TMO Progress Report 42-133 May 15, 1998

Concepts for Automated, Precise Low Earth Orbiter Navigation With the Global Positioning System

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The Global Positioning System (GPS) is widely used for satellite positioning and navigation and for numerous geolocation activities. Real-time, onboard positioning accuracies for low Earth orbiters (LEOs) currently vary from 50 to 100 m for stand-alone conventional GPS tracking to somewhat better than 10 m with sophisticated onboard data filtering. Wide-area differential techniques, such as those supported by the Wide Area Augmentation System (WAAS) under development by the U.S. Federal Aviation Administration, offer real-time, kinematic positioning accuracies ranging from a few meters to better than a meter over well-defined local regions. This article describes a concept for extending the wide-area differential GPS techniques to achieve global, real-time positioning of LEOs at submeter accuracies. GPS design and operation policy issues that currently limit real-time, onboard precision positioning are discussed. The article then examines a number of proposed system design enhancements under consideration by the U.S. Department of Defense for the next-generation GPS, termed GPS III. These potential enhancements, if implemented, would enable global real-time, stand-alone position accuracies of a few decimeters for kinematic users and better than 10 cm for LEOs. Such capabilities could dramatically impact NASA missions by greatly lowering ground operations costs, as well as navigation and orbit determination costs in general.

I. Introduction

The Global Positioning System (GPS) is now used extensively for orbit determination by scientific and other Earth satellites and for many other scientific, governmental, and commercial purposes around the world. For users without selective availability (SA) keys, GPS currently provides real-time kinematic positioning 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 several-meter 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 Transport System (STS) and Space Station, which, because of high drag (and frequent maneuvering by the STS) tend to follow irregular orbits.

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[1] Tracking Systems and Applications Section.

A variety of STS- and station-borne instruments would benefit from real-time accuracies of a few meters or better.

For space missions requiring ultraprecise satellite orbit determination, such as the sub-10-cm accuracy demanded for satellite altimetry programs of the 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 operations and reducing operations costs.

Several commercial space missions that will utilize onboard GPS receivers for precise orbit determination (POD) in low Earth orbit are imminent [2]. 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 users of the commercial systems with time-critical needs. 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.

A triagency effort involving 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. Although for many this performance is not needed in real time, the ability to achieve such accuracy autonomously on board 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 subdecimeter 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 postprocessing performance in real time can hardly be overstated.

Table 1 lists some key categories of performance for real-time positioning with GPS. This article focuses on submeter positioning of LEOs where precision WADGPS or an enhanced GPS (EGPS) capability is required. The essential elements of a global precision WADGPS are discussed first. The remainder of the article then explores means for obtaining the precise WADGPS performance globally in real time, and without differential corrections, from a proposed EGPS.

II. WADGPS

Commercial wide-area differential GPS (WADGPS) systems are now providing services nearly worldwide. Meanwhile, the U.S. WAAS—a particularly ambitious example of WADGPS—is moving toward initial operation in 1999 and full operation in 2001 to support a several-meter level of accuracy for general aviation navigation over the United States [3]. Similar efforts are being planned in Europe, Asia, and other locations. As noted above, a class of prospective users—from satellites to aircraft to surface vehicles—is emerging that will benefit from real-time positioning accuracies well surpassing what today's

Table 1. GPS performance requirements.

Required real-time 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 EGPS	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 selective availability is turned off.

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

systems can deliver. This is an opportune time to evaluate future interests in precise real-time orbit determination and positioning, taking into account the diversity of applications, performance requirements, the utility of current systems, alternative design options, and the relevant technologies that can now be brought to bear.

Figure 1 illustrates the basic configuration and operational concept for the Federal Aviation Administration's (FAA's) initial WAAS, to be operational in 1999. Twenty-four GPS monitor stations spanning the U.S. will collect GPS carrier phase and pseudorange data at 1-s intervals and send them continuously over real-time communication links to two master station analysis centers. The centers will continuously compute three crucial real-time corrections for single-frequency GPS users: GPS orbits, GPS clocks, and ionospheric delays. The corrections then will be broadcast to users in near-real time over geostationary satellites. Two of the corrections, the GPS orbits and ionospheric delays, will be computed and broadcast at the relatively slow update rate of once every 5 min. Because of GPS selective availability, under which the onboard clocks currently are subject to intentional high-frequency fluctuations (clock dithering), the WAAS clock corrections must be updated every 6 s and received by users within 9 s of real time. In addition, the monitor stations and processing centers will continuously run tests of GPS system integrity and transmit warning flags ("don't use" messages) for specific satellites and corrections within seconds of anomaly detection. Strict integrity is required for WAAS and WAAS-like systems being used for aircraft navigation.

