Precise Real-Time Low-Earth-Orbiter Navigation With the Global Positioning System (GPS)

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Technology currently is available to support real-time onboard knowledge of the position of a low Earth orbiter at the 5- to 15-m level using the civilian broadcast Global Positioning System (GPS) signal with sophisticated models and filtering techniques onboard the spacecraft. Without these techniques, the standard positioning service yields 50 to 100 m with the current level of selective availability (SA). Proposed augmentations and/or enhancements to the GPS system will make rms accuracies of from 10 centimeters to a few decimeters available to the real-time onboard user.

Presently, near-real-time processing of GPS tracking data can routinely provide low-Earth-orbit determination accuracy at the level of 5 cm. Such processing systems can, in fact, be fully automated; recent results from the Jet Propulsion Laboratory (JPL), where ongoing daily processing of low Earth GPS tracking data has been undertaken for several years, are presented in this article, showing orbit determination accuracies at the sub-10-cm level. At the present time, such solutions can be produced with about a 10-h delay after real time, but recent improvements in JPL's processing system soon will enable turnaround at the 1-h level or better for such precise orbit determination. We anticipate that orbit determination at the 1-cm-accuracy level will be demonstrated, with some refinements to the current system, in the not too distant future.

Continuing enhancements in the automation of data retrieval and precise orbit processing will result in continuing decreases in latency for ground-based generation of precise orbit products for Earth orbiters. Such ephemerides can be propagated slightly ahead to provide real-time knowledge. However, there are advantages to an onboard, real-time orbit-determination capability. These include unique mission requirements (military, strategic, and scientific), as well as the potential to dramatically lower navigation operations costs through the enabling of a fully autonomous spacecraft. JPL has been actively involved in the development of technology to enable a fully autonomous spacecraft in low Earth orbit. This article includes recent results of analysis of actual and simulated GPS data collected in space that demonstrate that a 10-cm (or better) real-time onboard orbit-determination capability presently is technologically feasible. In addition to space-based data, present-day

[1] Tracking Systems and Applications Section.

tests in real time of wide-area differential GPS (WADGPS) on aircraft in real time show upper bounds for space-based users with a global WADGPS at the level of 30-cm-rms horizontal and 60-cm-rms vertical. The article describes several alternative technology road maps that can be followed to make such a capability routinely available to a wide range of low Earth orbiters. The discussion will include the use of wide-area approaches as well as non-WADGPS approaches for achieving this capability. In addition to supporting a sub-10-cm real-time onboard positioning capability in Earth orbit, this system also could support a few-decimeters real-time kinematic positioning for ground, sea, and air users globally.

I. Introduction

The Global Positioning System (GPS) is now used extensively for orbit determination by scientific and other Earth satellites, and for many other science, governmental, and commercial purposes around the world. For users without selective availability (SA) keys, the GPS currently provides real-time kinematic positioning (no use of dynamic orbital models) at the level of 50 to 100 m. The majority of GPS users will be well served by the present system, or by widely available commercial differential GPS (DGPS) systems, which can provide from meter to several-meters real-time accuracy over prescribed local regions. However, a subset of users will continue to seek something more, both in geographical coverage and in positioning accuracy.

Many of these stricter demands will come from science activities around the world, representing interests such as satellite remote sensing, aerogeophysics, and in situ Earth science on land and water. Prominent among prospective space-based users are the Space Transportation System (STS) and the International Space Station (ISS), which, because of high drag (and frequent maneuvering by the STS), tend to follow irregular orbits. A variety of STS- and ISS-borne instruments would benefit from real-time accuracies of a few meters or better.

For space missions requiring ultra-precise satellite orbit determination, such as the sub-10-cm accuracy demanded for satellite altimetry programs of the Topography Experiment (TOPEX)/Poseidon class [1], a real-time, onboard orbit-determination capability could enable computation of onboard geophysical data records in real or near-real time. Such geophysical records could be transmitted to science investigators directly, greatly simplifying and reducing operations costs.

