples include repeat pass radar interferometry, where precise motion control is required to repeat a ground pass in order to detect minute changes over time, and many formation flying applications. The benefits extend to any mission where accuracy as well as latency are of the essence, such as ocean altimeters, laser and synthetic aperture radar (SAR) mappers, which seek orbit accuracies from centimeters to decimeters for environmental and natural hazard monitoring. 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 and planning enabled by precise real time positioning. 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.

The NASA Global Differential GPS (GDGPS) System was developed to enable Earth-orbiting satellites, airplanes, and terrestrial users to achieve unprecedented levels of real-time positional accuracy with both seamless and global coverage. The system is geared for users with dual-frequency GPS receivers that can eliminate the ionospheric errors by taking a linear combination of measurements in the two GPS frequencies. The errors in the GPS broadcast ephemerides and broadcast clocks are provided to the user by the 1-Hz GDGPS correction message. Terrestrial users may access this correction message through the internet, modems (including satellite modems, such as Iridium), dedicated communications lines, or using proprietary signals relayed through Inmarsat geosynchronous communication satellites by a variety of commercial partners. However, at present there is no effective mechanism to relay the GDGPS correction message to Earth orbiters. The TDRSS Augmentation Service for Satellites (TASS) is designed to address this limitation. In addition to the a special differential correction message TASS will broadcast information that will enable a spacecraft to optimally determine its orbit, figure out its exact ground track, and plan its mission, all with accuracy that is equivalent to today's ground processing.

Below we review the status of the GDGPS system, which underlies the new service, and discuss its demonstrated performance. We then describe the specification of TASS, including user hardware requirements, and the progress of the development efforts to date.

GDGPS SYSTEM DESCRIPTION

The Global Differential GPS (GDGPS) System is geared toward users carrying dual-frequency receivers, which are flown on a wide variety of remote sensing low Earth orbiter missions, and are prevalent in science applications. The imminent deployment of a second and possibility third civilian GPS frequency, and the multiple frequencies promised by Galileo 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. While accurate corrections for the GPS ephemeris and clock errors require a network of GPS reference sites, eliminating the need to provide maps of the highly variable total electron content allows the ground network to be relatively sparse.

The JPL architecture for GPS augmentation using a global real-time differential system was first put forward by [1,2]. The fundamental tenet of this 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 and instantaneous clock offset. The differential correction message is formed as a difference between the precise estimated orbit and clock states, and the broadcast states. This approach guarantees that the corrections will be globally and uniformly valid. A commercial North American Wide Area Differential GPS (WADGPS) system based on the JPL architecture and software was first implemented in 1995 by SATLOC Inc., primarily for the agricultural market [3]. 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 implemented and operated by Raytheon, the prime WAAS contractor.

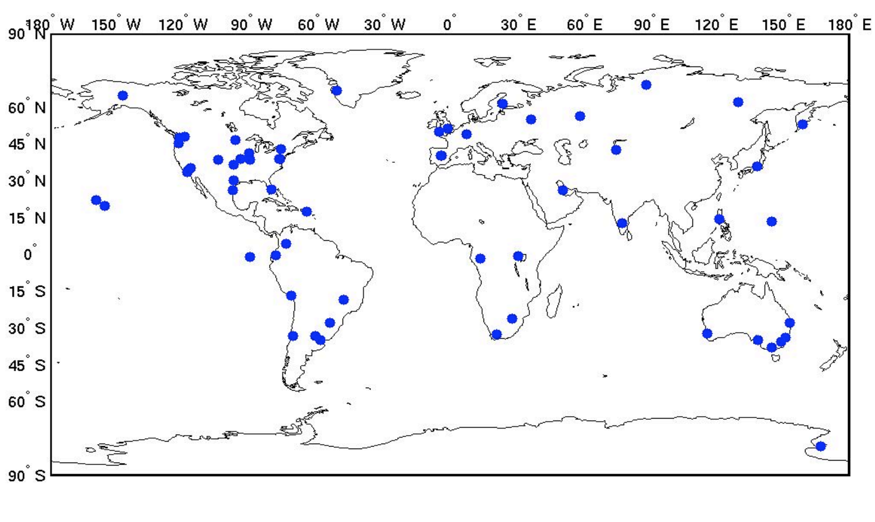

Fig. 1 The GDGPS real-time reference network of dual frequency GPS receivers as of December 2003.