Current WADGPS positioning performance is typified by the formal requirements established by the FAA for the final WAAS, to be completed by 2001. These requirements stipulate that a WAAS user's real-time position should be determined to an accuracy of 7.6 m in both the vertical and horizontal components with 95 percent probability (2σ) throughout the North American service volume [3]. This performance assumes a user without encryption keys, equipped with a single-frequency receiver applying WAAS-supplied corrections to GPS orbits and clocks and to the ionospheric delay model. Similar performance is anticipated from WADGPS systems being implemented (or planned) in Japan, Europe, and other regions. Such capabilities represent a substantial improvement over the standard GPS capability without encryption, which is 50 to 100 m, primarily due to the error from selective availability.

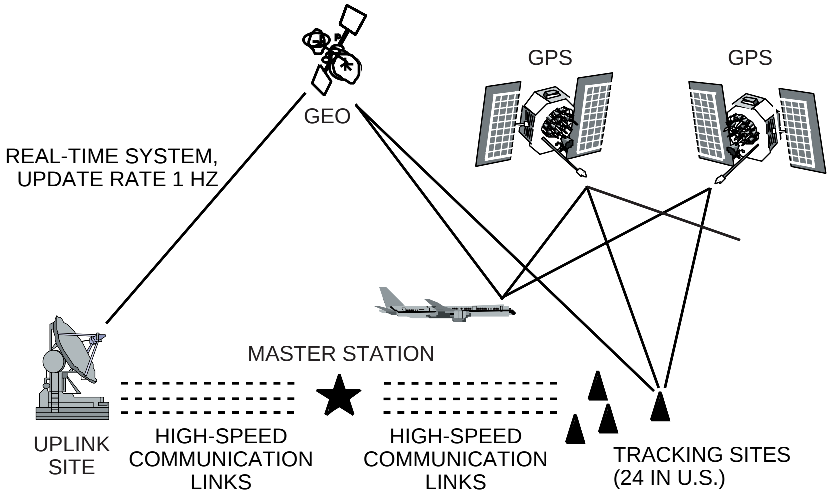

Fig. 1. Basic components for the FAA WAAS.

A. WADGPS Current Performance and the Potential of Global WADGPS

The following critical elements are needed to establish high-performance global WADGPS: an extensive global network of GPS monitor stations and network communications to enable data to be brought together in real time for processing; real-time analysis software for computing precise GPS orbits, clock parameters, and worldwide ionospheric delay corrections from the global GPS data; a mechanism to ensure reliability and integrity; and a reliable means of transmitting the WADGPS corrections to users in real time.

Most of these elements are, in fact, already available to some degree. For instance, the International GPS Service (IGS), a consortium made up primarily of government and academic institutions, maintains a global network of several hundred GPS ground sites. Analysis centers collect and process these global network data every day. The IGS data currently are collected at a low rate (30 s) rather than at the high rate (1 s) needed for WADGPS, and at present there are not communication links in place to deliver the global data in real time. On the other hand, the required system elements for global WADGPS have been demonstrated over localized regions. The FAA has several testbeds in place for WAAS testing in the United States. JPL has developed and delivered to the FAA and its WAAS prime contractor, Raytheon, the prototype WAAS software to compute GPS orbit, clock, and ionosphere corrections in real time [4]. This prototype WADGPS software—comprised of two main modules, Real-Time GIPSY (RTG) and WADGPS Ionospheric Software (WIS)—has been processing data from a continental United States (CONUS) network installed and maintained by a private company, SATLOC. SATLOC, with particular focus on the agricultural-user segment, currently is offering WADGPS services based on RTG and WIS over a wide area in the CONUS covered by geosynchronous satellites. Figure 2 shows recent single-frequency real-time kinematic (ground) user positioning results from this prototype system; similar results are obtained for dual-frequency users.

Recent studies show that the real-time GPS orbits corresponding to results shown in Fig. 2 improve from about 90 cm (U.S. network only) to about 40 cm if data from a global network were available for WADGPS. More importantly, a global WADGPS would provide seamless service to a global community, including both space and terrestrial users. For Earth orbiter navigation and several of the other applications listed in Table 1, the global coverage is essential.

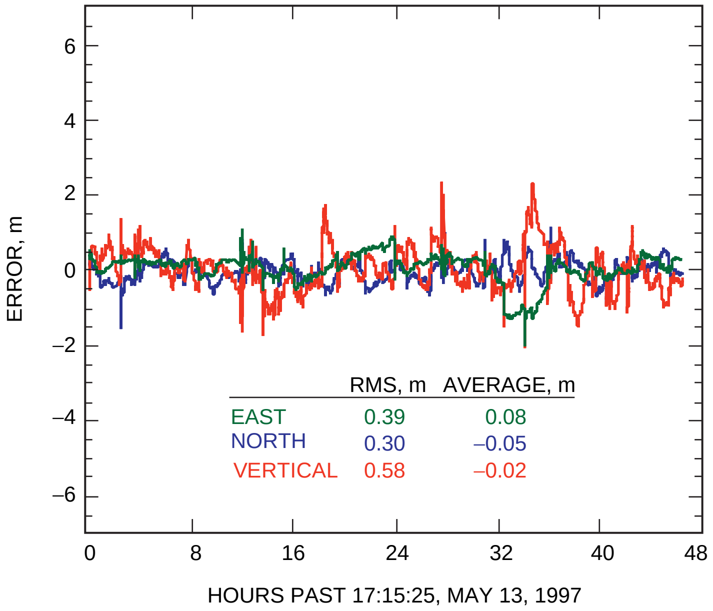

Fig. 2. Recent JPL WADGPS user positioning results with real-time SATLOC CONUS network data.