Several commercial space missions are imminent that will utilize onboard GPS receivers for precise orbit determination (POD) in low Earth orbit [8]. Those missions currently require extensive ground-based operations to retrieve and rapidly process the GPS flight and ground data for POD. The orbit information then is used after the fact at a mission processing center to calibrate remote sensing data. Near-real-time or real-time POD would enable this information to be delivered immediately to time-critical users of the commercial systems. For instance, low-Earth-orbiter (LEO) imagers can track agricultural conditions and farm yields, measure vegetation coverage, help locate fish and game, survey habitats of endangered species, measure changing global climatic conditions, and survey chemical components of the Earth's surface. A global wide-area differential GPS (WADGPS), or an equivalent enhanced GPS capability, would, if sufficiently accurate, enable extensive ground operations in these systems to be considerably reduced or even eliminated. When we use the words "enhanced GPS," we refer to the several possible improvements in the GPS system itself that probably will include the removal of the SA clock dither and the addition of a second civil frequency. In addition, measurements made between GPS spacecraft (cross links) may enable real-time corrections to GPS clocks.

A tri-agency effort involving the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Defense (DoD) to develop a new generation of operational weather satellites is considering instruments that will require real-time position knowledge to a few decimeters. In addition, various proposed free-flying space missions, including microwave and laser altimeters, synthetic aperture radar (SAR) mappers, and multispectral imagers, are seeking orbit accuracies ranging from centimeters to one meter. While for many this performance is not needed in real time, the ability to achieve such accuracy autonomously onboard could save greatly in the cost of ground operations.

Many GPS science applications utilize terrestrial vehicles rather than Earth orbiters. SAR imaging, topographic mapping, gravimetry, and other forms of remote and in situ sensing are carried out with balloons, aircraft, ships, buoys, and other vehicles. One of the most stringent goals comes from airborne SAR investigators, who wish to control aircraft flight paths in real time to at least a meter, and eventually to a few centimeters. Comparable goals apply to real-time kinematic geodesy, which could be much simplified and readily extended to remote locations with global sub-decimeter positioning. A variety of mobile science instruments worldwide could generate finished products in real time, ready for interpretation, with significant savings in data transmission and analysis costs. The scientific appeal of seamless worldwide positioning offering precise post-processing performance in real time can hardly be overstated.

Table 1 lists some major categories of performance for real-time positioning with GPS. This article focuses on two key areas of technology improvements to support high-precision low-Earth-orbiter positioning: (1) improved onboard models and filtering, including dynamics and GPS measurement models and (2) seamless global WADGPS or an enhanced GPS. The combination of these two elements can yield sub-meter performance. At JPL, we have developed Real-Time GIPSY (RTG) as a general software package that implements item (1). Flight tests onboard a NASA DC-8 using a commercial WADGPS signal [3,11] will be presented, showing rms errors of 30 cm in the horizontal components and 60 cm in the vertical using codeless dual-frequency GPS data and corrections broadcast through a geostationary satellite. Since the DC-8 is not in orbit, the onboard software cannot take advantage of the precise dynamical models in the RTG software, but it does demonstrate a complete end-to-end real-time system in actual operating conditions. This same system will be flown as a navigation experiment on the experimental NASA/Lockheed reusable launch vehicle (X33) using a single-frequency GPS receiver. In addition to the real-time DC-8 flight experiments, we have processed stored GPS data from orbiting receivers as if they were real time to demonstrate on-orbit performance with the current GPS constellation, a global WADGPS system, and possible enhancements to the GPS system itself.

Table 1. GPS performance requirements.

Real-time required accuracy, m	Technique	Users and applications
100–1000	SPS[a] GPS	Satellite routine navigation; low-cost terrestrial positioning
1–20	WADGPS or PPS[b] GPS	Precise satellite navigation; surveying; aircraft (cruise) navigation; military uses
<1	Precision WADGPS or Enhanced GPS	High precision satellite navigation; geodesy; high precision surveys; aircraft takeoff and landing navigation; SAR and precise Earth mapping

[a] Standard positioning service; available to civilian users without decryption. Note that current 50- to 100-m positioning errors will improve to 10 m when SA is turned off.

[b] Precise positioning service; available only to users authorized to carry decryption.

Before presenting the results of our real-time experiments, we will show the current state of near-real-time systems for low Earth orbit with samples from JPL's current operational processing of TOPEX/Poseidon data.

