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A Prototype WADGPS System for Real Time Sub-Meter Positioning Worldwide

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Biographies

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Byron Iijima is a member of the GPS Networks and Operations Group at JPL. For the past 8 years he has been developing technology for deep-space and GPS tracking applications. He is currently focused primarily on real-time mapping of the global ionosphere. He holds a Ph.D. in physics from MIT.

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Ulf J. Lindqwister received his Ph.D. in physics from Princeton University in 1988. Hc now supervises the GPS Networks and Operations group at JPL, which operates NASA’s permanent GI’S global network (exceeding 60 stations) and which produces ionospheric and tropospheric calibrations for NASA’s deep space and near Earth missions.

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Abstract

Many planned and proposed NASA science activities will benefit from precise real time positioning with wide area differential GPS (WADGPS). Future NASA users include orbital remote sensing instruments (altimeters, SARs, imagers) and a variety of airborne and Earth based investigations. Real time positioning requirements and goals range from a fcw meters to a fcw centimeters. Direct benefits will include the enabling of missions that arc not now possible (such as precision remote sensing from the. space shuttle and space station) and dramatic reduction of analysis costs for a diversity of current investigations. Specific NASA needs not satisfied by planned WADGPS systems, such as the FAA’s Wide Area Augmentation System, include continuous global coverage and sub-meter (in some cases sub-decimeter) absolute accuracy. NASA is now assembling a WADGPS system to provide sub-meter real time positioning worldwide. Enhancements may soon improve real time accuracy to< 10 cm. Kcy components include NASA’s global GPS reference network and JPL’s real time GPS data analysis software. To maximize accuracy, the system features precise dynamic GPS orbit determination; advanced stochastic estimation; simultaneous processing of range and phase data; and usc of the global “solar-magnetic” reference frame for ionospheric mapping, Full North American operation will begin in late FY 96, with initial global operation beginning in mid-FY 97.

Introduction

The first privately built wide area differential GPS (WADGPS) systems are now serving commercial customers. Meanwhile, the Federal Aviation Administration's Wide Area Augmentation System (WAAS)—a particularly ambitious example of WADGPS—is moving towards initial operation in 1998 and full operation in 2001. Similar commercial and governmental projects arc being planned around the world. As these systems take root and greater thought is given to their possible roles, there is emerging a class of prospective users-from satellites 10 aircraft to surface vehicles— who will benefit from real time positioning accuracies well surpassing what today's systems arc able to deliver. At JPL wc have built a prototype WADGPS system to test advanced techniques for meeting the positioning needs of NASA's dive.rsc science interests around the world. Here wc review NASA'S interests in WADGPS and plans to deploy a system for NASA users.

Current WADGPS performance is typified by the formal requirements established by the FAA for "Final WAAS," to be completed by 2001, These 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. 'l'his assumes a conventional Standard Positioning Service (SPS) user with a single-frequency receiver applying WAAS-supplied corrections to GPS orbits and clocks and to the ionospheric delay model.

Future WADGPS Users and Requirements

The WAAS architecture and operational concept were, devised under FAA direction for en route aircraft navigation and precision approach. But since the differential corrections arc to be broadcast openly, WAAS, like GPS itself, will attract users far outside its targeted base. While the great majority of opportunistic users will be fully served by Final WAAS, a subclass will continue to seek something more, both in geographical coverage and in positioning accuracy.

Some of these stricter demands will come from NASA-supported science activities around the world, representing interests ranging from satellite remote sensing to aerogeophysics to in situ Earth science on land and water. A conspicuous example among Earth orbiters is the space shuttle, which, because of high drag and frequent maneuvering tends to follow an irregular orbit. Occasional shuttle-boroc experiments will benefit from real time accuracies of a fcw meters or better. A variety of free-fl ycrs—ocean altimeters, laser and synthetic aperture. radar (SAR) mappers, multispectral imagers--seek orbit accuracies from centimeters to decimeters. While for many this is not needed in real time, the ability to achieve such accuracy autonomously onboard would save time and expense on the ground,

Not all of' NASA's science activities are in space. SAR imaging, topographic mapping, gravimetry, and other forms of remote and in situ sensing carried out from balloons, aircraft, ships and bouys could be similarly expedited with real time. sub-meter or sub-decimeter positioning. Possibly the most stringent goal comes from the airborne SAR group at JPL, which would like to control aircraft flight paths in real time to at least a meter and ultimately to a fcw centimeters. In addition, real time kinematic geodesy could be much simplified with sub-decimeter WADGPS and readily extended to remote locations, A variety of mobile science instruments worldwide could generate finished products in real time, ready for interpretation, with enormous savings in analysis cost and toil. The scientific appeal of seamless worldwide positioning offering post-processing performance in real time can hardly be overstated.