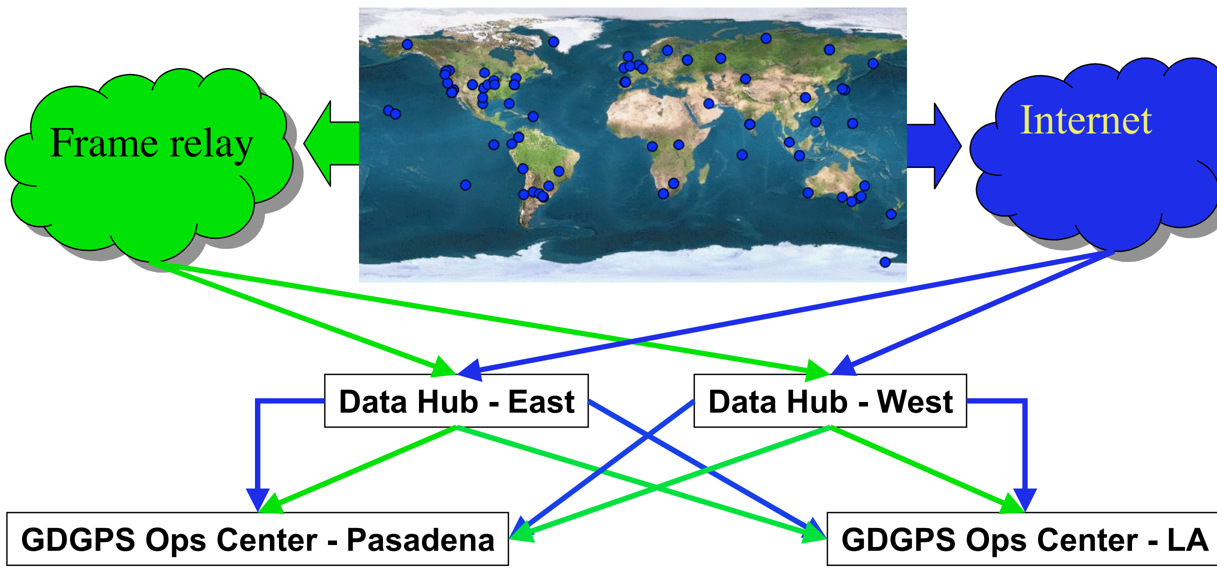

Fig. 2. Schematic description of the GDGPS System architecture

Architecture:

The GDGPS ground network of real time GPS receivers consists of roughly 70 dual frequency receivers, of which the large majority have been installed, operated, and maintained by JPL, and the rest are contributed by a number of commercial, and institutional partners (Figure 1). GPS measurements collected at the sites are streamed in parallel to two Data Hubs through a variety of Internet and dedicated land lines [4]. From the Data Hubs, which are geographically separated by thousands of kilometers to avoid common failure due to natural disasters and other local events, the data is streamed to an arbitrary number of Operations Centers via dedicated land lines, with the Internet serving as a backup communications channel. The data processing is carried at the Operations Centers on redundant chains of computers using the Real Time GIPSY (RTG) software package, which estimates the GPS orbit and clock states in real time, and derives a host of by-products. Two (redundant) United States Naval Observatory (USNO) Master Clock sites provide reference time for the GDGPS System (The USNO Master Clock also provides the official Universal Time Coordinated (UTC) reference for the U.S. Department of Defense). Figure 2 illustrates the architecture of the GDGPS ground segment.

Redundancy is the key to the system's reliability, by ensuring that there are no single points of failure in the system. In fact, at critical junctures the system is many folds redundant. For example, the real-time ground network is roughly 9-fold redundant, as is described below. Triple and quadruple redundant computer chains enable routine maintenance operations to be carried out while still maintaining multiple redundancy. The concept of redundancy is extended to the user by allowing each customer parallel and concurrent access to two Operations Centers, and accommodating multiple communications channels, including T1 lines, Frame relay, modems, and the Internet. From inception in early 2000 to date the system has demonstrated 99.999% reliability.

Products and Services

The products and services of the GDGPS System as well as their main attributes are summarized in Table 1. The core product is the precise real-time state of the GPS satellites. The GPS broadcast ephemeris is another product that is distilled from the raw data collected by the ground network. The differential correction message is then formed as the difference between the precise real-time states of the satellites and the broadcast ephemeredes, and is compactly packaged into a 44 Bytes/sec message stream. Another important product is GPS integrity monitoring. Here we capitalize on the highly redundant tracking network to provide authorized users (primarily the U.S. Air Force) with real time performance monitoring of the GPS constellation. With a minimum of 9 tracking sites observing each GPS satellites, and an average of 15 (Fig 3), strong majority voting schemes are enabled that ensure that a failure in one or more tracking sites does not give rise to false alarms.