II. TOPEX/Poseidon Operational Near-Real-Time and Predicted Orbits

TOPEX/Poseidon is a joint U.S. and French mission to measure ocean height [6]. Onboard are three precise tracking systems: satellite laser ranging (SLR), Doppler orbitography and radio positioning integrated by satellite (DORIS), and GPS. DORIS is a French Doppler system with excellent world-wide coverage. GPS was flown as an experiment onboard and was not the primary tracking system. When anti-spoofing (AS) is on, the GPS receiver onboard TOPEX/Poseidon operates as a single-frequency receiver recording both phase and clear acquisition (CA) range for processing on the ground. At JPL, we have for several years produced operational GPS-determined orbits [9,10] of TOPEX/Poseidon with a typical latency of 11 to 17 h after the last GPS data point is received onboard the spacecraft. Data from the spacecraft are transferred to JPL in 24-h files. Together with the TOPEX/Poseidon altimeter data, the resulting orbit solutions are used to support a variety of operational oceanographic applications. Most prominent is the assimilation of near-real-time sea-surface-height data into the operational forecast model at the National Center for Environmental Prediction. The use of TOPEX/Poseidon altimeter data with the near-real-time GPS-based orbits improved the model's forecast skill and contributed to the early prediction (6-month lead time) of the 1997–1998 El Nino [5]. The definitive precise orbit ephemerides (POEs) used in the final science products are delivered by Goddard Space Flight Center to investigators with a latency of about 40 days and are generated using SLR and DORIS data. Since the spacecraft is using a radar altimeter to measure the distance between it and the ocean surface, the critical orbit component is the radial component (from the center of the Earth to the spacecraft).

The POE currently has an accuracy of from 2 to 3 cm in the radial component. Figure 1 shows the JPL operational orbits over 10 days as compared with the POE. The rms difference over 10 days is 3.7 cm. The radar altimeter measurements can be used to infer a radial rms accuracy of 2.4 cm assuming the POE orbit has a radial rms accuracy of 2 cm. The JPL orbits are fully automated and require the efforts of less than one full-time person to produce.

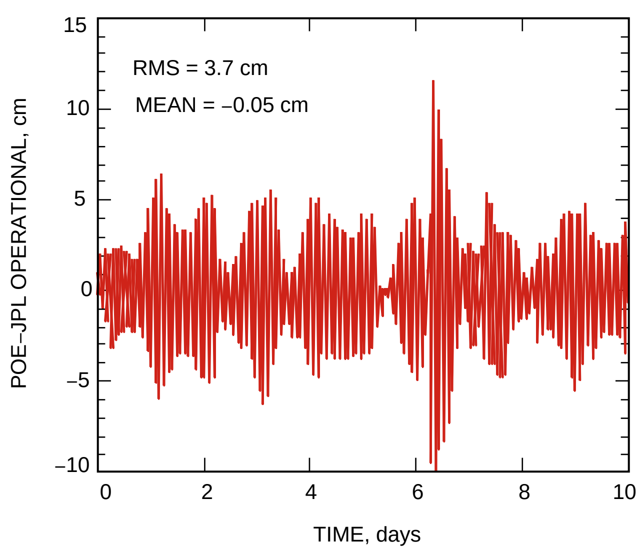

Fig. 1. The JPL TOPEX/Poseidon daily operational orbits compared with the definitive precise orbits. The operational orbits are available 11 to 17 hours after the last data point.

The GPS operational orbits discussed above can be used to predict the orbit to real-time, making a high-quality orbit available at the same time with the radar data. Table 2 shows the error in the orbit predicted 27 h into the future over the same 10-day time period shown above. Typical rms real-time radial accuracy is 5.6 cm using the predicted orbits. To obtain these types of accuracies with a single-frequency receiver in an operational mode required extensive development of both the force and signal modeling. (See [9] for details.)

Table 2. RMS errors in operational orbits predicted to real time.

Day	Radial, cm	Cross track, cm	Along track, cm
April 28, 1998	2.7	3.9	16.7
April 29, 1998	4.9	5.6	67.0
April 30, 1998	7.3	3.9	34.9
May 1, 1998	5.3	8.5	161.6
May 2, 1998	6.0	7.6	40.9
May 3, 1998	2.5	12.3	63.4
May 4, 1998	10.0	8.5	126.9
May 5, 1998	8.4	6.1	146.4
May 6, 1998	5.6	6.8	106.1
May 7, 1998	3.1	4.7	30.1
Average rms	5.6	6.8	79.4

III. Real-Time DC-8 Flight Experiment

In order to test real-time WADGPS positioning in an aircraft environment, tests were conducted on a NASA DC-8 aircraft. The primary mission of the aircraft test flight was collection of SAR measurements of the surface of the Earth. Real-time sub-meter positioning can significantly reduce SAR mission costs. The goal of the WADGPS experiment was to demonstrate absolute positioning in Earth-fixed coordinates to better than 1 m in all components. The tests showed real-time rms accuracy in the vertical to be 60 cm with an rms horizontal accuracy of better than 30 cm. Various tests of our post-process truth-positioning methods indicate that the truth positioning is better than several centimeters rms.

