Toward Decimeter-Level Real-Time Orbit Determination: A Demonstration Using the SAC-C and CHAMP Spacecraft

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BIOGRAPHY

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Timothy N. Munson received his Bachelors Degree in Civil Engineering and Geodesy from Virginia Polytechnic Institute and State University in 1981. In 1984, he began work at JPL as a Member of the Technical Staff in the GPS Systems Group. His work at JPL has been focused on GPS receiver design and test in both ground- and space- based applications. He is CogE for the GPS receivers on the TOPEX/Poseidon and Jason-1 spacecraft.

ABSTRACT

Satelite de Aplicaciones Cientificas-C (SAC-C) is a cooperative mission between NASA and the Argentine National Commission on Space Activities (CONAE). Launched in November of 2000, SAC-C is in a near-polar orbit and is at an altitude of 707 km. The JPL-provided Blackjack receiver on SAC-C is a multi-antenna, dual-frequency GPS receiver that can be re-configured in orbit. Position information from the zenith-pointing antenna is currently post-processed to decimeter levels. Real-time kinematic position accuracies are on the order of several meters. SAC-C will participate in coordinated flying as an element of the “AM constellation,” comprising SAC-C, Landsat 7, EO-1, and Terra. In order to demonstrate the capabilities of performing precise autonomous orbit determination and maintenance, JPL’s Real-Time GIPSY (RTG) software has been uploaded to the Blackjack receiver and run in real-time.

The RTG orbit determination module is a compact and portable software package optimized for real-time processing and is designed for use on embedded systems. RTG makes use of an extended Kalman filter as well as precise dynamic models for orbiting receivers. RTG simulations using actual GPS data from the CHAMP spacecraft (also carrying a BlackJack GPS receiver) together with JPL’s global differential GPS (GDGPS) corrections demonstrate 30 cm 3D RMS real-time orbit determination capabilities. However, because it is not possible to receive GDGPS corrections onboard SAC-C, uncorrected broadcast GPS ephemeris data are used for the onboard orbit determination, resulting in meter-level orbit determination accuracies. Truth orbits are generated by post-processing the GPS data using the GIPSY/OASIS II software. We will present the SAC-C autonomous OD performance analysis, as well as the high fidelity simulations of the capabilities of RTG when GDGPS corrections are available. We will also discuss the technology path toward the integration of GDGPS capabilities on future missions.

INTRODUCTION

Precision orbit determination is currently used in many applications such as altimetry, imaging and atmospheric science. Types of applications that will benefit directly from decimeter-level satellite positioning in real-time involve monitoring of natural hazards, such as volcanoes and earthquakes, where accuracy and latency are of the essence. Providing the capability of having precise real-time orbit information would benefit also a mission that currently requires any kind of post processing for positional accuracy. This would include missions such as satellite remote sensors, ocean altimeters, and synthetic aperture radar (SAR) mappers. While these types of missions may not require accuracy in real-time, the ability to achieve decimeter-level accuracy onboard would allow for completed science products in near real-time that are ready for immediate analysis, thus eliminating extra analysis cost and time.

In the following sections we will provide a description of the BlackJack receiver, the RTG orbit determination (OD) module and NASA's real-time Global Differential GPS (GDGPS) system. Results will then be presented from the RTG process running onboard SAC-C. Additionally, using real data from the CHAMP spacecraft, we will present the accuracies that are attainable for a low-Earth orbiter that is utilizing the real-time GDGPS corrections.

THE BLACKJACK RECEIVER

The BlackJack receiver, designed at the Jet Propulsion Laboratory, was built for use on scientific missions where accurate orbit knowledge is needed. The BlackJack is a dual-frequency receiver capable of using multiple antennas. To date, it has flown successfully on a number of missions, including SRTM [*Bertiger et al.,* 2000], CHAMP [*Kuang et al,* 2001], SAC-C, Jason-1 [*Haines et al.,* 2002], and GRACE [*Bertiger et al.,* 2002 and *Dunn et al.,* 2002].

