NOVEL CONCEPTS FOR PRECISE LOW EARTH ORBITER NAVIGATION WITH GPS

C. L. Thornton, S. M. Lichten, L. E. Young, T. P. Yunck
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

ABSTRACT

The Global Positioning System (GPS) is widely used for satellite positioning and navigation, and for numerous geolocation activities. Real-time, on-board positioning accuracies for low ear t h orbiters currently vary from 50-100 meters for standalone convent ional GPS tracking to somewhat better than 10 meters with sophisticated onboard data filtering. Wide area differential techniques, such as 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 paper describes a concept for extending the wide-area differential GPS techniques for global, real-time positioning of low earth orbiters at sub-meter accuracies. GPS design and operation policy issues which currently limit real-time, on-board precision positioning are discussed. The paper 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 centimeters for low earth orbiters (LEOs).

INTRODUCTION

The Global I'ositioning System (GPS) is now used extensively for orbit determination by scientific and other Earth satellites, and for many other science, government and commercial purposes around the world. For users without selective availability (SA) keys, GPS currently provides real-time kinematic positioning at the level of 50-100 meters. 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 shuttle and space station, which, because of high drag (and frequent maneuvering by the shuttle) tend to follow irregular orbits. A variety of shuttle- and station-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 an accuracy demanded for satellite altimetry programs of the TOPEX/POSEIDON class[1], a real-time, onboard orbit determination capability could enable computation of onboardgeophysical 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, which will utilize onboard GPS receivers for precise orbit determination (POD) in low-Earth orbit[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 is then 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 imagers can track of 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 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 tri-agency effort involving NASA, NOAA, and the U.S. Department of Defense (DoD) to develop a new generation of operational weather satellites is considering instruments that w i ll 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.

Table 1. GPS Performance Requirements

Accuracy required, real-time	'Technique	Users and Applications
100 m — 1000 m	SPS* GPS	Satellite routine navigation; low-cost terrestrial positioning
1 m — 20 m	WADGPS PPS* GPS	Precise satellite navigation; surveying; aircraft (cruise) navigation; military uses
< 1 m	Precision WADGPS Enhanced GPS (EGPS)	High precision satellite navigation; geodesy; high precision surveys; aircraft takeoff and landing navigation; SAR and precise Earth mapping

*SPS — Standard positioning service, available to civilian users without decryption. But note that the current 50-100m positioning error w i 11 improve to 10 m when selective availability is turned off.
*PPS — Precise positioning service, available only to users authorized to carry decryption

Many GI'S science applications utilize terrestrial vehicles rather than Earth orbiters. Synthetic aperture radar (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 significantsavings 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 key categories of performance for real time positioning with GPS. This paper focuses on sub-meter positioning of LEOs where precision WADGPS or an Enhanced GPS (EGPS) capability is required. The essential elements of a global precision WADGPS are first discussed. The remainder of the paper then explores means for obtaining the precise WADGPS performance globally in real time, and without differential corrections, from a proposed EGPS.

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 towards initial operation in 1999 and full operation in 2001 to support 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 w i 11 benefit from real time positioning accuracies well surpassing what today's 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.

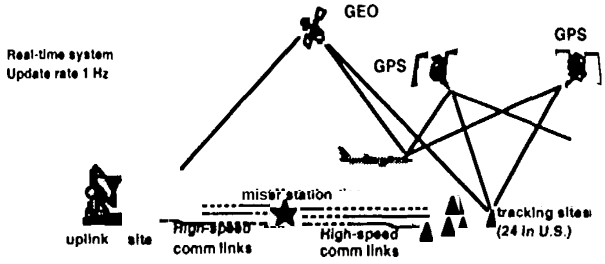

Fig. 1 Schematic diagram showing basic components for FAA WAAS.

Figure 1 illustrates the basic configuration and operational concept for the FAA's "Initial WAAS," to be operational in 1999. Twenty-four GPS monitor stations spanning the U.S. w i 11 collect GPS carrier phase and pseudorange data at I-see 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 will then 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 are currently subject to intentional high frequency fluctuations ("clock dithering"), the WAAS clock corrections must be updated every 6 sec and received by users within 9 sec 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 "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% probability (two sigma) 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 50-100 m, primarily due to the error from selective availability.

WADGPS Current Performance and 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.