Beyond the need for full global coverage, wc can distinguish two levels of enhanced real time performance attractive to NASA users: sub-meter and sub-decimeter. By late 1996, NASA will offer sub-meter WADGPS performance for both single- and dual-frequency users in North America (and limited coverage elsewhere), with techniques fully compatible with WAAS architecture and operations— i.e., with identical sampling rates and update intervals, and analogous messages. Follow-on efforts to achieve sub-decimeter accuracy will require departures from the WAAS paradigm, including the broadcast of ncw types of information to users.

Elements of the NASA Design

NASA possesses three critical elements that enable rapid, low-cost deployment of a high-performance global WADGPS: an extensive global network of high-performance GPS monitor stations with Internet connections; a real time version of JPL's GIPSY-OASIS 11 software, known as Real-Time GIPSY (RTG), for computing precise GPS orbits and clock parameters; and JPL's Global ionospheric Mapping (GIM) software for computing worldwide ionospheric delay corrections from the global GPS data, Moreover, in its 'l'racking and Data Relay Satellite System (TDRSS) NASA has an effective means for transmitting real time corrections to targeted orbiting and Earth-based users around the globe.

Wc assume here a basic familiarity with WADGPS and WAAS designs and principles of operation [1]-[3]. Figure 1 shows a subset of the global GPS reference network from which NASA obtains data. At present, JPL receives and processes data from over 160 sites worldwide every day. Of these, about 60 are operated by JPL directly, and more than 30 of those arc well-distributed globally. (The remainder arc concentrated mainly in California). Most of the JPL-operated sites arc equipped with Internet links that can support real time data transmission to the processing center at JPL.

Figure 2 depicts the general flow for a typical WADGPS system. The lower three boxes represent the three fundamental WADGPS computations: the slow GPS orbit correction, the fast GPS pseudorange correction, and the ionospheric correction. To achieve reliable sub-meter or sub-decimeter real time positioning globally, NASA's WADGPS design offers advances in all three areas, which wc summarize here. We note that since the most demanding users---those seeking fcw decimeter or better accuracy—will invariably employ dual frequency receivers to eliminate ionospheric error, considerable attention is given to the next largest error source, GPS orbits.

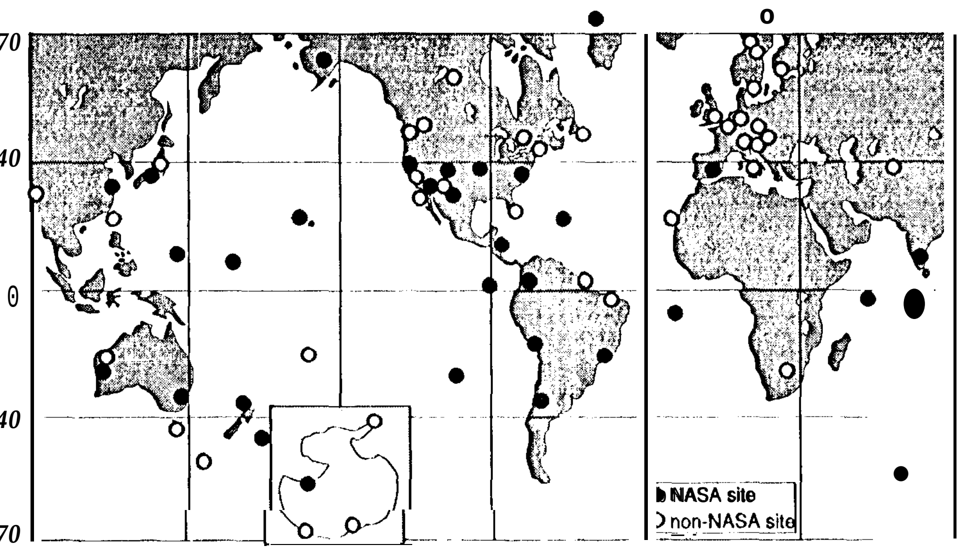

Fig. 1. Key sites of the global GPS network overseen by the International GPS Service.