B. High-Precision WADGPS System Elements

For real-time onboard positioning and orbit determination, a satellite would require flight software with the necessary orbit models, estimator, and propagator. A version of the RTG software can be embedded in an onboard GPS receiver or processor to support this capability. Three fundamental WADGPS computations are applied to the GPS broadcast message to obtain improved performance: the slow GPS orbit correction, the fast GPS range correction, and the ionospheric correction. To achieve reliable decimeter-level or better real-time positioning globally, a WADGPS design will require the capabilities described below for computing these three corrections.

1. The Slow Orbit Correction. Typical three-dimensional (3-D) accuracy for GPS orbits produced several days after the fact at JPL with the GIPSY–OASIS software and data from the global IGS network is 10-cm rms [5,6]. While these solutions can be predicted ahead to provide real-time GPS ephemerides, such predicted real-time solutions are somewhat less accurate ($\sim$1 m) than what can be achieved in a real-time WADGPS process ($\sim$40 cm). Key features of RTG and GIPSY–OASIS that enable solutions of the highest accuracy include the following [1,4,5,6]:

(1) Dynamic Orbit Determination—The satellite current states are estimated from a possibly long data history. Measurements are related to one another by a precise model of the satellite motion derived from models of the forces acting on the satellite. This introduces external information in the form of dynamical constraints on the trajectory, thus minimizing the number of parameters adjusted and maximizing solution strength. A rigorous dynamical orbit model permits the satellite state estimates to be mapped many hours into the future with little loss of accuracy.

(2) Precision Models—The success of dynamic orbit estimation rests on the strength of its models. These include models of the forces acting on the satellites (gravity, solar radiation, and thermal emissions); the observing geometry (receiver locations, transmitter and receiver phase center variations, GPS attitude, Earth rotation and wobble, solid tides, ocean and atmospheric loading, and crustal plate motion); propagation delays (neutral atmosphere, water vapor, and higher-order ionospheric effects); and such effects as carrier phase windup due to satellite yaw.

(3) Stochastic Estimation—Even the best models fall short of perfection. Deficiencies often can be partly overcome by judicious estimation of critical model parameters along with the satellite states. A few such parameters (atmospheric propagation delays and solar radiation pressure) exhibit a quasi-random character that cannot be fully captured in a deterministic model. These parameters can be represented as the sum of deterministic and stochastic components—random walks and white or colored noise.

(4) Phase and Pseudorange Processing—Carrier phase is modeled as a biased range measurement. GIPSY–OASIS and RTG process smoothed pseudorange and carrier phase data simultaneously for all computations. While the ultimate solution strength derives almost entirely from phase data, pseudorange adds robustness to the automated operation and helps detect system anomalies. Fully automated processing of phase data now is highly evolved and easily adapted to real-time use.

2. The Fast Correction. Often called the fast clock correction, this is actually a pseudorange correction analogous to the real-time corrections used in local area DGPS. The principal difference is that wide-area fast corrections are derived from an extended network rather than a single receiver. Their principal purpose is to remove GPS clock errors, which may be quite large (~30 m) owing to selective availability dithering. We note, however, that the fast correction contains a component of the residual orbit error remaining after the slow correction. The effective orbit error, thus, is further reduced by common mode cancellation when the fast correction is applied. For a user 2000 km from the centroid of the WAAS network, the reduction is about a factor of 10; a 50-cm orbit error would itself contribute only 5 cm to the user differential range error (UDRE). GPS clock errors are independent of geometry and, therefore, are removed to within the fast correction noise level.

RTG employs a robust approach that simultaneously estimates all satellite and receiver clock offsets every second while fixing the station positions and updated GPS orbits. This process is fast and ensures complete isolation of receiver clock and instrumental effects.

3. The Ionospheric Correction. Daytime ionospheric delays at 1.6 GHz (L-band) can reach tens of meters. Computing a submeter ionospheric correction over a continent (or around the globe) presents a major challenge—one that ultimately will drive the required number of reference sites. To succeed at an acceptable cost, we must find an ionospheric mapping technique that is both powerful and efficient. The approach taken in WIS treats the full global ionosphere as a semicoherent entity within its natural solar-magnetic frame.