The BlackJack collects several types of observable data, including pseudorange, carrier phase, and signal-to-noise ratio. The pseudorange data from the BlackJack are carrier smoothed over an interval of 10 seconds. Because the BlackJack is capable of providing high quality data [*Kuang et al.,* 2001], using its own internal navigation software it is capable of providing kinematic position solutions on the order of five to ten meters, 3D RMS, using only carrier-smoothed, single-frequency GPS pseudorange data.

The on-orbit reconfigurability of the BlackJack software is a unique and useful feature that makes it possible to provide software upgrades even after launch by simply uploading these software changes to the spacecraft. In a typical BlackJack software upload scenario, the new software is compressed and transmitted to the satellite during an in-contact period, transmitting over multiple periods if necessary. Once onboard the receiver, the BlackJack performs error checking on the compressed file and flags any errors found in the received packets. If any packet fails to arrive correctly to the receiver, the individual packet can be uploaded alone, without the need to re-transmit the entire library.

EMBEDDED RTG ORBIT DETERMINATION MODULE

Written in the C programming language, RTG is a software package designed for real-time applications in embedded systems. RTG is capable of supplying routinely accurate position solutions on the ground and on aircraft, in addition to being able to perform precise real-time orbit determination. Also, because of its generic programming in ANSI C, RTG is a highly portable software package. To date, it has been ported to a variety of platforms including Linux, Sun, HP, VxWorks, MacOS, and the BlackJack-specific, proprietary operating system, RogueOS.

The OD flight module of RTG is a modified version of the full RTG package, pared down for use in orbit. It makes use of an extended Kalman filter (EKF) and includes the level of precise dynamic modeling that can be found in GIPSY/OASIS II. The models used in the latest flight version of the RTG OD module include a full EGM-96 70 by 70 gravity field, the DTM 94 atmospheric drag model [Berger et al., 1998], a solar radiation pressure model, Earth orientation and polar motion models as well as a relativity model. In addition, RTG has the capability to utilize the reduced dynamic technique [*Wu, et al.,* 1991] in which empirical accelerations are estimated in order to account for any dynamics left unmodeled.

One feature added to the editing capabilities of the OD flight module of RTG is a routine capable of checking the one-second L1 and L2 observables for breaks in the phase data. First, the phase and range data are verified for time continuity and are then checked for phase breaks. Detected breaks are marked and the L1 and L2 phase and range observables are subsequently combined to form ionosphere-free range and phase measurements. The ionosphere-free phase measurement is then aligned to the range by removing the integer ambiguity in the narrow wavelength. Next, the measurement data are passed into RTG for processing at the desired rate of the solutions. Once inside the main RTG OD module, the data are edited by performing an innovation test. In order to perform the test, the residual and formal errors are computed. If these values are larger than expected, the data point does not pass the innovation test and is not included in the filter.

In porting RTG to the BlackJack receiver, it is partitioned into three separate shared libraries. Of these libraries, only the main OD library interfaces directly with the BlackJack software. The main library is 244 kilobytes in size and contains the majority of the necessary libraries for RTG, including the EKF and all force models other than the gravity field. Because of its large size, the 70 by 70 EGM-96 gravity field has been separated into its own library. The gravity field library is 104 kilobytes in size and contains all of the coefficients necessary to represent the full gravity field. The third library contains all of the setup parameters, including those pertaining to the estimation and model descriptors. This library dictates what state parameters are estimated and in what sense the estimation is performed. Model descriptions that change on a regular basis, such as the tables for the atmospheric flux as well as those for timing and polar motion, are also included in this library. Also included in this library is a list containing descriptions of the GPS satellites that comprise the current constellation, which may need to be changed as new GPS satellites are added to the constellation. This last library is 32 kilobytes in size and is much smaller than the other two in order to allow for it to be more readily uploaded, if desired.

NASA'S REAL-TIME GLOBAL DIFFERENTIAL GPS (GDGPS) SYSTEM

NASA's real-time GDPGS system is an end-to-end system that is capable of supplying accurate GPS orbits and clocks for autonomous positioning of a ground, air, or space user carrying a dual-frequency receiver. The basis for the GDGPS system architecture is a state-space approach, where the orbits of the GPS satellites are precisely modeled, and the primary estimated parameters are the GPS satellite epoch states. The message that is then obtained from the system is the difference between the broadcast GPS orbits and clocks and those determined using the state-space estimation method. Using this approach of providing corrections to the GPS orbits and clocks ensures that the corrections will be globally and uniformly valid.