The real-time DC-8 solutions were produced using differential corrections transmitted through a geostationary satellite to a receiver onboard the DC-8. Much of the software producing the corrections is licensed by SATLOC, Inc. from JPL [3,11]. This software, referred to as Real-Time GIPSY (RTG) and Wide Area Ionosphere (WIS), computes corrections to GPS orbits, clocks, and the ionosphere. This software system also has been licensed by Raytheon as the prototype for the Federal Aviation Administration (FAA) Wide Area Augmentation System (WAAS) [4]. In addition to the receiver for differential corrections, there was a standard dual-frequency Ashtech Z12 for GPS data and a laptop computer for performing real-time positioning using RTG software [3]. Earlier flight tests used a single-frequency Ashtech G12 receiver and identified several software improvements that were used in the flight reported on here. This flight also led to improvements and bug fixes that we think will further improve the real-time performance. Further details of the system can be found in the references.

Figure 2 shows the 2-hour flight path of the DC-8 from Edwards Air Force Base (A.F.B.) to the Los Angeles region and finally over the Pacific ocean. The crossing tracks over Los Angeles were flown to

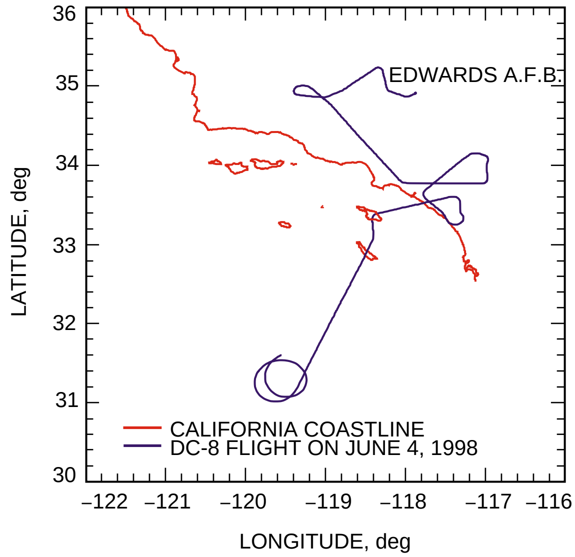

Fig. 2. DC-8 flight on June 4, 1998.

collect data for the primary mission, SAR, while the circles over the Pacific ocean were flown to support calibration of a cloud-observation instrument. At that point, the laptop computer that was processing the real-time positioning with RTG failed.

The resulting 2-h real-time 1-Hz solution was differenced with a truth solution generated by post-processing the raw GPS data from the same Ashtech Z12. The post-processing used a worldwide network of GPS receivers to determine the GPS orbits and a network of five ground stations over the mid and western United States to generate 1-s GPS clocks. To validate the truth solution, the same post-processing data methods were used on a fixed receiver at a known location. Table 3 shows that this validation resulted in rms errors at the 1-cm level.

Table 4 gives the accuracy statistics in east, north, and vertical components for the phase center of the GPS antenna mounted on the upper portion of the DC-8 fuselage. The large means probably are due to errors in how the carrier phase bias breaks were determined. These processing errors have since been identified and corrected. Figure 3 shows a plot of the errors in time, corresponding to the statistics shown in Table 4. The larger errors at cold start are due to the initial poor determination of the GPS carrier phase biases.

Table 3. Truth-solution test of a stationary receiver.

Component	Mean, cm	Standard deviation, cm	RMS, cm
East	0.2	0.6	0.6
North	−0.2	0.6	0.7
Vertical	0.5	1.5	1.6

Table 4. DC-8 real-time position errors on June 4, 1998.