The Slow Orbit Correction

The GIPSY software, developed over the past decade for various NASA science programs, today computes the orbits of all 24 GPS satellites continuously with data from a 38-receiver subset of the global network. The estimated 3D accuracy for [hose orbits, as reported in the weekly JPL submissions to the International GPS Service (IGS), is about 15 cm RMS. Although the most precise orbits are computed in post-processing, GIPSY, which is built around a sequential Kalman filter/ smoother, has been adapted for real time operation (RTG). GIPSY features critical to high GPS orbit accuracy include:

• *Dynamic Orbit Determination* —. In this technique the satellite current states (3D position and velocity) arc estimated from a history of data, Measurements arc related to onc another try a precise model of the satellite motion derived from models of the forces acting on the satellite. In other words, the estimator fits to the measurements a model orbit derived from the laws of motion (f=ma). This introduces external information in the form of dynamical constraints on the trajectory, thus minimizing the. number of parameters adjusted and maximizing solution strength [4]. A rigorous dynamical orbit model permits the satellite slate estimates to be mapped many hours into the. future with little loss of accuracy. A 5-min update for all 24 GPS orbits takes a fcw cpu seconds on a desktop computer.

• ***Precision Models*** — The success of dynamic orbit estimation rests on the strength of its models, These include models of the forces acting on the satellite.s (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, waler vapor, and higher order ionospheric effects); and such effects as carrier phase windup duc to satellite yaw. RTG incorporates the latest models for all effects of significance. The models have been validated by comparison with other implementations and through extensive usc,

• *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 fcw such parameters (atmospheric propagation delays, solar radiation pressure) exhibit a quasi-random character that can't be fully captured in a deterministic model. RTG therefore allows any parameter to be represented as the sum of deterministic and stochastic components. The latter may take the form of a random walk, white noise, or an exponentially correlated first order Gauss-Markov process (colored noise). When wc estimate a parameter stochastically, wc exploit geometric information in the measurements to make localized empirical corrections to the underlying deterministic models. Depending on how wc constrain the stochastic estimate.s, those corrections may be large or small, highly localized or more diffuse. A decade of processing GPS data has provided us with highly refined stochastic models for a number of kcy system parameters.

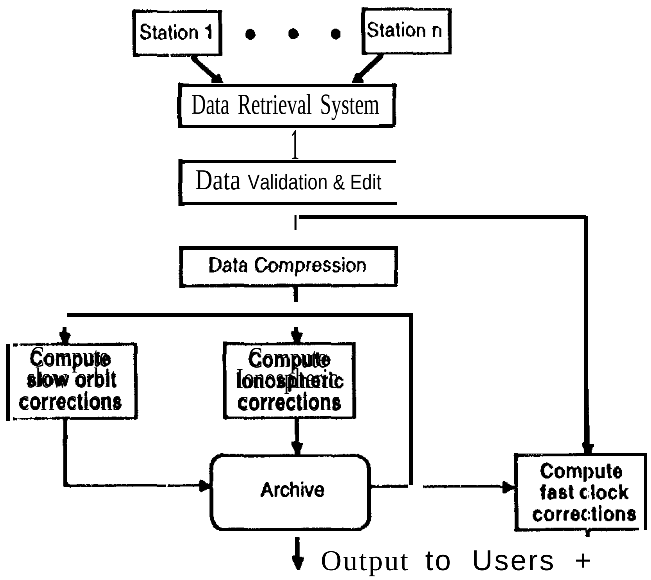

Fig. 2. High level flow for a typical WADGPS system.