The ionosphere forms a shell around the Earth, with the region of greatest electron density directed always toward the Sun (Fig. 3). At any ground point, the zenith electron content varies markedly as the Earth rotates within the nearly stationary shell. Conventional ionospheric mapping techniques must cope continuously with those dramatic and generally unmodeled variations. By contrast, in the solar-magnetic frame, which is fixed with respect to the Sun–Earth line, the ionosphere maintains a comparatively stable structure.

WIS employs global network GPS data and a Kalman filter to continually update a full, simultaneous shell solution in the solar-magnetic frame [4,5]. A triangular tessellation or gridding of the shell provides nearly uniform solution spacing over the spherical surface; a fast linear interpolator can map the solution to any desired point. The values at each vertex are modeled stochastically with carefully tuned time correlations between updates. In addition, spatial correlations are introduced among nearby vertices, and the L1/L2 channel delay biases are estimated for all satellites and receivers (except one). More details are provided in [4,5]. Worst-case ionospheric dynamics in the solar-magnetic frame suggest a solution update interval of 5 to 15 min for WADGPS operation.

Other civil solutions to the ionospheric error include the use of today's dual-frequency codeless receivers or of dual-frequency code receivers when a second civil frequency becomes available.

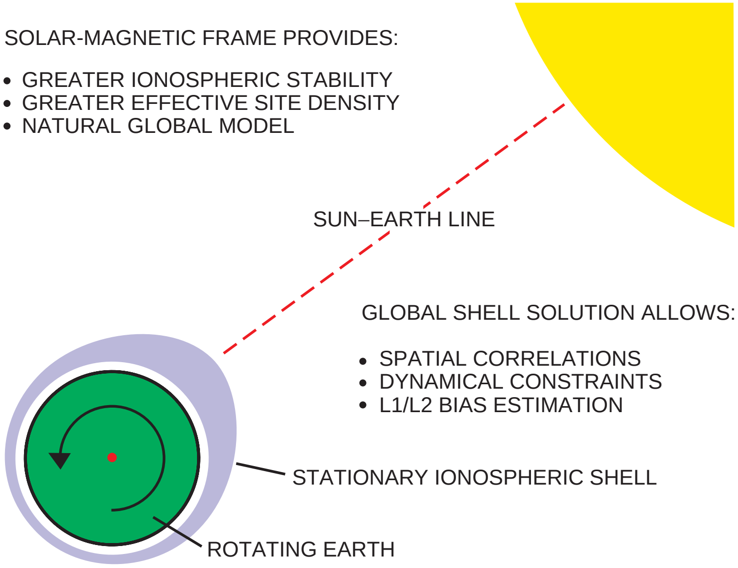

Fig. 3. The solar-magnetic frame in which the ionosphere is relatively stationary and unchanging.

C. Issues in Providing a Global WADGPS Capability

In the near future, the implementation of multiple WAAS-like systems around the world will enable different paths to be followed to achieve a global WADGPS capability.

1. Global Data Analysis. One realization of global WADGPS would be simply a global, larger-scale version of regional systems such as WAAS. Significant operational complexities would be encountered in such a system, as it would require high-speed, real-time data links to a fairly large global network of ground sites. Such real-time links could be costly to implement and operate. In addition, support of single-frequency receivers would be difficult on a global scale, at least for high-accuracy applications, since the number of ground sites needed to adequately sample the ionosphere could number in the hundreds. The organization of such an international network likely would be complex.

2. Interoperability for Regional WADGPS Systems. This approach would attempt to reconcile and seamlessly link different WADGPS systems in different regions. The U.S. FAA WAAS is an example of one of these regional WADGPS systems. For this to occur, different countries would need to coordinate their algorithms, data formats, and system definitions; provide for interoperability from one system to the next; and enable continuous coverage for users passing out of one system into the other. This approach is being investigated in the United States and elsewhere, and in the near term it may be the only feasible way to achieve something like global WADGPS. As with the approach in Section II.C.1, however, there are political complexities that would have to be handled for this approach.

3. Improvement in WADGPS Positioning Accuracy. For the approaches in either Section II.C.1 or Section II.C.2, the issue of improving user positioning accuracy is still relevant. Figure 4(a) shows the anticipated position accuracy for a kinematic (space or terrestrial) user of CONUS WADGPS applying the high-precision techniques described above for calculating the broadcast corrections and for calculating the user position after applying these corrections. Note that recent achieved accuracies shown in Fig. 2 are consistent with Fig. 4(a). Also shown is the expected accuracy from global WADGPS (using similar data analysis techniques) and for an enhanced GPS (EGPS) system described in the next section.