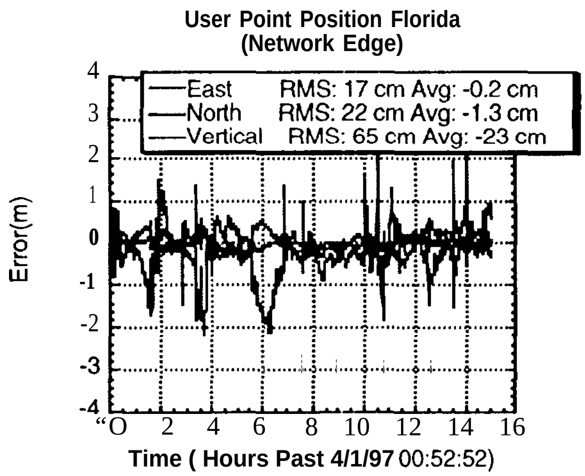

Fig. 2. Recent JPL WADGPS results with real-time SATLOC CONUS network data.

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 are currently collected at low-rate (30 see) rather than at the high rate (l-see) needed for WADGPS, and a t 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. The NASA/Caltech Jet Propulsion Laboratory (JPL) has developed and delivered to the FAA and its WAAS prime contractor, Hughes Aircraft, the prototype WAAS software to compute GPS orbit, clock and ionosphere corrections in real-time[4]. This prototype WADGPS software has been processing data from a continental United States (CONUS) network installed and maintained by a private company, SATLOC. SATLOC has commercialized this software, with particular focus on the agricultural and farming user segment, and is currently offering these WADGPS services over a wide area in the CONUS covered by geosynchronous satellites. Fig. 2 shows recent dual-frequency real-time user positioning results from this prototype system; similar results are obtained for single-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.

High-Precision WADGPS System Elements

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 following capabilities in computing these three correction (for real-time onboard positioning and orbit determination, a satellite would also require flight software with the necessary orbit models, estimator, and propagator):

The Slow Orbit Correction Typical 3D accuracy for GPS orbits produced several days after the fact at JPL using data from the global IGS network is 10-12 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 (- 1 m) than what can be achieved in a real-time WADGPS process (- 40 cm). Key features of JPL's system (described in Ref. 1) that enable solutions of the highest accuracy include:

- *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 lit t le loss of accuracy.

- *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, 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, 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.

- *Stochastic Estimation* — Even the best models fall short of perfection. Deficiencies can often be partly overcome by judicious estimation of critical model parameters along with the satellite states. A few such parameters (atmospheric propagation delays, 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, white or colored noise.

• *Phase and Pseudorange Processing* —Carrier phase is modeled as a biased range measurement. JPL's system processes smoothed pseudorange and carrier phase data simultaneously for a 11 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 is now highly evolved and easily adapted to real time use.

THE IONOSPHERIC CORRECTION

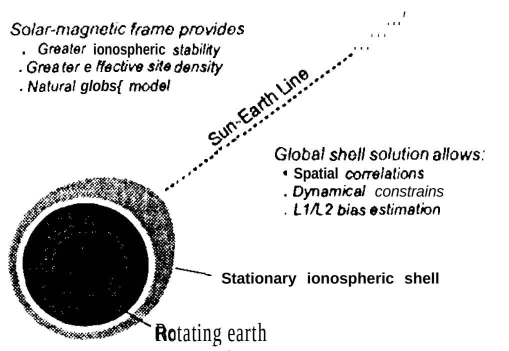

Fig. 3 Solar-magnetic frame in which ionosphere **is relatively stationary and unchanging.**

<u>The Fast Correction</u> 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 is thus 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 ten; 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 are therefore removed to within the fast correction noise level.

JPL's software employs a robust approach which 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.

<u>The Ionospheric Correction</u> Daytime ionospheric delays at L-band can reach tens of meters. Computing a sub-meter ionospheric correction over a continent (or around the globe) presents a major challenge—one that will ultimately 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 JPL's software treats the full global ionosphere as a semi-coherent entity within its natural "solar-magnetic" frame.

The ionosphere forms a shell around the earth, with the region of greatest electron density directed always towards 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.

JPL's current ionospheric mapping operation employs global network GPS data and a Kalman filter to continually update a full, simultaneous shell solution in the solar-magnetic frame[1]. 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 a 11 satellites and receivers (except one). More details are provided in Ref. 1. Worst case ionospheric dynamics in the solar-magnetic frame suggest a solution update interval of 5-15 min for WADGPS operation.

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

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 would likely be complex.

(2) Interoperabi'ity 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 will 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 (1), however, there are political complexities which will have to be handled for this approach.

