First orbit determination performance assessment for the OCX navigation software in an operational environment

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Abstract

Half-way through its iterative development cycle, the navigation software for the GPS Next Generation Operational Control System (OCX) has achieved a major milestone in early 2012, pulling together multiple software strands developed in earlier iterations to provide for the first time an OCX GPS orbit and clock determination capability, significantly exceeding the orbit and clock determination (zero age of data) accuracy requirements

While significant refinements and additional features are on course for implementation in the remainder of the OCX development effort, the software is now sufficiently mature to characterize its orbit determination performance in real-world operational scenarios.

The operational environment for testing the OCX navigation software is provided by JPL's Global Differential GPS (GDGPS) System [www.gdgps.net]. With its vast global network of real-time GNSS tracking sites it is possible to select a subset of sites to closely approximate the geographic distribution of the actual OCX tracking network, as well as the type and frequency of the OCX range measurements. The GDGPS offers a unique opportunity to deep-soak the nascent OCX navigation software in this environment, identify and eliminate bugs very early in the software life cycle, and tune its performance with vast amounts of real data processing.

We will describe the key orbit determination performance attributes of the OCX navigation software after several months of operations in the GDGPS system under an OCX-like operational scenario, and demonstrate that user range errors (URE) of sub-10 cm RMS are routinely achieved. We will also describe some innovative design features of the software and its key quality attributes.

Introduction

The contract to develop and implement the next generation GPS operational control segment was awarded by the U.S. Air Force in February 2010 to an industry team led by Raytheon. The project, known as OCX, is a complete overhaul of the GPS operational control segment, including new architecture, infrastructure, hardware, and software required to comply with a set of demanding performance requirements. Within the Raytheon team ITT (as lead) and JPL have the responsibility for the Navigation System, encompassing the positioning, navigation, and timing capabilities of GPS.

To meet and exceed the OCX navigation performance requirements, the orbit determination and ephemeris prediction software at the core of the navigation system adapt major elements of JPL's navigation technology, proven in the operations of its Global Differential GPS (GDGPS) System [www.gdgps.net]. Key design goals for the navigation subsystem include accurate ephemeris (expressed primarily in terms of user range error, or URE), ease of model upgrades, and a smooth and safe transition from the legacy system to OCX. Bertiger et al. (2010b) described the team's approach for complying with the navigation requirements, the supporting analysis, and the key architectural elements of the navigation system.

The development of the OCX navigation software follows an iterative approach, with six 6-month long consecutive iterations. While the development is currently at its half-way point, the high heritage of the software and the availability of a real-world testbed in the GDGPS System, enable us to deliver and validate early key navigation software functions, including the orbit determination software.

Below we describe the key quality attributes of the OCX orbit determination software, and discuss its heritage in JPL's navigation technology. We then describe how the GDGPS system is used to assess and validate the performance of the software under operational conditions resembling actual OCX operations, demonstrating a zero age of data user range error (ZAOD URE) of sub-10 cm RMS, exceeding OCX requirements. We conclude by discussing the potential future benefits from the ongoing availability of a live, unclassified, operational testbed to ensure long-term quality and cutting edge performance of the software, as well as reduce lifecycle cost.

User Range Error (URE)

Because the error in pseudorange-based kinematic positioning is, to first order, directly proportional to the URE (via the Dilution of Precision - DOP factor [Jorgensen, 1984]), URE is a key quality metric for the GPS signal. It is a function of both the error in the broadcast satellite orbit and the broadcast satellite clock. In the OCX requirements, the terrestrial service volume form of the URE is defined as:

$$URE = \sqrt{(dr - dt)^2 + (dc^2 + di^2)/50} \quad (1)$$

where dr is the error in the satellite's radial position, dt is the error in the satellites clock, dc is the error in cross-track position, and di is the error in-track position. These error terms correspond to the difference between the orbit and clock states of the spacecraft as represented by the *broadcast navigation message* and the actual state of the spacecraft. The navigation message representation of the spacecraft state includes additional errors due to the fitting of the message parameters, inter-signal calibration, and prediction errors. Here we will focus strictly on the orbit and clock errors from the OCX navigation filter without any prediction. .