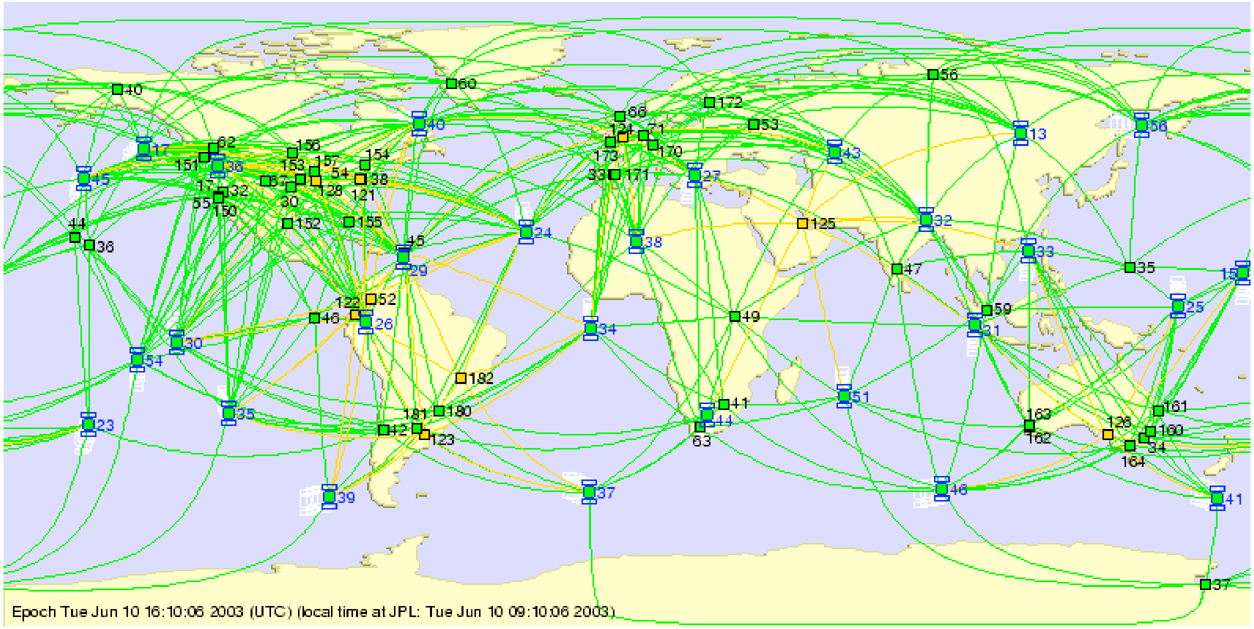

Fig. 3. A snapshot from the GDGPS integrity monitoring web page depicting the active links between real-time tracking sites (squares) and satellites (squares with 'wings'). Green links indicate nominal measurements. Yellow links indicate no measurements despite satellite in view. Red links (not present here) indicate measurement anomaly.

Table 1. Real Time products and services of the GDGPS System

Products or Services	Format and Latecy	Key Attributes	Comments
Raw measurements	Real-time binary data stream		The raw measurements from the GDGPS network
GPS orbit and clock states	1 min ASCII files	1 min temporal resolution	
Broadcast ephemeris	Real-time binary data stream 5 minutes ASCII files		Distilled from the global data
Differential corrections	Real-time binary data stream	1 sec temporal resolution for clocks 30 sec temporal resolution for orbits 44 Bytes/sec	
Global ionospheric (TEC) maps	5 minutes ASCII files		
50 bps navigation message	Real-time binary data stream		Full navigation message bit-by-bit
GPS integrity monitoring	Real-time binary data stream 30 sec Web server	4 sec time to alarm	
Virtual reference site	Real-time binary data stream		Custom designed

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<u>Performance</u>

Most of the raw measurements arrive at the Operations Centers within 1 sec of real-time, but we wait typically 3-4 seconds to get nearly 99% of the data. Due to network redundancy the products are completely insensitive to partial or complete loss of data from any given station. The estimation of the GPS orbits and clocks are carried out with the RTG software using an extended Kalman filter. The resulting GPS orbits are accurate to better than 20 cm 3D RMS (as compared to the JPL "Final" post-processed orbit products, which are accurate to a few centimeters). The clock solutions, which are references to USNO UTC, is similarly accurate. Figure 4 depicts the recent accuracy of the GPS orbit products.