(3) Improvement in WADGPS positioning accuracy For either of (1) or (2), the issue of improving user positioning accuracy is still relevant. Figure 4a shows anticipated position accuracy for a kinematic (space or terrestrial) user of WADGPS applying the techniques described above for calculating the broadcast corrections and for calculating the user position after applying these corrections. Also shown is expected accuracy from global WADGPS (using similar data analysis techniques), and for an extended GPS (EGPS) system described in the next section. Fig. 4b is calculated for a user in very low-Earth orbit with only limited capability for exploiting dynamics; and Fig. 4c 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 extended 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. 4a). The tropospheric delay has two components, the slowly varying dry portion contributing about 200 cm total zenith delay, and the more rapidly varying portion due to water vapor, typically 5 to 30 cm of total zenith delay. For post-processed 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 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.

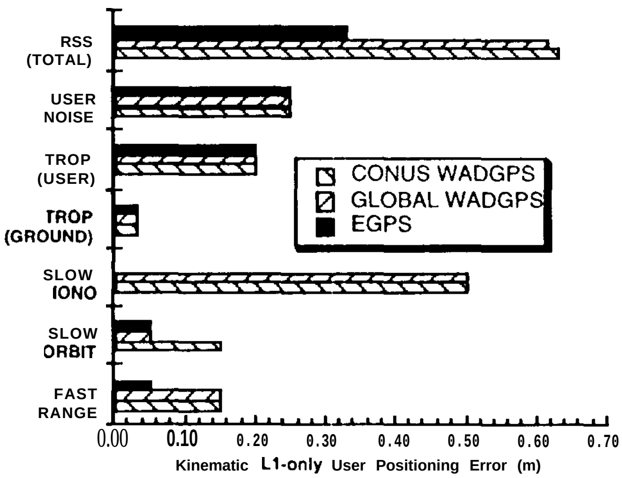

Fig. 4a Anticipated kinematic L1-only user positioning accuracy

The plots in Fig. 4a-b-c all include a component for "user noise." This would include the receiver data noise and multipath, which can in fact 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 value (25-cm) is assumed in Fig. 4a for the kinematic user (perhaps a vehicle or aircraft susceptible to multipath), a lower value is assumed in Fig. 4b where some additional averaging occurs from the partially dynamic fitting possible for a low-Earth orbiter, and a very low value (5 cm) is assumed in Fig. 4c where longer dynamic fits will results in further noise reduction.

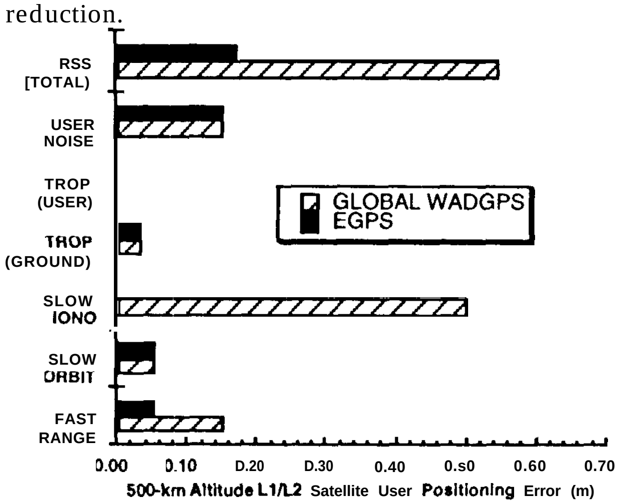

Fig. 4b Anticipated user positioning accuracy for 500-km low-Earth orbiter

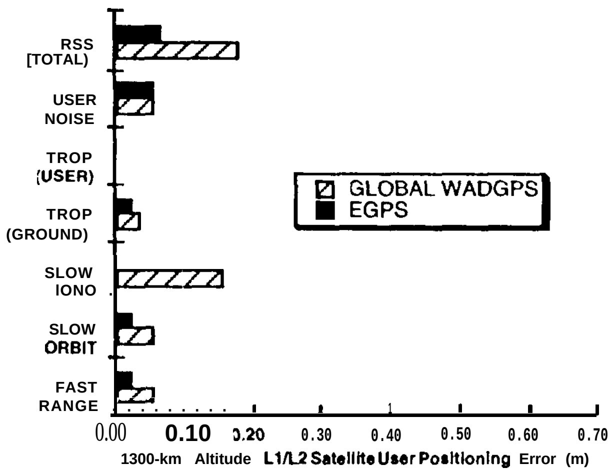

Fig. 4c Anticipated user positioning accuracy for 1300-km low-Earth orbiter

Fig. 4d shows results recently obtained for the 1330-km Topex/Poseidon satellite, where 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. 4c. Fig. 4d shows the improvement in the Topex/Poseidon position as a longer arc length of data are fit, incorporating dynamic estimation. After about 1 day, the solution has settled down to better than 15 cm in each component.