In order to be capable of estimating very accurate GPS ephemerides and clocks, data from the NASA Global GPS Network (GGN) are used. The GGN is operated and maintained by JPL and currently consists of thirty ground stations worldwide. A map of the GGN as of June 2002 is shown in Figure 1. GPS data are collected at each site at a rate of 1 Hz and arrive at a processing center with an average latency of less than 1.5 seconds. Multiple operation centers process the data in parallel to provide an overall redundancy to the system.

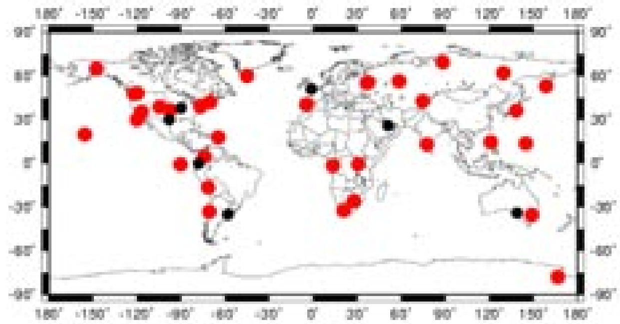

Figure 1: The locations for the sites in NASA's Global GPS Network as of June 2002.

Data from each site in the GGN are streamed back to the operation centers over the open Internet and processed using the Internet-based Global Differential GPS (IGDG) software in order to determine the GPS satellite orbits and clocks. IGDG is capable of computing GPS satellite orbits and clocks that have accuracies of 20 to 30 cm, 3D RMS [*Mullerschoen, et al.*, 2001]. These GPS orbits and clocks are differenced with the broadcast ephemerides to form the global differential corrections. The differential corrections are packed into a compact format in order to allow for efficient relay to the users. The corrections are available through an Ethernet connection or through telephony, including wireless telephones such as those provided by the Iridium system. Additionally, the corrections are available globally over latitudes of –75° to +75° from three Inmarsat satellites at 100° W (Americas), 25° E (Africa), and 100° E (Asia Pacific) using global L-band beams leased by a commercial partner, Navcom Technology, Inc., a Division of John Deere.

SAC-C ON-ORBIT DEMONSTRATION

Satelite de Aplicaciones Cientificas-C (SAC-C) is a mission of the Argentine National Commission on Space Activities (CONAE) and was launched in November of 2002. It is flying in a near-polar orbit at an altitude of 707 km. The mission focus for SAC-C is as an Earth-observing satellite, both for terrestrial and atmospheric monitoring. A picture of the SAC-C spacecraft is shown in Figure 2. The GPS antenna for precise orbit determination is zenith-pointing and mounted on the same surface as the magnetometer boom. A photograph of the SAC-C spacecraft on a mount in an anechoic chamber for electromagnetic interference (EMI) testing is shown in Figure 3, with the location of the GPS antenna noted.

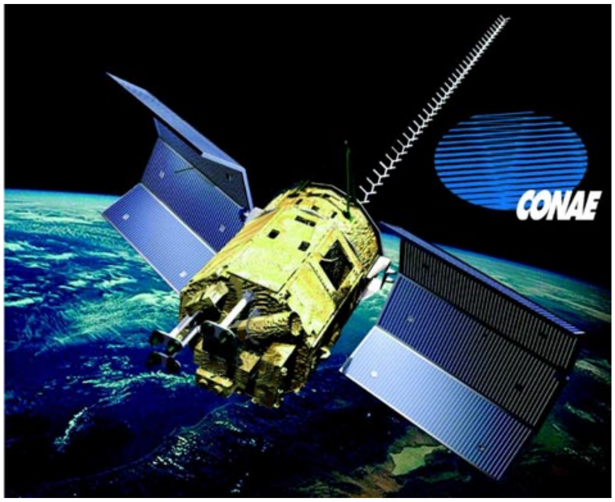

Figure 2: A drawing of the SAC-C spacecraft in orbit (courtesy of the SAC-C mission site, www.conae.gov.ar/sac-c).