The OCX requirements for the URE are a function of Age of Data (AOD). AOD is the lag between the epoch time of the orbit and clock values as represented in the navigation message, and the time tag of the last measurements used in the orbit and clock estimation. ZAOD (zero AOD) implies that the estimated orbital state at time t are based on range measurements up to and including time t, and no orbit prediction is involved. Table 1 lists the ZAOD URE requirements for legacy satellites (GPS II) and for GPS III satellites and GPS II satellites with modernized signal. The difference in requirements stems from the more precise navigation message format available to GPS III satellites and in modernized signals, such as L2C. Since the orbit determination is independent of either the navigation message type (fit errors) or the signals observed by the user (inter-signal calibration error), the requirement is derived by removing these two errors in quadrature with a resulting requirement of 14 cm RMS URE (Table 1).

Table 1. The orbit determination error allocation are derived from the ZAOD URE requirements (glossing over some fine details), after removing in quadrature the known contributions from the navigation message fit errors, and the inter-signal calibration errors (inflated by the ionosphreic-free linear combination of signals).

	GPS II with Legacy Signals	GPS III; GPS II with modernized signals
ZAOD URE RMS	30 cm	15 cm
Message fit Error	7 cm	3 cm
Inter-Signal Calibration Error	2*2.54 = 5.08 cm	2*2.54 = 5.08 cm
Derived Orbit Determination Error Allocation	28 cm	14 cm

Design Heritage and Operational Experience with the GDGPS System

The OCX orbit determination software is based on JPL's Real Time GIPSY (RTG) software, operationally proven within the Global Differential (GDGPS) System, which is functionally similar to the current GPS Operational Control Segment (OCS) navigation system.

The GDGPS System is a GPS augmentation system on a global scale. 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 orbital states and instantaneous clock offsets. The clock offsets are estimated as white noise process every epoch. This approach guarantees that the estimated ephemerides are globally and uniformly valid and that the system isolates clock anomalies.

The GDGPS ground network of real time GPS receivers consists of more than 100 semi-codeless dual frequency receivers (Figure 1). The high level of network redundancy (at any time each SV is tracked by an average of 20 stations) is key to the high operational reliability of GDGPS. GPS measurements collected at the tracking sites are streamed in parallel to three geographically-separated Operations Centers. Data processing is carried at the Operations Centers on redundant chains of computers using the 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).

GDGPS has been operational since 2000 with a track record of 99.999% reliability. A complete array of real-time GPS state information, environmental data, and ancillary products are produced in support of the most demanding GPS Augmentation operations, Assisted GPS (A-GPS) services, situational assessment, and environmental monitoring [www.gdgps.net].

The quality of the GDGPS real-time GPS ephemerides and clocks are routinely verified against the cm-level accurate JPL post-processed orbit and clock products, and consistently demonstrate sub-10 cm URE.

Using an appropriate subset of its tracking network, GDGPS is ideally suited to serve as a testbed and validation tool for the high performance OCX navigation software, significantly reducing Program risk by enabling test and validation with real data, in a real-time operational environment.

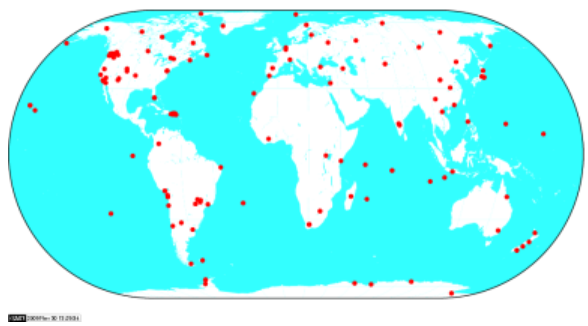

Figure 1. The network of real-time GPS tracking sites feeding the GDGPS System as of 2012

The OCX Orbit Determination Software - RTGX

The OCX orbit determination software is derived from JPL's RTG and GIPSY software packages [Webb and Zumberge, 1997; Bertiger et al. 2010a], and benefits from decades of modeling refinements and operational experience at JPL. However, the new OCX software, called RTGX, contains several important improvements.

Whereas GIPSY is in FORTRAN and RTG is in C, the core logic of RTGX is a new design, and is written in C++. Utility libraries and several measurement and force models were inherited from RTG and were kept in C to minimize development effort. New code, including updated models, were written in C++. The careful use of object oriented design approach and a disciplined development and testing process has led to significant improvements in quality, performance, and ease of use. The flexible design supports configuration for any GNSS orbit determination as well as positioning of receivers on earth and in space, including crosslinks. In addition to the OCX application discussed here RTGX is being used operationally with GDGPS to estimate GLONASS and GPS differential corrections.