Component	Mean, cm	Standard deviation, cm	RMS, cm
East	-16.5	21.9	27.5
North	-12.9	25.8	28.8
Vertical	-41.7	47.8	63.4

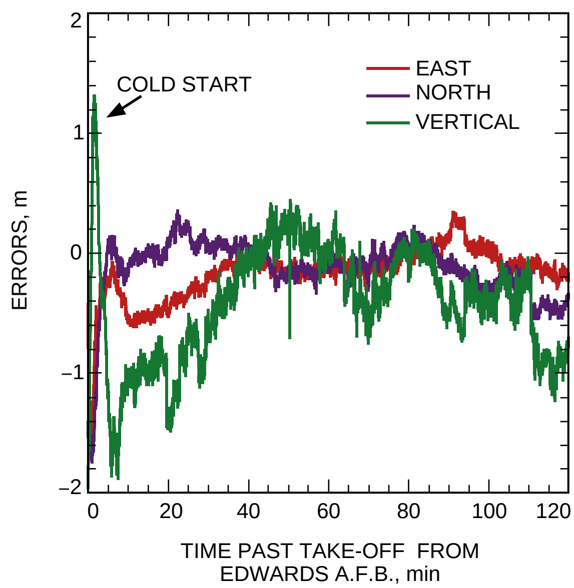

Fig. 3. DC-8 real-time position errors on June 4, 1998.

IV. TOPEX/Poseidon Real-Time Orbits

To test the performance of the GPS in real time on a LEO, actual GPS data from TOPEX/Poseidon were processed on the ground as they would be onboard, with software such as RTG. Since the data were processed from files rather than a data stream, GIPSY/OASIS II (GOA II)[2,3] was used instead of RTG for convenience. Almost all the precise models in GOA II are identical to RTG and would be available in flight code. Compiler options allow optimization of load size for flight applications of RTG in embedded processors.

Figure 4 shows the results with 3 days of data from 1995. Each line represents a cold start with the three-dimensional (3-D) error plotted every hour for 27 h. The dynamical models smooth out the effects of SA after about 4 h. RMS error after the 4-h convergence period is 3 to 5 m. SA errors dominate and are at the typical level of 25-m rms.

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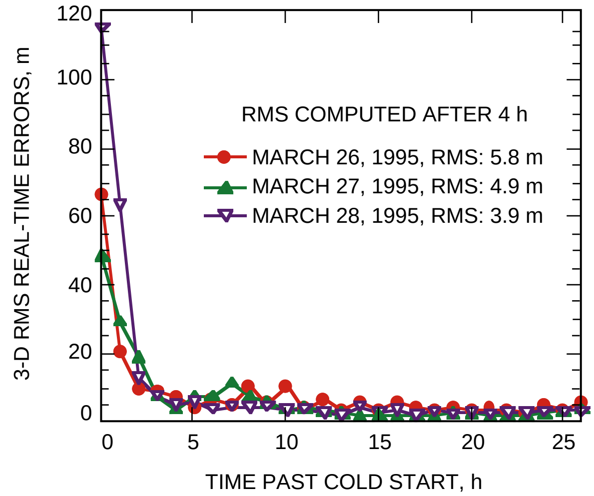

Fig. 4. The 3-D error after a cold start using broadcast GPS orbits and clocks for TOPEX/Poseidon at a 1300-km altitude.

V. Global WADGPS and Enhanced GPS

The orbit accuracy shown in Fig. 4 is realizable today using existing software (RTG, for instance) and existing flight hardware (RAD 6000, for instance). Increases in accuracy will be obtainable in the future through various proposed global enhancements to GPS. These enhancements may include improvements to the GPS infrastructure and technology, or enhancements to the WADGPS augmentation systems, or both. An example of WADGPS enhancement is the implementation of WAAS-like systems in various countries around the world [4]—that is, the establishment, effectively, of a global WADGPS capability. The U.S. Government-sponsored WAAS implementations include plans for data interchange that would make global seamless corrections to GPS available. Enhancements to the GPS system include better broadcast orbits and clocks, turning off SA, a second civil frequency, and real-time clock synchronization via satellite cross-links. Below we use TOPEX/Poseidon and a lower-orbit spacecraft at 700 km, GPS/Meteorology (Met) [2,10], to illustrate the expected performance of onboard, real-time orbit determination with some of the upcoming changes to GPS. All of the cases make use of actual data taken onboard the spacecraft, but here we simulate a range of expected improvements to the GPS system from global WADGPS or enhanced GPS. Two cases were considered to bracket the expected errors of possible global or enhanced GPS systems: (1) Use the broadcast orbit as the real-time GPS orbit. Fixing this orbit, use data from 20 global ground stations to solve for (filtering only, no smoothing) the GPS clocks; (2) Use the precise orbit (good to about 20 cm) as the fixed GPS orbit and add white noise at each measurement time to the GPS clock determined with the precise orbit. Case (1) will be pessimistic with respect to the orbit error. Case (2) might be optimistic as compared with some global systems, but may be a reasonable representation of possible future capabilities. Case (1) will be referred to as broadcast orbits with enhanced real-time clocks. Case (2) will be referred to as precise orbits and clocks.