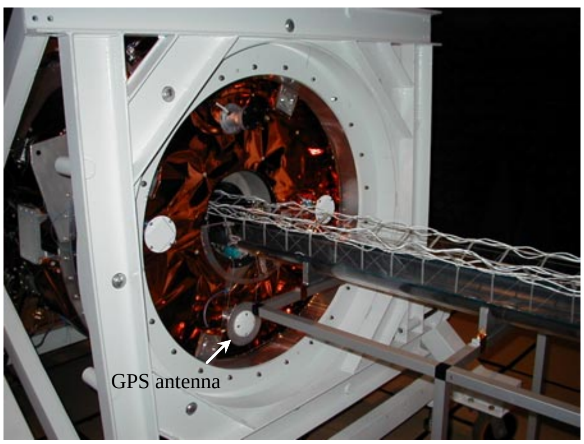

Figure 3: Photograph of the SAC-C spacecraft on a mount in the anechoic chamber for EMI testing.

SAC-C is the first spacecraft to operate RTG onboard in real-time. RTG resides in flash memory inside the BlackJack receiver. The processor for the BlackJack on SAC-C is a 200 MHz 603e PowerPC chip. RTG interfaces directly with the BlackJack software in order to obtain the dual-frequency pseudorange and phase observables at a 1 Hz rate. In addition to the observables, RTG obtains the broadcast GPS ephemeris through the BlackJack software. Since the antenna and RF front-end of the receiver onboard SAC-C are not capable of receiving the global differential GPS correction signal from the Inmarsat satellites, only the broadcast GPS ephemerides are used. A successful flight of RTG onboard SAC-C is useful in order to demonstrate its readiness level to fly onboard a future spacecraft carrying a receiver capable of obtaining the correction message.

When processing the GPS data on SAC-C, the one-second observables are fed into RTG and checked for phase and time continuity. Every 30 seconds the data are processed through RTG's EKF in order to produce state solutions. In the case of SAC-C, the state solution consists of position, velocity, receiver clock bias, coefficient of drag, solar scale, and the radial, cross and along-track reduced dynamic accelerations. Drag and solar scale are estimated as constant values while the reduced dynamic accelerations are estimated as stochastic parameters. The level of process noise used for the reduced dynamic accelerations has a correlation time of 65 minutes and a steady-state process noise level of 15, 200, and 100 nanometers per second squared for the radial, cross-track and along-track components, respectively. Dynamic models that are used for RTG on SAC-C are the EGM-96 70 by 70 gravity field, the DTM94 atmospheric drag model, and solar pressure and relativity models.

The 30-second solution data are saved onboard the spacecraft until the data can be downloaded to the ground. Data from SAC-C are nominally downloaded twice per day. After download, the results computed on orbit are extracted from the raw data packets and compared to the post-processed GIPSY results, which are good to the decimeter level. Because there is no external way to confirm the orbit accuracy of the GIPSY solution for SAC-C (such as satellite laser ranging), past experience with processing BlackJack data as well as using the offset described by the daily orbit solution overlaps are used as the means to assess the accuracy of the "truth" orbits.

Initial results for the RTG OD process for SAC-C are shown for September 28, 2002 in Figure 4 for position and in Figure 5 for velocity. These figures show the orbit difference between the RTG onboard solution and the GIPSY post-processed solution. For this comparison, the GIPSY solution uses JPL's quick-look products [Muellerschoen et al., 1995] for the GPS orbits and clocks. Note that the results shown below are for a filter arc that spans approximately 4.5 hours, where the first 30 minutes of convergence time have been removed. Additionally, in order to demonstrate the position accuracy of the BlackJack receiver without the aid of RTG, a comparison between the onboard BlackJack point-position solution and the GIPSY precise orbits are shown in Figure 6 for position and Figure 7 for velocity.