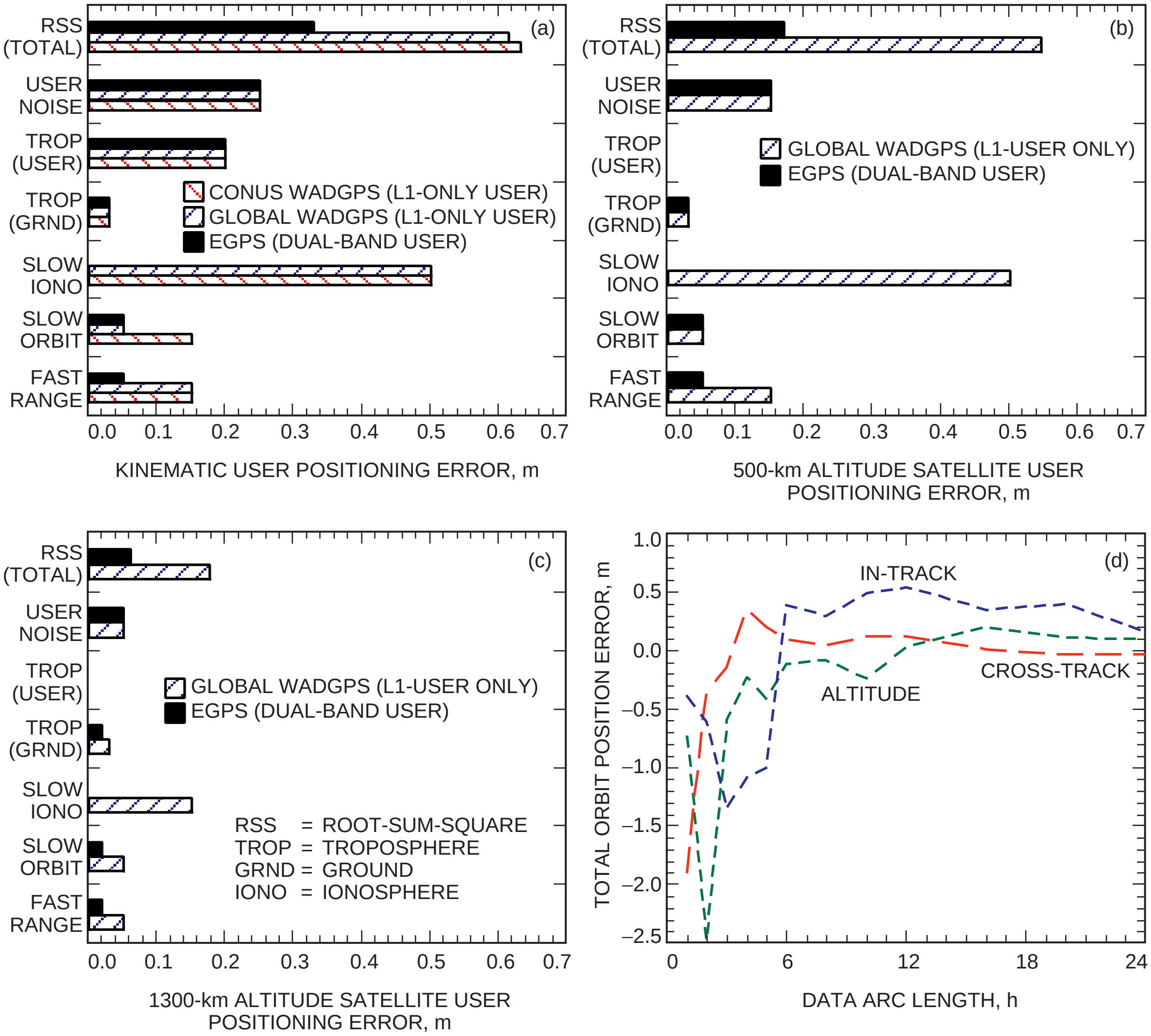

Fig. 4. Positioning accuracy: (a) anticipated kinematic user positioning accuracy, (b) anticipated user positioning accuracy for a 500-km low Earth orbiter, (c) anticipated user positioning accuracy for a 1300-km low Earth orbiter, and (d) TOPEX/POSEIDON positioning with global high-accuracy WADGPS processing.

Figure 4(b) is calculated for a user in very low Earth orbit with only limited capability for exploiting dynamics, and Fig. 4(c) is calculated for a low Earth orbiter at an altitude where good knowledge of dynamics enables substantial averaging down of errors in positioning by applying a dynamic fit over an enhanced time interval. The EGPS results assume that users take full advantage of the anticipated future availability of two civilian GPS frequencies to effectively eliminate ionosphere-induced errors.

For high-precision terrestrial users, the neutral atmospheric delay is one of the largest sources of error [see Fig. 4(a)]. The tropospheric delay has two components—the slowly varying dry portion contributing about 200 cm of total zenith delay and the more rapidly varying portion due to water vapor, typically 5 to 30 cm of total zenith delay. For postprocessed solutions, the best strategy has been to estimate the tropospheric delay at each receiver as a stochastic variable, where it can be estimated to 5 mm. For real-time terrestrial applications, this estimation process will be moved into the user equipment (receiver). The accuracy of real-time tropospheric estimation is expected to be 2 to 3 cm.