RTGX is designed to ingest measurements of pseudorange and phase via shared memory or files. Shared memory is typically used for real-time applications and files for simulations of real-time measurements or for post-processing. Its underlying design supports fairly arbitrary radiometric measurements that include not only GNSS phase and range but also Doppler and Satellite Laser Ranging (SLR).

RTGX possesses state of the art models for the GPS measurement and satellite dynamics. The OCX requirements call for compliance with the 2010 IERS Conventions [IERS Technical Note 36, 2010]. These are augmented, where appropriate, with manufacturer-provided satellite models, antenna phase and group delay variations (in azimuth and elevation) for transmitters and receivers, and JPL-developed models, such as for solar radiation pressure [Bar-Sever and Kuang, 2004]. All the models are selectable, and the highly modular software can easily incorporate future modeling improvements.

While the RTG filter is based on UD factorization [Bierman, 1977], RTGX reverts to GIPSY's SRIF formulation [Bierman, 1977], but with a novel implementation that supports multi-threading. With a large parameter space the SRIF implementation is easier to parallelize, and the switch to SRIF formulation was done in order to improve throughput with modern CPU architectures. The multi-threading options may eventually be extended to multiprocessors using the Message Passing Interface (MPI) [http://www.mpi-forum.org/].

RTGX is designed to accommodate any type of range measurements, for example, from any Global Navigation Satellite System (GNSS), including the accommodation of pseudorange biases, which are a feature of the FDMA GLONASS signal.

One of the most important quality improvements implemented in RTGX is the documentation technology. We have opted to use Doxygen [www.doxygen.org], a free software under the GNU General Public License. Doxygen is a document generator, enabling the merging and cross-referencing of inline documentation and external documentation, such as mathematical models. Doxygen makes it easy to keep the documentation up to date as the code evolves. It also enhances user experience through the use of web-like interface, links to actual code, and automatically-generated and professionally-looking Universal Modeling Language (UML) diagrams.

RTGX features a new and innovative user interface informed by the many different applications and radio-metric data types processed over the 30-years of the software's evolution. The new interface, called RTG-Tree, is an abstraction of a tree-like structure (trunk, branches, leaves), allowing the user total control of the many options of RTGX while promoting human understanding and intuition in a relatively compact format. In developing the new input, we considered other input standards including Fortran-like namelists, XML, and YAML [www.**yaml**.org]. Namelist would not have had a simple enough C++ implementation and did not offer a nice human interface that supported inheritance. XML was too verbose to be human friendly and editable with a text editor. YAML is very close to our tree format, but lacked all the inheritance features we needed to make information common to large constellations easy to input and understand. In addition to the ease of use features, the implementation RTGX allows for on-the-fly software configuration changes when the running process receives a signal, without the need for a restart. For instance, one can on-the-fly re-direct certain output, eliminate or add satellites or ground stations, and update Earth orientation parameters.

The OCX orbit determination process retains the GDGPS multi-step approach, where at the first step the GPS orbital and clock states are estimated at a low rate. The estimated orbital states are then propagated forward to the next epoch (typically 1 – 15 minutes ahead, during which the orbital states are highly predictable), and are fed into a filter stage that estimates at a high rate (typically 1 - 60 seconds) only the clock states and a few other parameters such as phase biases.

In OCX each filter stage is an instantiation of the exact same RTGX software, with a slightly different configuration (through the RTG-Tree input). In fact, the same software set, under different configurations, can also perform point-positioning using fixed orbit and clock states. This property is very useful as a quality and validation tool during the software development, and reduces overall lifecycle cost when used in multi-functions systems such as GDGPS and OCX.

The OCX navigation software will implement a third step, where the high rate clock estimates are fed into a special timescale filter, designed to model the temporal stochastic properties of the estimated clocks, and adjust the clock estimates to produce a well-behaved unified time scale complying with the OCX stability and predictability requirements, and steered to USNO-UTC. The timescale filter is being developed by the Naval Research Laboratory (NRL) under contract to JPL.

The satellite states produced by the first stage orbit and clock filter form the ZAOD states, and are subject to the orbit determination performance requirements. Following the GDGPS concept of orbit prediction operations, a short history (up to a few days) of ZAOD orbital states are the input to a separate process that produces orbit predictions (up to 64 days) from which the broadcast ephemeris are then derived via a least squares fit. These predicted orbits are subject to a set of non-zero AOD URE requirements [Bertiger et al, 2010b].

The development of the OCX orbit determination software is presently at the mid-point of its roughly 3-year development effort. Thanks to the high heritage in GIPSY and RTG, the development team was able to implement the basic orbit determination capability early, thus reducing risk to the overall program from this critical and complex function. Certain features and refinements are the focus of the remaining development effort.