•*Phase and Pseudo range* Processing -- The WA AS operational paradigm, as presented in the formal specification [3], calls for all corrections to be computed with pseudorange data only, though the pseudorange may first be smoothed with carrier phase. By contrast, most analysis systems in usc around the world to compute precise (<1 m) after-the-fact GPS orbits employ the far more powerful phase observables exclusivel y, In such systems, phase is modeled as a biased range measurement. RTG processes 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.

•*Automated Quality Control —At* the completion of each orbit update, a quality control routine examines all data residuals, identifying anomalous points, Previously undetected phase breaks arc. either repaired or flagged for estimation of a ncw range bias. Isolated anomalous points arc discarded and the solution is readjusted through a rapid "downdating" technique. This autonomous process adds only a fcw percent to the total execution time while markedly improving orbit accuracy and system robustness.

•*Cycle Ambiguity Resolution* — The use of phase data opens the possibility of resolving integer cycle ambiguities in doubly-differenced observables-– a process that can effectively double. the already dominant strength of carrier phase. Although GIPSY ingests undifferenced data to produce its initial orbit solution, it features a follow-on process which resolves cycle ambiguities globally in doubly -differenced pairs, then readjusts the solution, This newly refined technique exploits precise pseudorange to strictly limit the ambiguity search, and is unique in its ability to fix ambiguities quickly over global distances. It has by itself improved the 3D accuracy of JPL's production GPS or-hits from --20 to ~10 cm. This capability has not yet been incorporated into RTG

The WADGPS slow orbit correction simply replaces the GPS broadcast ephemeris with a more accurate onc so that, after the fast correction, the resulting differential orbit error over a wide area remains small. To be of any value, therefore, the orbit correction must offer a reasonable improvement. The current broadcast ephemeris is accurate to about 5 m (3D), though this typically varies from about 2 to 10 m, as determined by comparisons with the precise orbits produced by JPL and the. International GPS Service. Orbit corrections computed with RTG will reduce this error by an order of magnitude, to <50 cm.

The Fast Pseudorange 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 arc 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." Wc note, however, that the fast correction contains a component of the residual orbit error remaining after the slow orbit correction. The effective orbit error is thus further reduced by common mode cancellation when the fast correction is applied. In accord with a familiar "rule of thumb," the orbit error reduction is roughly in proportion to the distance of the user from the network centroid divided by the distance to the GPS satellite [5], For a user 2000 km from the centroid, the reduction is about a factor of ten; a 30 cm orbit error would contribute only 3 cm to the user differential range error (UDRE). GPS clock errors arc independent of geometry and arc therefore completel y removed (to withi n the accuracy of the estimate) by the fast correction.

One can derive the fast corrections by averaging local range corrections computed for each satellite at all reference sites. The local corrections arc formed by differencing tbc modeled and observed pseudoranges (after dual frequency ionospheric correction), where the model is derived from the best available satellite and receiver positions and clock offsets. While this procedure is fast, it requires up-to-the-second knowledge of all receiver clock offsets. With RTG wc can employ a more robust approach which simultaneously estimates all satellite and receiver clock offsets (which include the effects of residual orbit errors and instrumental delays) every second, while fixing the station positions and (updated) GPS orbits. Though somewhat more time-consuming, this process is still fast and ensures complete isolation of receiver clock and instrumental effects fi om the fast correction.

RTG's principal advantage in the fast correction is its usc of precise phase measurements, whose biases arc continuously estimated. The point-to-point phase noise is only a fcw millimeters, allowing very accurate quadratic ***prediction*** of GPS clocks, based on the. most recent 1 -scc solutions, several seconds beyond tbc last data point, to compensate for system latency. By contrast, the point-to-point scatter of smoothed pseudorange is often more than a decimeter, which can add several decimeters to tbc predicted clock errors,

The Ionospheric Correction

Daytime ionospheric delays at L-band can reach 10 m or more. Computing a sub-meter ionospheric correction over a continent (or around the globe) presents a major challenge—one