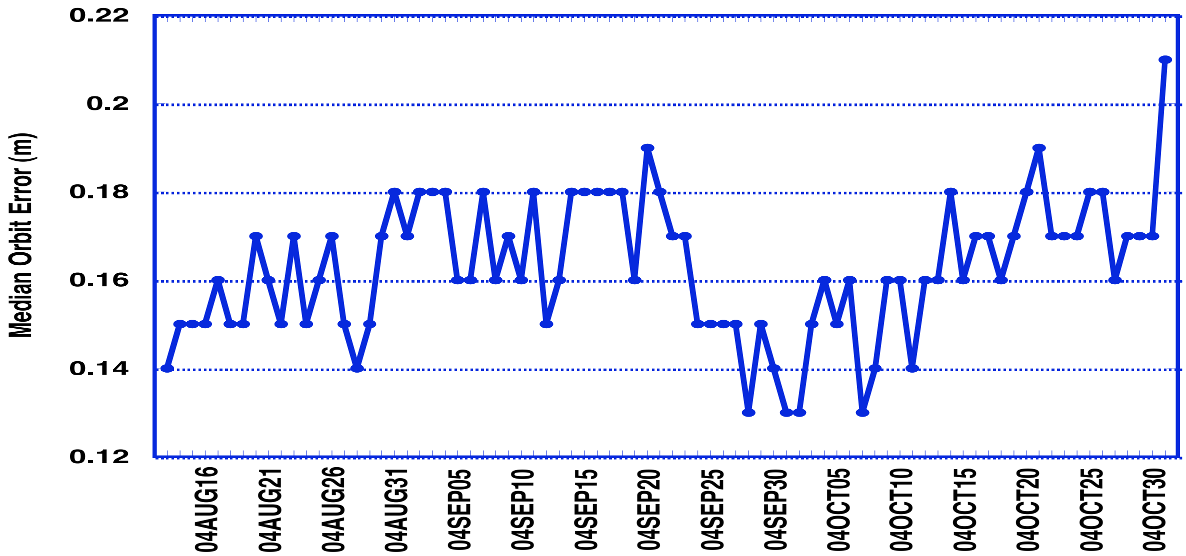

Fig. 4. Median daily accuracy of the 3D RMS error in the real-time GPS orbits from August 11, 2004 to October 30 2004.

The orbit and clock correction message has sub-centimeter resolution for uncompromising accuracy. It is available with a nominal latency of 4 second at the GDGPS Operations Centers. Extensive user positioning experiments have been carried out for a variety of applications [4,5,6,7]. Using data from high quality GPS receivers (dual frequency, all in view, phase tracking geodetic quality receivers) we have demonstrated 10 – 20 cm 3D RMS real-time positioning accuracy for ground, airborne, and spaceborne applications. The demonstrations of orbit determination were carried out using actual GPS data from JPL's Blackjack GPS receivers onboard the CHAMP, SAC-C, GRACE, and Jason spacecraft. Since at present there is no effective mechanism to get the GDGPS corrections to the spacecraft (a deficiency TASS is aiming to correct), we processed the data on the ground in a purely real-time mode, that is, with our real-time GPS orbit and clock states as input to the orbit determination process, and using the RTG software. Figure 5 depicts the real-time orbit determination error for Jason, as measured against the post-processed orbit, which is accurate to a few centimeters [8].