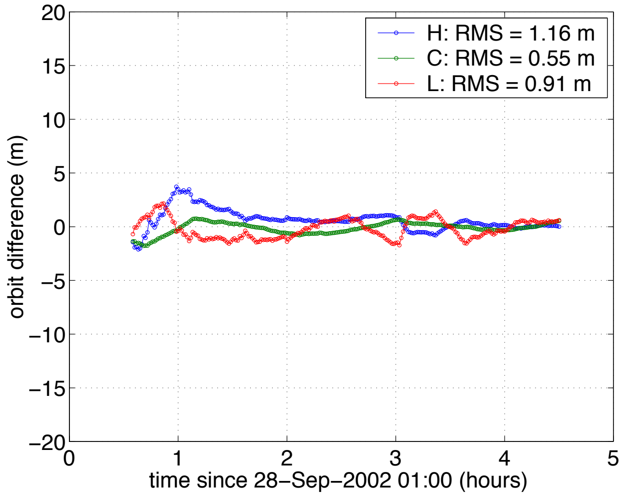

Figure 4: Orbit position differences between the RTG onboard solution and the GIPSY post-processed solutions in the radial, cross-track, and along-track directions for September 28, 2002. The first 30 minutes of convergence time have been removed.

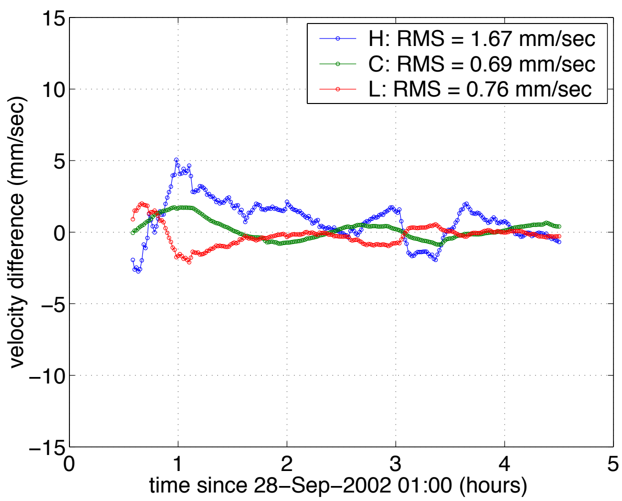

Figure 5: Orbit velocity differences between the RTG onboard solution and the GIPSY post-processed solutions in the radial, cross-track, and along-track directions for September 28, 2002. The first 30 minutes of convergence time have been removed.

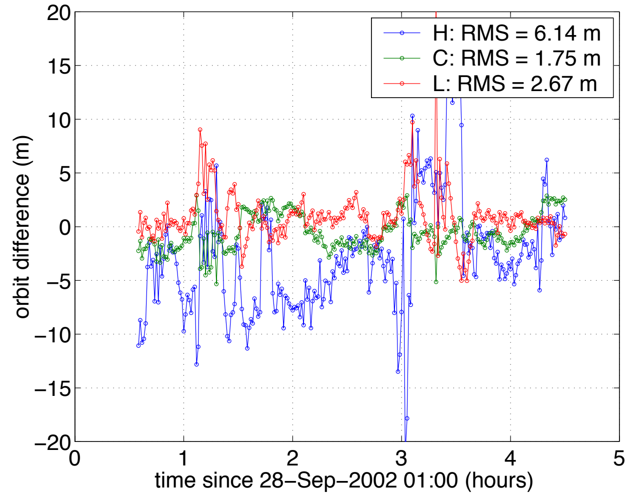

Figure 6: Orbit position differences between the BlackJack onboard point-position solution and the GIPSY post-processed solutions in the radial, cross-track, and along-track directions for September 28, 2002.