A. Case (1): Broadcast Orbits With Enhanced Real-Time Clocks

Onboard data from February 20, 1997 (different from the above tests), for TOPEX/Poseidon were filtered as if processed in real time. The broadcast orbits on this day happened to be atypically bad, so the broadcast GPS orbits were adjusted to more typical errors, shown in Fig. 5. This adjustment was made by scaling the difference in the broadcast GPS orbits and the precise GPS orbits determined after the fact (good to about 20 cm). We will now refer to this adjusted orbit as the broadcast orbit. Figure 6 shows the results of this solution. The enhanced clocks lead to much more rapid convergence

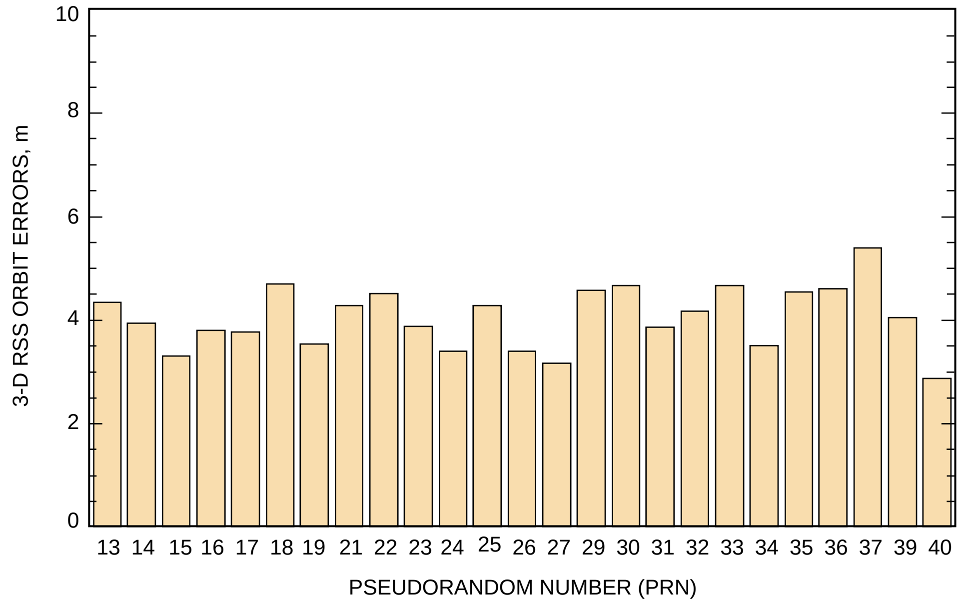

Fig. 5. The adjusted broadcast GPS orbit errors used in the TOPEX/Poseidon data demonstration.

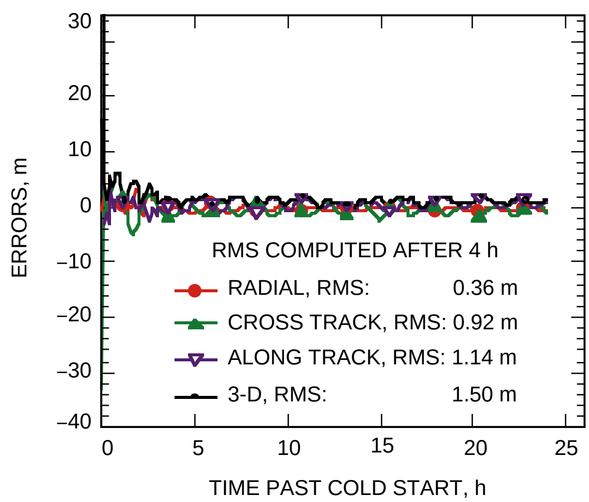

Fig. 6. TOPEX/Poseidon real-time position accuracy with broadcast level GPS orbit errors and enhanced real-time clock errors (Case 1).