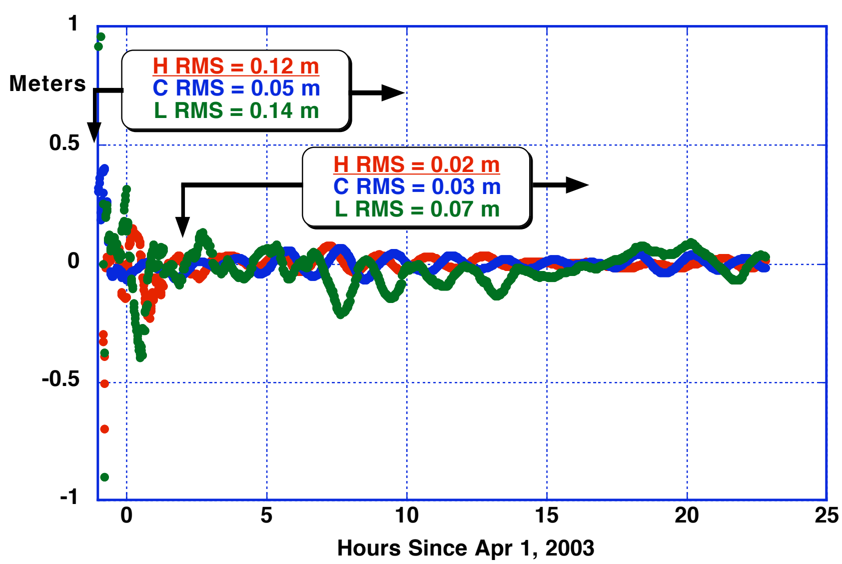

Fig. 5. Real-time orbit determination error for Jason using RTG and GDGPS-based GPS orbit and clock state, including settling period of about an hour. Truth orbit provided by the Jason post-processed orbits.

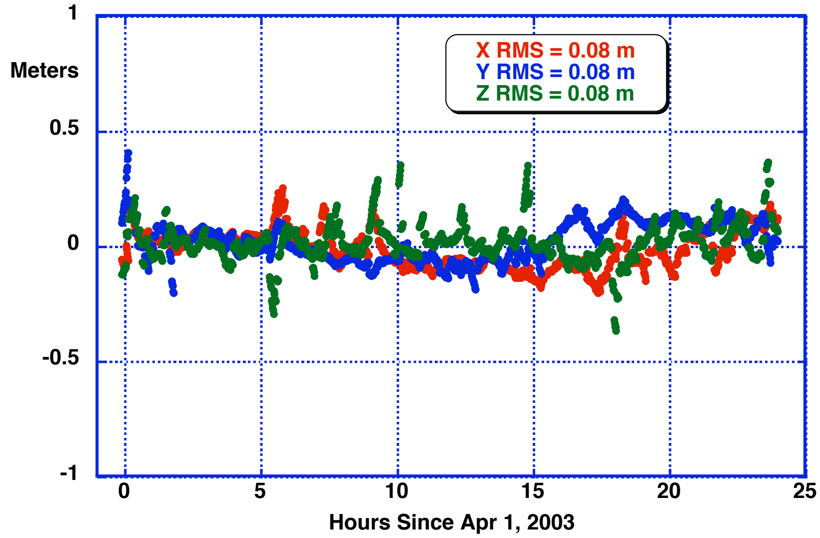

Fig. 6. Errors in the real-time determination of baseline length between the two GRACE spacecraft, after removal of a single bias term. Truth is provided by the post-processed orbits, which are accurate to 2-3 cm RMS.

The ability to obtain high accuracy, real-time positioning onboard spacecraft can considerably simply formation flying, where precise knowledge of the inter-spacecraft baseline is required. Instead of exchanging the raw GPS measurements, which require substantial bandwidth, each spacecraft can perform its own precise real-time orbit determination and exchange only their states. We have demonstrated this approach with the two GRACE spacecraft, at 500 km altitude and roughly 200 km apart, where the real-time determination of the baseline was accurate to 8 cm RMS in each components (Figure 6). For shorter baselines the error is expected to be smaller due to cancellation of common mode errors.

Finally, to demonstrate the capability for onboard real-time orbit determination operations the orbit determination module of the RTG software has been embedded in JPL's Blackjack GPS receiver, and uploaded to the SAC-C spacecraft in flight (*Satelite de Aplicaciones Cientificas-C* is a cooperative mission between NASA and the Argentine National Commission on Space Activities. Launched in November of 2000, SAC-C is in a near-polar orbit and is at an altitude of 707 km). Since at present we cannot relay the GDGPS corrections to spacecraft, orbit determination operations were carried out using the un-corrected GPS broadcast ephemeris. The orbit determination accuracy, roughly 1 m 3D RMS, was therefore dominated by errors in the representation of the GPS state [6]. The order of magnitude improvement in orbit determination accuracy enabled with the availability of precise real time GPS satellite states, as we have demonstrated, illustrates the potential benefits from TASS.