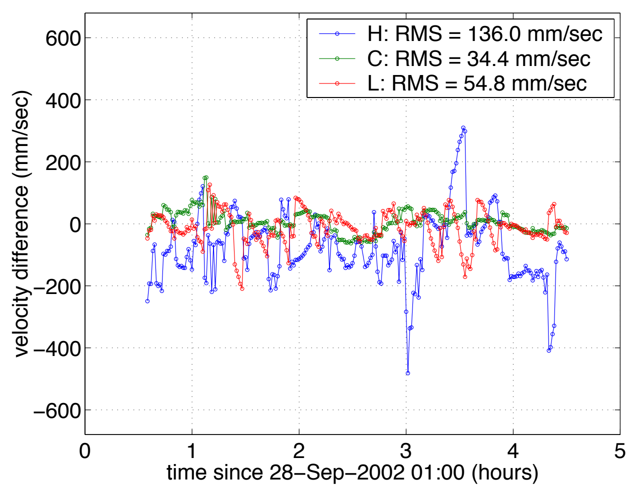

Figure 7: Orbit velocity differences between the BlackJack onboard point-position solution and the GIPSY post-processed solutions in the radial, cross-track, and along-track directions for September 28, 2002.

Note that the results shown above only illustrate a short period of time on September 28. Due to a problem in the editor that limits the length of the filter passes, only short filter arcs are being produced by RTG. Code modifications are being implemented that will enhance the editor, which presently is not sensitive enough to detect occasional outliers of pseudorange data. Because of the nature of the current architecture of the EKF inside the OD module, certain outlying data cause the filter to diverge without the ability to recover. In order to avoid divergences in the solution, the filter is set to restart if only one measurement passes the innovations test. The filter then restarts using the current notion of spacecraft position from the BlackJack. The imminent improvements in the editor will allow the EKF to be less susceptible to the occasional data outlier, thus producing longer filter processing arcs

Despite the problem with the short data arcs, the accuracies shown above of 1.16, 0.55 and 0.91 meters RMS for position (Figure 4) and 1.67, 0.69, and 0.76 mm/sec RMS for velocity (Figure 5) in the radial, cross-track and along-track directions correspond to the expected levels of accuracy from the filter. This is confirmed by running the RTG OD module in a post-processing mode on the 10-second observable data downloaded to the ground from SAC-C. Also note in Figure 6 that the BlackJack is providing position accuracies better than 7 meters, in the radial, cross-track and along-track components for this time period.

The difference between the RTG onboard solution and the GIPSY post-processed solution can be attributed to several factors. The largest difference between the two processing schemes is the use of quick-look versus broadcast GPS orbits and clocks. Additionally, the gravity field models used differ between the two methods. The GIPSY processing scheme uses the TEG4 gravity field while RTG is using the EGM-96 gravity field. The TEG4 gravity field, determined by the University of Texas' Center for Space Research (CSR), is derived from the GPS tracking and accelerometer data from the CHAMP mission [*Tapley et al.*, 2001]. Another model difference between the two processing methods is that GIPSY is modeling the spacecraft as a cylinder and RTG is using a simple bus model. This will affect how the accelerations induced by drag and solar radiation pressure are applied to the spacecraft. Finally, both methods lack an accurate attitude model, which contributes to errors in both of the results.

CHAMP DEMONSTRATION OF REAL-TIME GLOBAL DIFFERENTIAL CORRECTION

The CHallenging Minisatellite Payload (CHAMP) was launched on July 15, 2000 into a near-polar, 450 km altitude orbit. CHAMP was built by GeoForschungsZentrum (GFZ) Potsdam. CHAMP's primary mission is to simultaneously map the Earth's magnetosphere and gravity field. The CHAMP satellite is equipped with multiple operational GPS antennas: one antenna pointed in the zenith direction for precise satellite positioning, one aft-mounted antenna for atmospheric occultation measurements, and one nadir-pointing antenna for use in GPS reflections experiments. A picture of the CHAMP spacecraft with the zenith and aft-pointing antennas visible is shown in Figure 8.