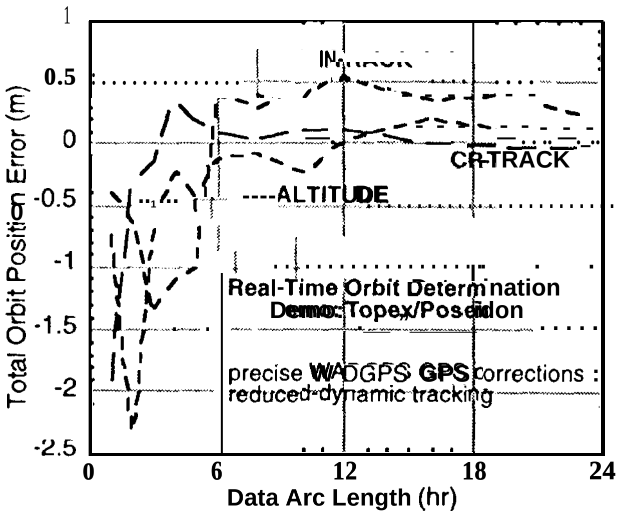

Fig. 4d TopexfPoseidon positioning with global high-accuracy WADGPS processing.

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

Extended GPS (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 studying design options to improve the GPS system performance for various users. Through our participation in this study, we are aware of the the following potential enhancements to GPS which could result in both a global and a very high-accuracy real-time positioning capability, such as is represented by the "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 i t incorporates some functions of what are presently separate WADGPS operations into the enhanced GPS system itself (Figure 5).

GPS constellation augmentation A recommendation for increasing the number of operating GPS satellites from 24 to .30 are 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 performanceimprovements.. 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 RAIM (Receiver Autonomous Integrity Monitoring). The additional satellites would also improve positioning over the entire earth by providing for mom solution strength in typical multi-parameter fits such as those previously described for high precision WADGPS.