The plots in Figs. 4(a) through 4(c) all include a component for user noise. This would include the receiver data noise and multipath, which in fact can be highly variable for different types of users. We assumed that carrier-aided smoothing of the pseudorange would be used in all cases. A higher noise contribution (25 cm) is assumed in Fig. 4(a) for the kinematic user (perhaps a vehicle or aircraft susceptible to multipath); a lower contribution is assumed in Fig. 4(b), where some additional averaging occurs from the partially dynamic fitting possible for a low Earth orbiter; and a very low contribution (5 cm) is assumed in Fig. 4(c), where longer dynamic fits will result in further noise reduction.

Figure 4(d) shows results recently obtained for the 1330-km TOPEX/POSEIDON satellite, from which actual GPS flight data were processed in a forward-running filter (estimator) after the fact but in a real-time mode to approximate a high-accuracy global WADGPS capability. The results are consistent with Fig. 4(c). Figure 4(d) shows the improvement in the TOPEX/POSEIDON position as a longer arc length of data is fit, incorporating dynamic estimation. After about 1 day, the solution has settled down to better than 15 cm in each component.

It can be seen that the EGPS offers the most potential for very high-accuracy real-time positioning in all cases. EGPS is discussed in the next section.

III. EGPS: An Alternate Approach for the Long Term

For long-term planning purposes, it makes sense to coordinate efforts to expand WADGPS capabilities with anticipated technology improvements to the GPS constellation and infrastructure. A recent study effort, designated as GPS III, has been evaluating design options to improve the GPS system performance for various users. Through our participation in this study, we are aware of the following potential enhancements to GPS that could result in both a global *and* a very high-accuracy real-time positioning capability, such as is represented by the enhanced GPS (EGPS) portions of Fig. 4. In other words, the following EGPS features would result in the equivalent of both global expansion of WADGPS plus major accuracy improvements in user positioning. A key feature of EGPS is that it incorporates some functions of what are presently separate WADGPS operations into the enhanced GPS system itself (Fig. 5).

A. GPS Constellation Augmentation

A recommendation for increasing the number of operating GPS satellites from 24 to 30 is likely to be implemented following the discontinuation of SA, perhaps starting in 2006. The increased number of operational satellites, in combination with an expansion of the global ground network used for GPS ground segment operations to about 24 ground sites, would result in some important system performance improvements. The additional satellites would improve availability and enable robust integrity monitoring in real time within the user receiver itself, i.e., they would enable the use of receiver autonomous integrity monitoring (RAIM). The additional satellites also would improve positioning over the entire Earth by providing for more solution strength in typical multiparameter fits such as those previously described for high-precision WADGPS.

Additional ground tracking sites, particularly those at high latitudes, will provide improved geometry, leading to more accurate operational ephemerides. Additional ground tracking sites also will provide constant surveillance of each GPS satellite to speed up response to failures. A spare master control site can prevent single-site failures from impeding normal GPS constellation operations.

B. Enhanced Cross-Links

Enhanced cross-links would enable significant reduction of user error attributed to the fast correction. These enhanced cross-links basically would provide for real-time precise clock synchronization continuously while eliminating the need for high-accuracy clocks *anywhere* in the system (ground sites or space vehicles) for navigation, although a few good clocks on the satellites, or at a ground site with frequent