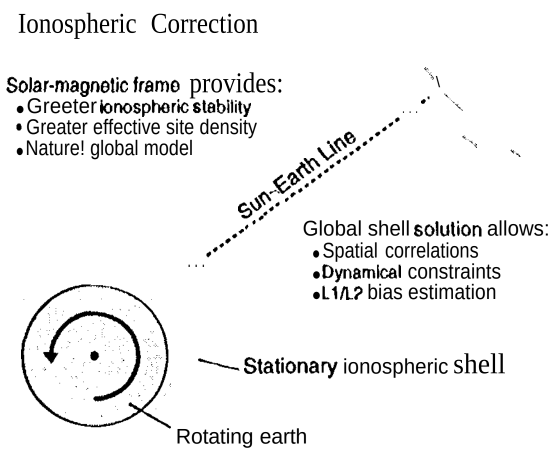

Fig. 3. Key features of JPL's Global ionospheric Mapper.

that will ultimately drive the required number of reference sites. To succeed at an acceptable cost wc must find an ionospheric mapping technique that is both powerful and efficient. The approach taken in NASA's GIM software treats the full global ionosphere as a single entity within its natural "solar-magnetic" frame [6].

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 remains comparativel y stable. A well-deployed global observing network like that operated by NASA quickly sweeps out the ionospheric shell, sampling it nearly continuously in space and time.

NASA's current ionospheric mapping operation with GIM employs global network GPS data and the GIPSY Kalman filter to continually update a full, simultaneous shell solution in the solar-magnetic frame. A triangular tessellation or gridding of tbc shell provides nearly uniform solution spacing over the spherical surface; a fast bilinear interpolator can map the solution to any desired point. The values at each vertex arc modeled stochastically with carefully tuned time correlations between updates, In addition, spatial correlations are introduced among nearby vertices and the L1/L2 delay biases are estimated for all satellites and receivers (except one), so that the system is continuously self-calibrating [6]. (GIM's L1/L2 delay bias solutions have proved so accurate that the DoD intends to artopt them in place of pre-launch bias calibrations in tbc broadcast data message,) This yields a far stronger solution than can be achieved by the usual process of interpolat ing bet ween indcpcndcnt ionosphere measurements made at individual sites.

The solution process is initiated with an a priori ionospheric model, such as the Bent mode]; within a few hours, however, (and perpetually thereafter) the solution becomes almost purely data driven, The result is an ionospheric map that is both fully global and more accurate than any other---and therefore well suited to NASA's far-flung science activities, Worst case ionospheric dynamics in the solar-magnetic frame suggest a solution update interval of 5-15 min for WADGPS.

The global solar-magnetic strategy retains its advantages even for purely regional networks, such as a North American WAAS. Since the solution is initiated with a global ionospheric model, in regions far (i.e., spatially and temporally decorrelated) from the region observed, it simply returns that mode]. As the network moves with the rotating earth, the estimator continually updates the full shell solution, Where there arc ncw data, the solution is adjusted; where there arc none, it preserves the latest estimates, which can be made to relax gradually towards the model values if ncw information never arrives. The solution is always strongest, of course, in the region over the observing network,

Execution Times

Here wc summarize the. computation times required to generate the three corrections. Wc assume the usc of a modern 40 mflops workstation, such as a Sun, an HP 9000/735, or a high end Macintosh or PC.

Slow Orbit Correction

Two major computations go into the orbit update: integrating the model trajectories (including generation of variational partial derivatives) and running tbc Kalman filter, To assess the first, wc integrated a single GPS orbit for21 hrs, generating partials for the current state, three solar pressure parameters, and a yaw rate parameter, All models were activated, including a 12x 12 gravity field along with gravitational effects from the sun and moon and from ocean and solid earth tides. The execution required 4.56 cpu seconds on an HP-735 workstation, A S-rein integration for 24 satellites will therefore take less than 0.5 sec.

The filter execution time, which is dominated by the two inner loops of the Householder transfonnation, is given approximately by

$$T \approx M \times P^2 / \text{flops}$$

where M is the number of measurements and P the number of parameters adjusted. A 24-site network collecting phase and pseudorange data from (on average) 8 satellites each will generate 2x8x24=384 measurements pcr second, For a 5- min orbit update, RTG will compress the 1-s data to S-rein normal points by carrier-smoothing ("Hatch-filtering") pseudorange and sampling ("decimating") phase., Wc estimate 9 parameters for each satellite (6 states, clock, solar pressure, Y-bias), two for each receiver (clock and zenith troposphere), and biases for all 8x24 = 192 phase measurements, or 456 parameters at each update. The filter execution time is therefore $384 \times 456^2 / 4 \times 10^7 \approx 2$ sw. With orbit integration and other computational overhead tbc full 5-rein update takes less than 3 cpu seconds.