Performance Analysis Methodology

The value of the GDGPS System as a real-world testbed for the OCX navigation software at all stages of its development cycle cannot be overstated. Decades of experience in precision real-time and post-processed GPS orbit determination have taught us that massive processing of real data is far superior to data simulations or data snapshots for debugging, testing, and validating operational software. No simulation or unit-testing can adequately capture the rich error spectrum and features of real data in an operational environment.

To run RTGX within GDGPS we expanded the front-end data gathering and conditioning class to include the internal data type of the GDGPS ground tracking network (GDGPS-BINEX). These data arrive at 1

Table: 2. Orbit determination filter states and their characteristics

Parameter	Type	Apriori Sigma	Process Noise	Update Interval (Seconds)	Time Correlation
Satellite Position/Velocity	Constant/Epoch State	10 meters 1 cm/sec			
Solar Scale	Constant	0.1			
Y-Bias	Constant	0.1			
Once Per Rev Along Track & Cross Track Acceleration	Stochastic	1 nm/sec^2	1 nm/sec^2/sec$^{0.5}$	43201	Random Walk
Wet Troposphere Zenith Delay	Stochastic	50 cm	5x10^{-3} cm/sec$^{0.5}$	300	Random Walk
Gradient Troposphere	Stochastic	100 cm	5x10^{-4} cm/sec$^{0.5}$	300	Random Walk
Station and SV Clocks	Stochastic	0.1 secs	0.1 secs	300	White Noise

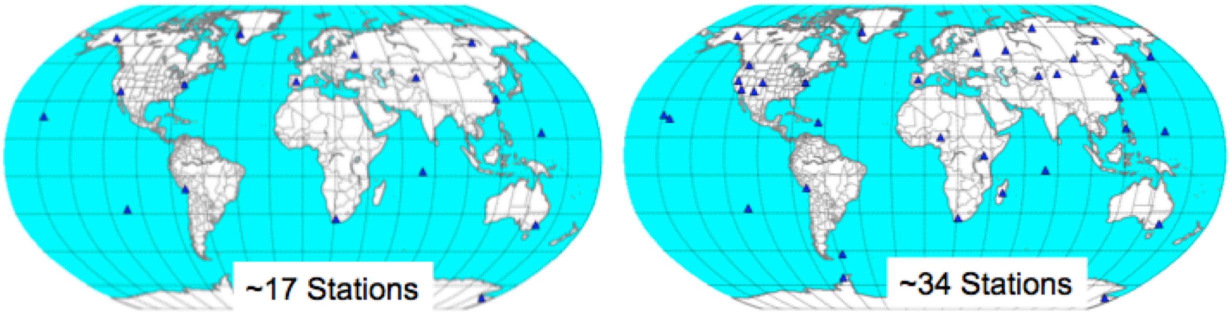

Figure 3. The two GDGPS sub-networks used for testing RTGX.

Hz, but RTGX can be configured to downsample the data to an arbitrary frequency.

We have chosen to run RTGX with two network configurations. The first one is a 17-site subset of the GDGPS network that attempts to approximate, albeit sub-optimally in terms of observing geometry and data reliability the geometry of the OCX tracking network [Bertiger et al, 2010b]. The second network configuration is roughly double in size (37 sites) to compensate (and more) for some of deficiencies of our GDGPS 17-site sub-network (Figure 2). In both cases we configured RTGX to use the same orbit determination strategy derived from the standard GDGPS orbit determination operation, which is also recommended for OCX orbit determination operations [Bertiger et al, 2010b]. The key elements of the estimation strategy are:

- Use ionospheric free combination of semi-codeless L1P and L2P pseudorange and phase measurements (aka the primary signal pair). Other ionospheric-free signal combinations are possible and perform similarly.
- State of the art measurement models, including: solid tides, ocean loading, tropospheric delay, satellite attitude, antenna variation maps, phase windup, light time, and relativity. Conforming to IERS 2010 Conventions where applicable.
- State of the art satellite dynamics models, including: point mass attraction of the Earth, Moon, Sun, and planets, Earth gravitational field, solid tides, pole tides, ocean tides, solar radiation pressure, earth radiation pressure, and relativity.
- The estimation strategy, featuring white noise stochastic processes for both satellite and station clocks [Bertiger et al., 2010b], is summarized in Table 2.