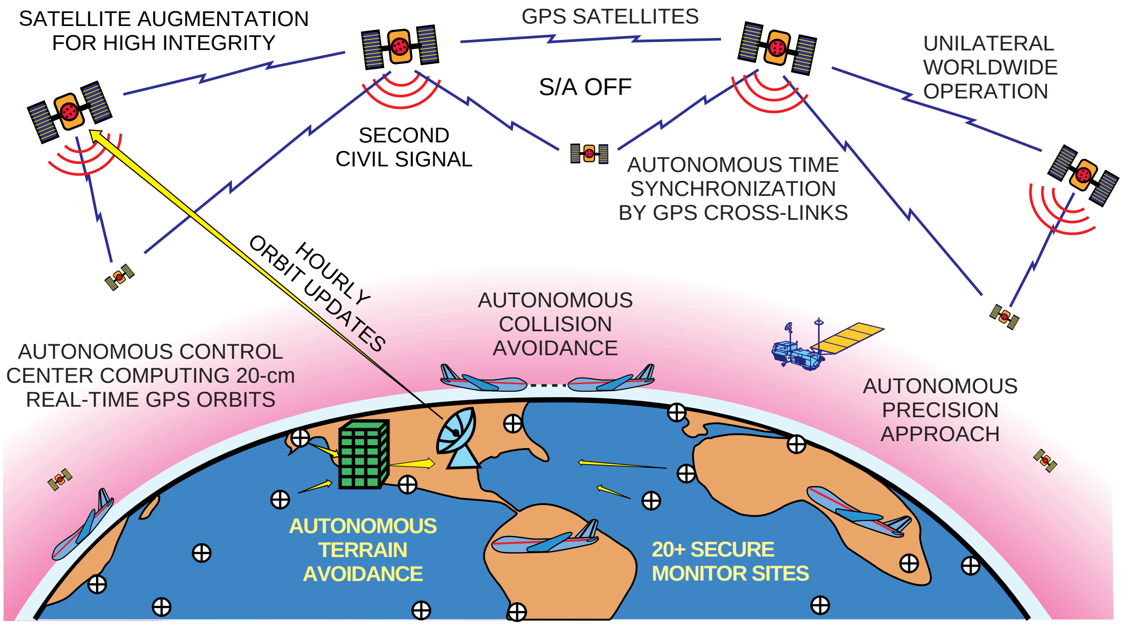

Fig. 5. Enhanced GPS.

satellite uplinks, would keep the GPS clock close to UTC. This could reduce the cost and complexity of the satellites while providing a major performance enhancement. With the expected elimination of selective availability within the next 4 to 10 years, there would be an additional simplification in operations, perhaps resulting in reduced requirements for cross-link tracking rates. The existing Block IIR satellites have cross-links capable of supporting 1-ns- (30-cm)-level synchronization. This would be adequate to provide submeter real-time positioning from EGPS. Subdecimeter autonomous user positioning, such as that proposed for EGPS in Fig. 4(c), likely would require improvement in cross-link synchronization and reduction of cross-link observable noise to a few tenths of nanoseconds.

C. Second Civilian User Frequency

A second civilian user frequency would enable users to calibrate directly the effects of the ionosphere. Since the ionosphere correction dominates much of the user error budget near the Earth, this is a major enhancement in terms of performance. Perhaps of even greater significance, however, would be the capability to provide, for those users who require it, the equivalent of high-accuracy WADGPS with only a small number ($\sim$24) of ground sites around the world. This substantial reduction in the number of ground stations versus that needed for a full global WADGPS (scores or even hundreds) results from an elimination of the need for a global ionospheric correction. The enhanced cross-links also help reduce the number of ground sites required for a WADGPS system since the fast correction can be sustained by the combination of a minimal ground network plus the cross-links.

Real-time kinematic tracking (RTK) is greatly enhanced by a second civil frequency. In RTK, it is necessary to determine the integer cycle ambiguity in differential carrier phase between a pair of stations. The application of this technique currently is limited by the data noise present on codeless observables formed from the encrypted L2 signal. A properly spaced second civil signal with a nonencrypted ranging code would decrease the time to achieve reliable RTK results by at least an order of magnitude.

Another enhancement under consideration for GPS III is the possible inclusion of a third civil signal, a science link, Ls. This signal could be used to extend the current widelaning technique used to facilitate carrier cycle ambiguity resolution [7,8]. Because of uncalibrated differential ionosphere between the receivers, widelaning currently is limited to users only a few tens of kilometers away from a reference site.

Three frequencies will allow dual widelaning (also called trilaning), which can be effective at arbitrary separations because the extra observables from Ls allow solving for the differential ionospheric delay.

If the third civil frequency is at L-band, one could expect to obtain an ionosphere-corrected range observable from the trilaning accurate to about 10 to 15 cm, depending on the actual frequency selected. On the other hand, if the proposed Ls is broadcast at 5 GHz (C-band) modulated by a wideband (100-megacycle/s) ranging code, one could directly obtain ion-free pseudorange accuracies near 1 cm, without the need for carrier smoothing or carrier ambiguity techniques. The combination of higher transmission frequency and wideband code would effectively reduce the total effects of multipath and thermal noise to the centimeter level.

D. Broadcast Ephemeris Improvement

The combination of improvements to algorithms and processing techniques (see descriptions in Section II), the use of a global ground network of 24 sites, and improved satellite cross-links should enable real-time GPS orbits to be operationally produced at the level of about 20-cm accuracy. This is an important accuracy enhancement when compared with the current level of broadcast ephemeris accuracy (3 to 8 m). Similarly, the broadcast GPS clocks could be accurate to 10 cm or better when SA is eliminated, the GPS cross-links are improved, and orbit determination algorithm enhancements are incorporated (as described in Section II.B.1).

In summary, the EGPS would introduce a new concept of operations for GPS in which the GPS operational segment itself would be able to provide the equivalent of high-accuracy global WADGPS positioning. This would enable real-time positioning to <50 cm for kinematic or maneuvering users (terrestrial or space). Real-time performance for Earth orbiters would depend on altitude, with several-decimeter accuracy possible for users either at low altitude or having frequent maneuvers, and better than 10 cm in real time for Earth orbiters at altitudes of 1000 km or higher. Not only would these accuracy improvements be a boon to many scientific and commercial GPS applications, but the reduction of user-segment operational costs could be enormous. This is because EGPS would greatly simplify separate augmentations to the primary GPS operational segment itself (such as separate WADGPS networks and processing). Civilian users equipped with dual-frequency receivers will enjoy stand-alone, real-time accuracies equivalent to, or in some situations better than, those now available after the fact from sophisticated ground-processing facilities.