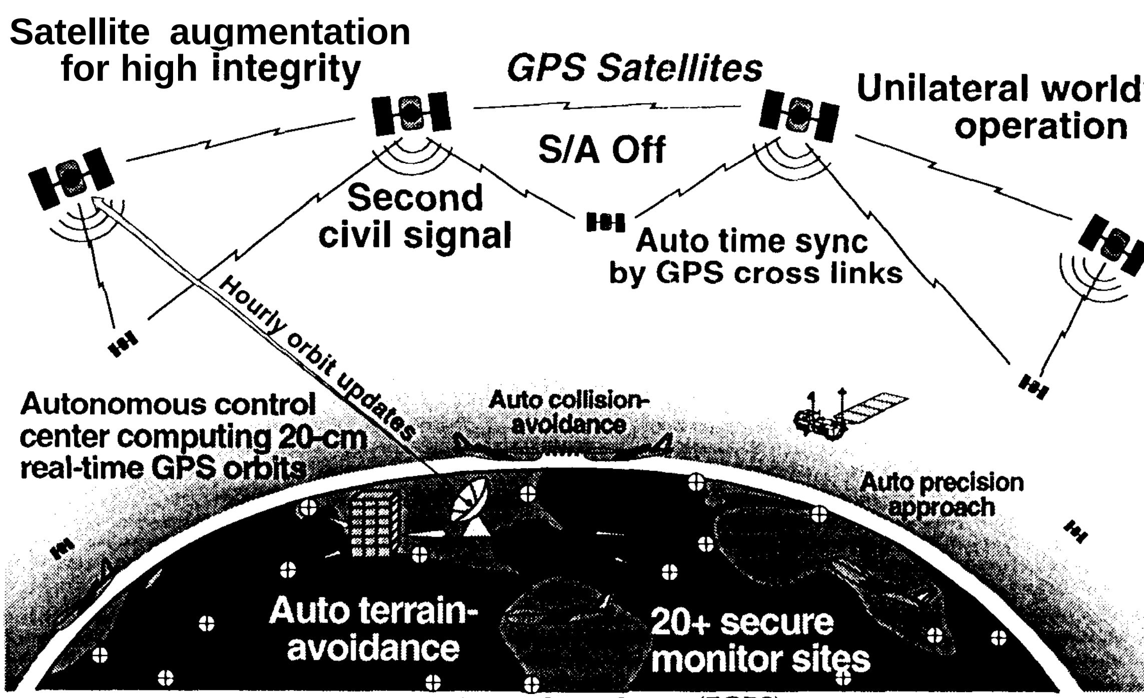

Fig. 5 **Enhanced** GPS **(EGPS)**

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

Enhanced cross-links Enhanced cross-links would enable significant reduction of user error attributed to the "fast correction." These enhanced cross-links would basically 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 satellite uplinks, would keep the GPS clock close to UTC. This could reduce 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 level (30 cm) synchronization. This would be adequate to provide sub-meter real-time positioning from EGPS. Sub-decimeter autonomous user positioning, such as that proposed for EGPS in Fig. 4c, would likely require improvement in crosslink synchronization and reduction of crosslink observable noise to a few tenths of nanosecs.

Second civilian user frequency A second civilian user frequency would enable users to directly calibrate 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 high accuracy global positioning with only a small number of ground sites around the world, perhaps equal in total just to the number needed in the CONUS alone for WAAS. The substantial reduction in number of ground stations for EGPS (- 24 or less) 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 (b) also help reduce the number of ground sites required 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, i t is necessay to determine the integer cycle ambiguity in differential carrier phase between a pair of stations. Theapplication of this technique is currently limited by the data noise present on codeless observable formed from the encrypted L2, signal. A properly spaced second civil signal with a non-encrypted ranging code would decrease the time to achieve reliable RTK results by at least an order of magnitude.

Another enhancement under considerate ion 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]. Widelaning is currently limited to user-s only a few tens of kilometers away from a reference site because of uncalibrated different ial ionosphere between the receivers. Three frequencies will allow “dual widelaning” (also called “trilaning”), which can be effective at arbitrary separations because the extra observable from Ls allow solution 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 10-15 cm, depending on the actual frequency selected. On the other hand, if the proposed Ls is broadcast at C-band modulated by a wideband (loo 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.

Broadcast Ephemeris Improvement The combination of improvements to algorithms and processing techniques (see descriptions in the WADGPS section), 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 to the current level of broadcast ephemeris accuracy (3-8 meters). 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 the Slow Correction section above).

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 an for kinematic or maneuvering users (terrestrial or space); real-time performance for Earth orbiters with EGPS would depend on altitude, with several decimeter accuracy possible for users either a t low altitude or having frequent maneuvers, and better than 10 an in real-time for Earth orbiters at altitudes of 1000km or higher. Not only would these accuracy improvements be a boon to many scientific and commercial GPS applications, but the impact on 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 standalone, 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 WA AS-like systems) to the international scale[3] will be significantly expedited and simplified by the EGPS upgrades discussed in this paper.

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 which 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 10-15 years.

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 which 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 would also 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 timeframe, with EGPS we anticipate 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 significantly reduced, and interoperability between various systems such as WAAS will be greatly facilitated.

ACKNOWLEDGEMENT

'The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Tech-nology, under contract with the National Aeronautics and Space Administration. Partial sponsorship is gratefully acknowledged from the U.S. Air Force and from the FAA. Real-time GPS solutions presented in this paper were obtained using data from the SATLOC ground network in the United States.

REFERENCES

[1] "GPS Precise Tracking Of Topex/Poseidon: Results and Implications," Bertiger, W. I., 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, and T. P. Yunck, B. E. Schutz, P. A. M. Abusali, H. J. Rim, M. M. Watkins, and P. Willis, *JGR Oceans Topex/Poseidon Special Issue,* Vol. 99, 1994, pp. 24449-24464.

[2] "Ground Cent rol," Los Angeles Times, March 120, 1997, pp. D1, D5.

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

[4] W. 1. 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, CA, Jan., 1997.

[5] "A Prototype WADGPS System for Real Time Sub-Meter Positioning Worldwide," T. P. Yunck, Y. E. Bar-Sever, W. 1. Bertiger, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, T. N. Munson, R. J. Muellerschoen, and S. C. Wu, *Proceedings of the Institute of Navigation ION GPS-96,* Kansas City, MO, September 1996.

[‘] "GIPSY-OASIS II: A High Precision GPS Data Processing System and General Satellite Orbit Analysis Tool," 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, *Technology 2005*, NASA Technology

[7] Blewitt, G. "Carrier Phase Ambiguity Resolution for the Global Positioning System Applied to Geodetic Baselines up to 2000 km," *Journal Geophys. Res., 94*, (B8), *pp. 10187-10203 (1989).*

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