THE TDRSS AUGMENTATION SERVICE FOR SATELLITES (TASS)

NASA is planning to use its tracking and data relay satellite system (TDRSS, Figure 7), presently consisting of a fleet of 10 geosynchronous communications satellites, to relay the GDGPS differential correction message to satellites in Earth orbit. Recognizing that the GDGPS differential corrections alone may not be sufficient to enable full autonomous and secure operations in Earth orbit, we have augmented the correction message with real-time information about Earth orientation, solar flux, and GPS integrity. Earth orientation parameters were added in support of imagers that require precise geolocation, and also to enable accurate calculation of the spacecraft acceleration due to the Earth gravity field. The solar flux parameters are required for the accurate calculation of atmospheric density and the attendant drag accelerations. Finally, GPS integrity flags are required for missions where GPS input is used for critical operations, such as maneuvers and proximity operations.

The TASS message was implemented as a 256 bits per second data message, encoded with rate 1/2 Viterbi code (resulting in 512 symbols per second), and spread with a 2.5 MHz pseudorandom noise code. This signal is modulating the 2106.4 MHz carrier of the TDRSS Multiple Access Forward channel. The raw TASS message (256 bps) is formed at the GDGPS Operations Center, and then transmitted over secure communications line to the TDRSS uplink stations (at New Mexico and Guam). There it is Viterbi encoded, spread, modulated onto the carrier, and uplinked.

Fig. 7. An artist image of a TDRSS satellite

Table 2 summarizes the information content of the TASS message. The TASS message also includes an authentication sequence to ensure that the message cannot be spoofed. The message has also built-in encryption capability to prevent unauthorized usage.

Table 2. Information content of the TASS message

Information	Frequency	Resolution
GPS Orbit corrections	Every 32 second	Sub-cm
GPS Clock Corrections	Every 2 seconds	Sub-cm
GPS Integrity flags	Every second	binary
Earth orientation parameters	Every hour	cm on Earth surface
Solar flux	Every three hours	

Three TDRSS satellites are required to provide global coverage. Special configuration of the TDRS phased array communications antenna was devised in order to provide a 10° beam width (as measured from boresight), which extends coverage up to 1000 km altitude over the poles, with roughly 28 dBW EIRP at boresight, and 22 dBW EIRP at 10° off boarsight. The signal is left hand circularly polarized. The antenna pattern is depicted in Figure 8.

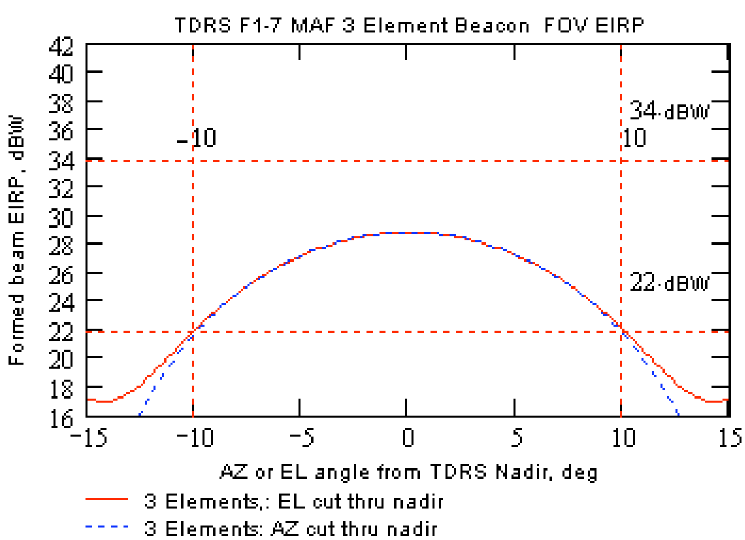

Fig. 8. EIRP as a function of boresight angle with the TASS transmit antenna configuration.

Test of a prototype TASS service have been successfully conducted over the last year. As a prototype TASS message we used the standard GDGPS correction message, and it was relayed to the TDRSS uplink site in New Mexico over the Internet. We have developed special hardware and firmware to encode the message and modulate it on the TDRSS uplink frequency. The TASS signal in space was successfully received on the ground with nominal SNR using a Blackjack GPS receiver with one of its 48 L-band RF channels replaced by an S-band down-converter. The total latency of the message received on the ground was 7 second (measured from the time the GPS raw measurements were recorded by the GDGPS ground network). The ultimate latency of TASS message will be 5 seconds, achieved by reducing the latency of the GDGPS operations from 4 to 3 seconds, and replacing the Internet connection to the uplink site with a speedy dedicated line.

FUTURE PLANS

We plan to implement TASS as continuous service starting with one TDRS, within the next year, and rapidly progressing into full global coverage with three satellites. The exact time table for this deployment is presently being worked out in consideration of potential users.

ACKNOWLEDGEMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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