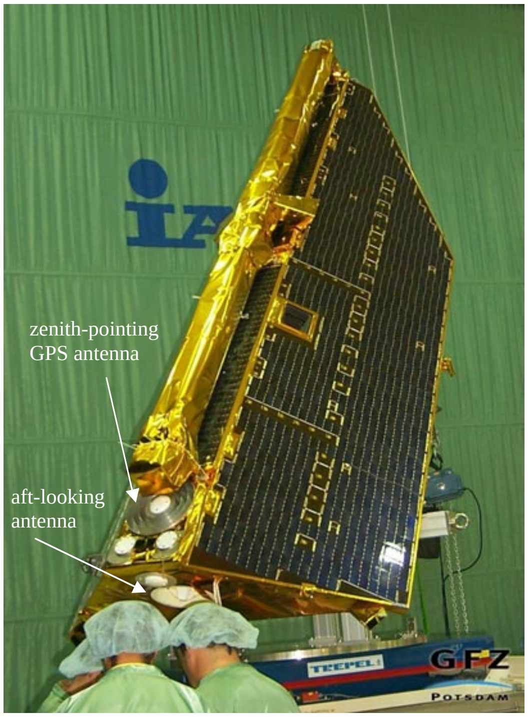

Figure 8: Photograph of the CHAMP satellite with the magnetometer boom in the stored configuration (courtesy of the GFZ-Potsdam website, http://op.gfz-potsdam.de/champ, © GFZ-Potsdam, Germany).

To demonstrate the potential for using the global differential corrections in real-time onboard a spacecraft, we processed CHAMP data using NASA's real-time global differential GPS corrections. CHAMP is chosen to demonstrate this capability because the data from CHAMP are of slightly better quality than the data from SAC-C. The antenna connected to the BlackJack on CHAMP makes use of a choke ring antenna and is in a relatively benign multipath environment. Unlike CHAMP, SAC-C is not equipped with a choke ring antenna and the antenna is located in a much more severe multipath environment. Note in Figure 3 the sources of multipath on SAC-C include several prominent objects such as the magnetometer boom, the spacecraft mounting ring, and the body of the spacecraft just below the GPS antenna. Additionally, because CHAMP has a star tracker as a source for spacecraft attitude, the attitude model for CHAMP is better defined than that for SAC-C. With fewer factors affecting the accuracy of the CHAMP orbit solution, the performance of RTG when using the global differential corrections is easier to quantify when using data from the BlackJack receiver onboard CHAMP.

The post-processed GIPSY solution for CHAMP is used as the "truth" comparison. The GIPSY solution is produced using the precise FLINN GPS orbits and clocks

[*Heflin et al.*, 2002]. The FLINN GPS orbits are typically determined at the 5-centimeter level. The resulting GIPSY solution for the CHAMP orbit is good to better than 10 centimeters, 3D RMS [*Kuang et al.*, 2001]. This level of orbit accuracy of the GIPSY solution has been verified by two methods. First, it was independently confirmed using SLR data. In addition, the overlaps of the GIPSY orbit solution were computed. The errors implied by the daily orbit overlaps concur with the sub-decimeter-level accuracy determined by SLR.

In order to test the attainable accuracy levels of RTG using the GDGPS correction message, RTG is run on a UNIX system with data downloaded from the CHAMP BlackJack receiver. In order to demonstrate the total capabilities of RTG in real-time, the data are processed using the GPS orbits and clocks determined in real-time, as they would be used when GDGPS corrections are available. The comparison between the RTG and GIPSY solutions for July 15, 2002 are shown in Figure 9 for position and Figure 10 for velocity.

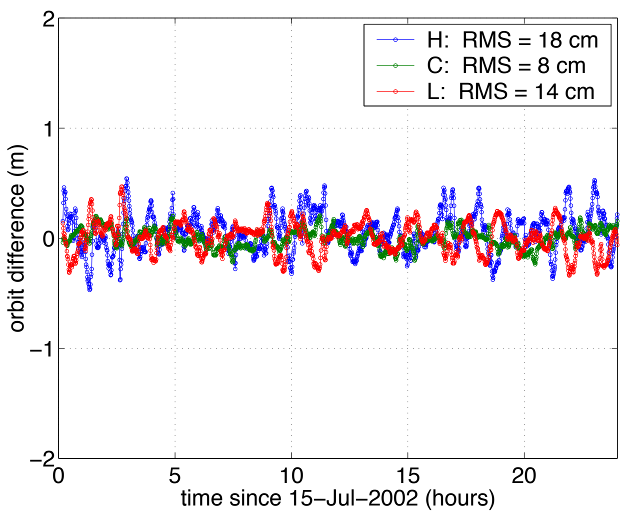

Figure 9: Orbit position differences between the RTG solution using the GDGPS corrections and the GIPSY post-processed solutions using precise FLINN orbits and clocks. The differences are shown in the radial, cross-track, and along-track directions for July 15, 2002.