The elimination of most high-accuracy clocks from the system and an upgrade of the operational GPS segment to a more automated processing system would be beneficial developments within the GPS system itself. WAAS-like systems of the future could benefit from lower operations costs, higher accuracy, and better integrity monitoring if EGPS were to be instituted. It should be especially noted that current efforts to expand WAAS (or WAAS-like systems) to the international scale [3] will be significantly expedited and simplified by the EGPS upgrades discussed in this article.

Finally, it should be pointed out that changes such as the envisioned EGPS must be acceptable to the GPS military segment. In other words, issues such as national security and troop effectiveness must be investigated and be acceptable to the military organizations that are responsible for GPS. Nevertheless, current indications are that we can expect most and perhaps all of these enhancements to be adopted by GPS within the next 10 to 15 years.

IV. Summary

In order to support high-accuracy (<1-m) real-time positioning of Earth orbiters, the equivalent of a global WADGPS capability is needed. The expansion of regional WADGPS systems to a global system is one of several extensions of GPS that are likely to occur over the next decade. However, in the long-term, several additional enhancements to GPS are anticipated which, when coupled with the planned removal of selective availability, will enable decimeter-level real-time positioning accuracy for certain satellite users of GPS. Terrestrial users also would experience significant improvements in accuracy with the enhanced GPS (EGPS).

In the coming decade, systems like WAAS will become operational and will be coordinated to provide some level of global WADGPS. However, looking beyond that time frame, we anticipate with EGPS that many of the global WADGPS features, along with the desirable feature of improved accuracy, can be incorporated into GPS directly. In this latter phase, as various EGPS features become available, the complexity and cost of precise global and regional positioning will be reduced significantly.

As global WADGPS and/or EGPS become reality in the coming years, we anticipate significant reductions in NASA ground operations costs for navigation and orbit determination support.

Acknowledgments

Partial sponsorship from the U.S. Air Force and from the FAA is gratefully acknowledged. Real-time GPS solutions presented in this article were obtained using data from the SATLOC ground network in the United States.

References

[1] W. I. Bertiger, Y. E. Bar-Sever, E. J. Christensen, E. S. Davis, J. R. Guinn, B. J. Haines, R. W. Ibanez-Meier, J. R. Jee, S. M. Lichten, W. G. Melbourne, R. J. Muellerschoen, T. N. Munson, Y. Vigue, S. C. Wu, T. P. Yunck, B. E. Schutz, P. A. M. Abusali, H. J. Rim, M. M. Watkins, and P. Willis, "GPS Precise Tracking Of TOPEX/POSEIDON: Results and Implications," *JGR Oceans TOPEX/POSEIDON Special Issue*, vol. 99, pp. 24,449–24,464, 1994.

[2] "Ground Control," *Los Angeles Times*, pp. D1, D5, March 10, 1997.

[3] J. Ceva, "Hughes Aircraft's Architectural Design of the Federal Aviation Administration Wide Area Augmentation System: An International System," 48th International Astronautical Congress, IAF-97-M.6.04, Turin, Italy, October 6–10, 1997.

[4] W. I. Bertiger, 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 Prototype Real-Time Wide Area Differential GPS System," ION National Technical Meeting, Santa Monica, California, January 1997.

[5] T. P. Yunck, Y. E. Bar-Sever, W. I. Bertiger, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, T. N. Munson, R. J. Muellerschoen, and S. C. Wu, "A Prototype WADGPS System for Real-time Sub-Meter Positioning Worldwide," *Proceedings of the Institute of Navigation ION GPS-96*, Kansas City, Missouri, pp. 1819–1826, September 1996.

[6] S. M. Lichten, Y. E. Bar-Sever, W. I. Bertiger, M. Heflin, K. Hurst, R. J. Muellerschoen, S. C. Wu, T. P. Yunck, and J. Zumberge, "GIPSY-OASIS II: A High Precision GPS Data Processing System and General Satellite Orbit Analysis Tool," *Technology 2005*, NASA Technology Transfer Conference, Chicago, Illinois, October 23, 1995.

[7] G. Blewitt, "Carrier Phase Ambiguity Resolution for the Global Positioning System Applied to Geodetic Baselines up to 2000 km," *Journal Geophys. Res.*, vol. 94, no. B8, pp. 10,187–10,203, 1989.

[8] G. Blewitt and S. M. Lichten, "GPS Carrier Phase Ambiguity Resolution up to 12000 km: Results From the GIG'91 Experiment," *Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning*, presented March 1992, Columbus, Ohio, 1992.