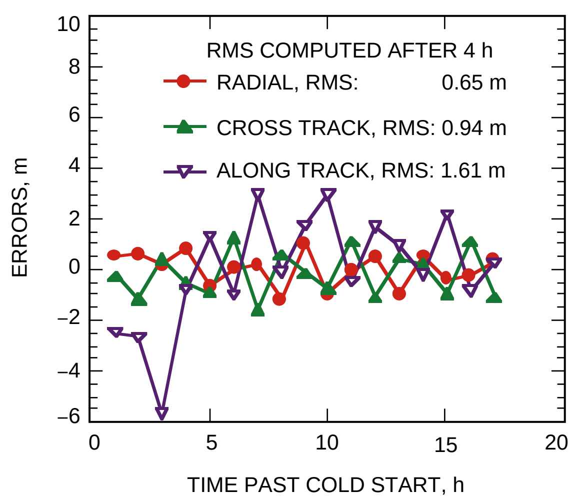

Fig. 7. The real-time orbit using onboard data from GPS/Met on July 16, 1996 (Case 1).

of the solution following cold start than does the above case with broadcast orbits and broadcast clocks. RMS radial accuracy is less than 50 cm, with errors in the other components of about 1 m.

Figure 7 shows a similar scenario for the GPS/Met spacecraft. It carries a dual-frequency, codeless receiver with its antenna mounted to the side to support radio occultation science experiments [7]. This makes for poorer GPS observing geometry.

B. Case (2): Precise Orbits and Clocks

Figure 8 shows rms accuracy at the decimeter level for radial and cross-track components a few hours after an initial cold start. This is better performance than the 27-h predictions to real-time shown in Table 2.

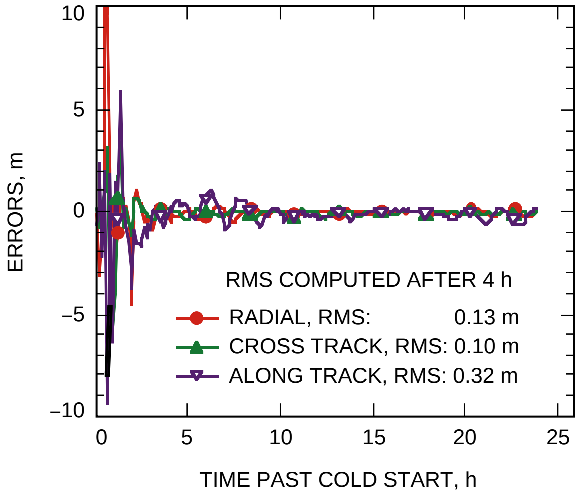

Fig. 8. TOPEX/Poseidon real-time positioning with precise orbits and clocks (Case 2).

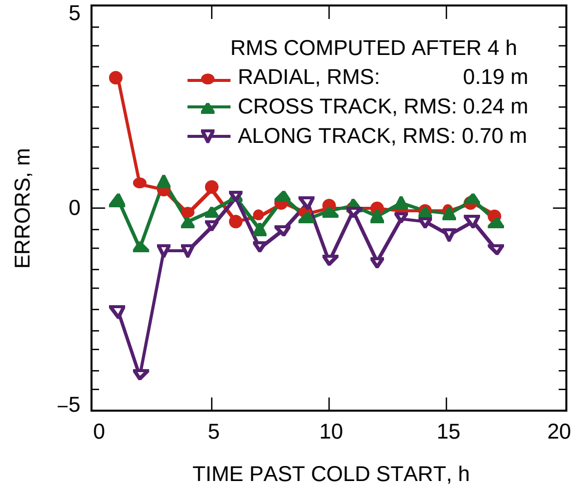

Fig. 9. GPS/Met at 700 km: real time using precise orbits and clocks.

Figure 9 shows the corresponding plot for GPS/Met with worse performance than TOPEX/Poseidon. The orbit for GPS/Met is lower and, thus, drag and gravitational forces are less well modeled. In addition to the poorer force modeling, the antenna on GPS/Met points off to the side, yielding poorer GPS observing geometry. The rms accuracy was from 20 to 70 cm as compared with post-process truth orbits with better than 10-cm accuracy.

VI. Conclusions

With improved onboard software, the current GPS system, using broadcast orbits and clocks, can support low-Earth-orbit real-time positioning at the 4- to 5-m level. An example of such enabling software is RTG. RTG has been used in real time for positioning of aircraft and will be used in sub-orbital tests of the X33.

Either global WADGPS or certain enhancements to the operational GPS system could support accuracy at the decimeter to meter level in the future. It is likely that a global WADGPS capability will be developed as multiple countries begin implementing compatible WAAS-type augmentations to GPS. U.S. Government policy decisions could accelerate enhanced user positioning accuracy.

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