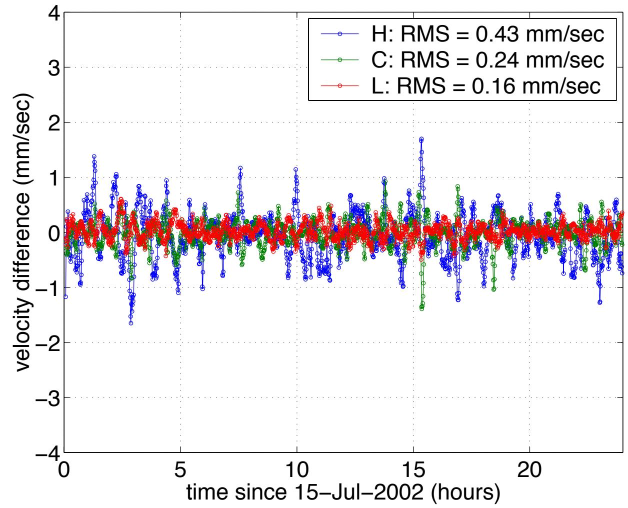

Figure 10: Orbit velocity differences between the RTG solution using the real-time GDGPS corrected orbits and the GIPSY solutions post-processed using precise FLINN orbits and clocks. The differences are shown in the radial, cross-track, and along-track directions for July 15, 2002.

The two plots above are the differences between the RTG solution and the solution determined using GIPSY/OASIS II. For the position estimates, the RMS of the differences is 18, 8 and 14 centimeters in the radial, cross-track, and along-track directions. The 3D RMS of the position differences over the entire day is 24 centimeters. In velocity, the differences are 0.43, 0.25, and 0.16 millimeters per second in the radial, cross-track, and along-track directions, with a 3D RMS difference of 0.53 millimeters per second. This demonstrates the capability of RTG to perform orbit determination at the decimeter level in real-time, which is sufficiently accurate to be beneficial to many space borne scientific applications.

FUTURE PLANS

In the immediate future, software updates are in the process of being made that will improve the quality of the real-time solution. Plans exist to upload a more sophisticated data editor that has a higher sensitivity to detecting measurement outliers that cause divergence in the EKF. For further improvements in editing capabilities, an additional software improvement planned for the future is to add a smoothing technique to the space borne real-time OD module that smoothes the solutions back over time. RTG would then use the higher-quality smoothed solutions to edit incoming data at a more stringent level.

The next step in hardware development is to utilize an integrated differential GPS receiver for use in space applications. This would require having a receiver that is capable of tracking and decoding a signal carrying the GDGPS correction message, such as the Inmarsat correction signal. Starting with the current BlackJack technology, the addition of the Inmarsat signal would require modification of the receiver front end and tracking architecture so that it is capable of receiving the GPS signals at the L1 and L2 frequencies and the Inmarsat signal at 1545 MHz.

SUMMARY

The OD module of RTG was successfully ported to the BlackJack GPS receiver flying onboard SAC-C. GPS position and velocity solutions are being computed in real-time onboard SAC-C using broadcast GPS orbits and clocks. These real-time results are downloaded to the ground and verified against SAC-C orbits precisely determined in a post processing using GIPSY/OASIS II.

In addition to demonstrating the readiness level of RTG to fly onboard a spacecraft, we presented the attainable accuracies that are available for a low Earth orbiter when using the GDGPS corrections. With the inclusion of the GPS orbit and clock corrections from NASA's GDGPS system, the results for CHAMP demonstrate that it is possible to achieve position solutions to better than 30 cm 3D RMS in real-time with only modest software and hardware changes.

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