The thus-estimated orbit and clock states can be evaluated against the cm-level-accurate post-processed solutions produced operationally at JPL using GIPSY with data from a network of about 80 ground receivers. At each measurement epoch the difference between the real-time orbit and clock states and the ‘truth’ orbit and clock states are converted to the terrestrial service volume form of the (ZAOD) URE metric using Eq 1.

Results

Using the configurations specified in the previous section, RTGX has been run in the operational GDGPS environment for a cumulative total of 3 months over the period June – August, 2012 for debugging and testing. The number of eclipsing satellites vary from 5 to 11 during this period. From July 11 through August 15 it ran continuously in its two configurations. The RMS URE for each satellite was computed over 24 hours of each day (per specifications). The distribution of the daily RMS URE for all satellites (Block IIA, IIR, and IIF) is presented in Figure 4 together with the relevant statistics. Table 3 summarizes the key orbit determination performance statistics over this robust testing period, demonstrating a significant margin against the derived requirement of 14 cm RMS URE (Table 1).

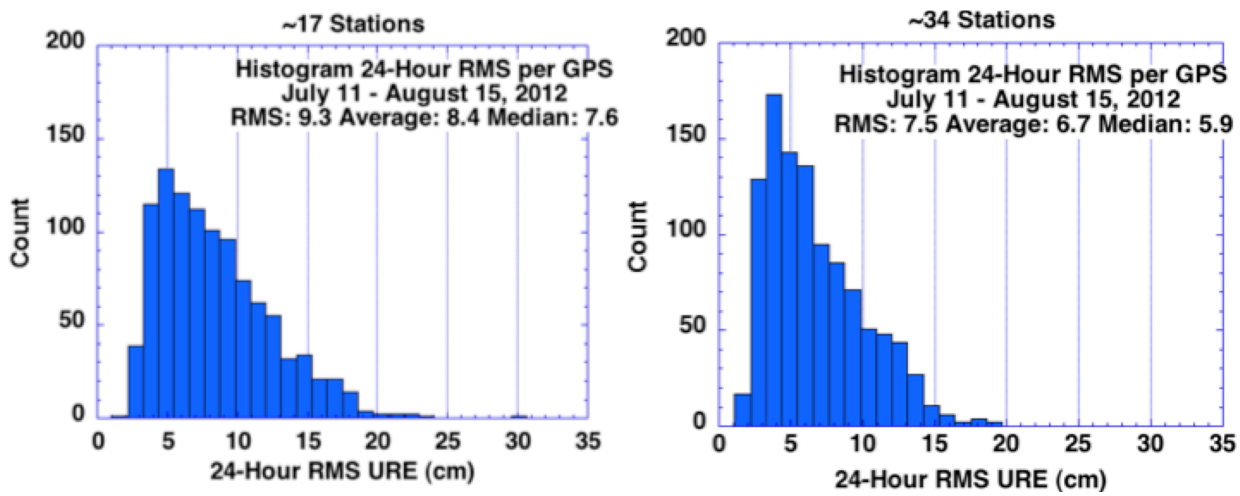

Figure 4. RMS URE histograms carried out over all satellite during July11-Aug 15 test period.

Table 3. ZAOD orbit determination performance of RTGX with two network configurations

	17 Site Network	34 Site Network
Radial Orbit Error (RMS)	7.3 cm	6.4 cm
Clock Error (RMS)	11.5 cm	9.6 cm
URE (RMS)	9.3 cm	7.5 cm

Another valuable test of the software's modeling fidelity and accuracy is precise point positioning. Here truth is available at sub-cm levels, and it is more sensitive than orbit determination to the fidelity of Earth models such as tides. To this end we configured the software (via RTG-Tree) to position a set of well known reference sites using JPL's most precise post-processed orbit and clock states, and compared the estimated positions to their official ITRF2008 coordinates [http://itrf.ensg.ign.fr/ITRF_solutions/2008/]. Figure 5 depicts the performance, in terms of difference with ITRF2008, for five randomly selected sites: Algonquin Park, Canada (ALGO), Greenbelt, MD (GODE), Fort Irwin, CA (GOLD), Tahiti (THTI), and Washington, DC (USN3). The positioning performance is compared to state of the art positioning with the GIPSY software, which includes phase ambiguity resolution [Bertiger et al., 2010a]. The RTGX-based positioning is shown to be only a few mm worse than the state of the art, validating the geodetic quality of the software.

Finally, we also examined the convergence performance from cold start. The initial orbital states at cold start are accurate to 2 meters, representing realistic capability based on crude metrology. Figure 6 depicts a typical converge performance for the 17 station network configuration. In general, convergence to sub-10 cm URE is achieved within the first 6 hours.

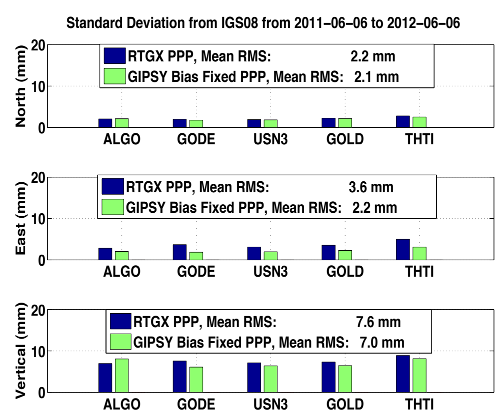

Figure 5. Static GPS point positioning with RTGX and GIPSY differenced with ITRF2008 truth coordinates. In both cases GIPS-based precise post-process orbit and clock states were used.

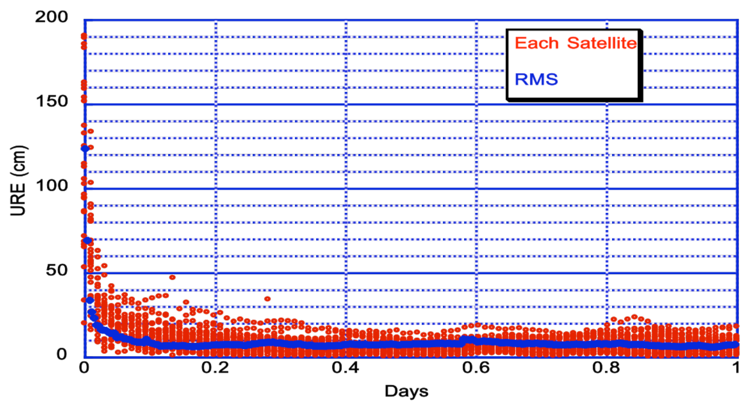

Figure 6. ZAOD URE as a function of time from cold start.

Conclusions

Mid-way through its development cycle, the OCX orbit determination software, RTGX, is far exceeding its key orbit determination URE performance metric. Future enhancements and tuning are likely to improve the performance further.

RTGX represents a significant enhancement of RTG, leading to improved GDGPS positioning performance. The availability of a real-world real-time operational testbed, in GDGPS, has been key to reducing development risk and speeding up the development cycle. Going forward, even after formal delivery of the OCX navigation software to the Air Force, a continuous operational testing of the software within GDGPS, promises to be just as valuable. The benefits include:

- Soaking, debugging, and tuning with very large real world data sets over long periods of time.
- Enables the maintenance and evolution of a live software, responding to the ever changing constellation and potential signal anomalies.
- Enables the ongoing evolution of the software in keeping with the development and refinement of new models and orbit determination skills.
- Reduce software lifecycle cost by continuously upgrading the software, in comparison to software that is only episodically upgraded.
- Enables a rapid response from the development team to bugs and anomalies discovered in operating in the limited-access, secured OCX environment

Acknowledgement

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References

Bar-Sever, Y. E., and Kuang, D., IPN Progress Report 42-160, JPL, 2004. This document is available online at http://ipnpr.jpl.nasa.gov/progress report/42-160/title.htm

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.

Bertiger W., S. Desai, B. Haines, N. Harvey, A. Moore, S. Owen, J. Weiss. 2010a. Single Receiver Phase Ambiguity Resolution With GPS Data. Journal of Geodesy. Accepted for publication Feb. 2010, DOI: 10.1007/s00190-010-0371-9.

Bertiger, W. I., Y. Bar-Sever, N. Harvey, K. Miller, L. Romans, J. Weiss, L. Doyle, T. Slorzano, J. Petzinger, A. Stell, "Next Generation GPS Ground Control Segment (OCX) Navigation Design", Institute of Navigation GNSS Meeting, Portland, OR, September 2010b.

Bierman, G.J. (1977). *Factorization Methods for Discrete Sequential Estimation*. Academic Press

IERS Conventions (2010). Gérard Petit and Brian Luzum (eds.). (IERS Technical Note ; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6

Jorgensen, P. S., "Navstar/Global Positioning System 18-Satellite Constellations," Global Positioning System Volume II, Institute of Navigation, pg. 1-12, 1984.

Webb & Zumberge, "*An introduction to GIPSY-OASIS II*", JPL Publication D11088, 1997