Fast Pseudorange Correction

For the fast correction wc first compute a range. model from the GPS orbit solution and station models, then the satellite and receiver clock solutions, The model computation, which is much simplified from the corresponding computation for the orbit solution, takes about 0.2 scc for 24 receivers and satellites. In the solution step wc again have on average 384 measurements and wc estimate 47 parameters---a clock for 24 sate.llitcs and 23 receivers, with onc held fixed for reference- --every second. By the same formula, this gives an approximate execution time of 21 msec.

Slow Ionospheric Correction

The. ionosphere computation is also dominated by filter execution. The triangular global grid used for the standard JPL ionospheric maps has 642 nodes, though that can be varied.

Accurate global ionosphere mapping requires a considerably denser network than do orbit and clock estimates (which can bc recovered well with as few as a dozen receivers around the globe). Today wc typically usc 55 receivers, producing about 440 leveled phase measurements at each epoch to generate the global maps. This gives a filter execution time of $440x642^2$ / 4x107= S cpu scc for a single 5-min update. Other steps in the processing increase the total to about 10 cpu sec.

System Latencies

A principal concern for WADGPS is the latency of the fast corrections, which users must apply within seconds of raw data acquisition at the reference sites. l'able 1 summarizes the execution times for the major compilations and their contribution to the fast latency. These times assume 24 monitor stations, 24 GPS satellites, and data analysis performed with RTG on a moderate speed (40 Mflops) workstation. Note that only onc entry---the smallest-contributes to the fast correction latency. The system completes all orbit solutions and fast model computations before the data to be used in the fast corrections arc acquired; only the fast clock solution itself must be carried out after those data are received. Our sample configuration gives a computing delay of about 21 msec; data editing and conditioning will add a fcw milliseconds more. If wc were to adopt the simpler technique of averaging pseudorange corrections rather than solving simultaneously for all clocks, the computation time for the fast correction would fall below 1 mscc.

While lcss critical, latencies for the slow corrections must also be understood. Since those corrections are computed infrequently, wc clearly (scc Table 1) have. ample cpu margin, Indeed, an ionosphere update maybe needed only every 1 5 rein, and each orbit update, as we've noted, will remain accurate for hours. As an aside wc observe that the WAAS data message gives the orbit corrections in the form of adjustments to satellite x,y,z coordinates, which must be derived from the broadcast ephemeris. Strictly speaking, such corrections are

Table 1. Approximate Execution Times (24 receivers and 24 satellites)

Computation	Execution Time	Contrib. to Fast Latency
GPS Orbit integration (S rein)	*<0.5 .s*	*o*
GPS Orbit Estimation (5 rein)	*<2.0* s	*o*
Fast Model Computation (1 s)	*<0.5* s	*o*
Fast Clock Estimation (1 s)	-21 ms	'-21 ms
Ionospheric Correction (5 rein)	<10s	*o*

valid at only a single instant, and because of orbital motion they quickly degrade. Thus even with a perfect orbit solution the derived x,y,z corrections will go stale within minutes and have to be recomputed--though the more costly orbit solution itself need not be.

Status and Recent Results

At this writing, a complete prototype system to generate real time WADGPS corrections is undergoing testing at JPL. The system is being tested in two ways. First, real time 1 -sec data from a commercial North American network, sent over dedicated frame-relay phone lines, arc being ingested over test periods ranging from hours to days and all corrections arc being computed, Execution times arc consistent with Table 1. In addition, wc continue to test the system with data from the large NASA global network. The global data (and on occasion the North American data) arc processed off line, but exactly as though they were arriving in real time.

Ionospheric Calibration Results

To assess ionospheric calibration accuracy, data were collected from two North American networks, shown in Fig. 4, on 2 Sept 96. The solid circles indicate the eight real time sites operating that day, used to compute true real time ionospheric delay maps for all of North America, updated every 1 S min. Independent data were acquired simultaneously from nine test

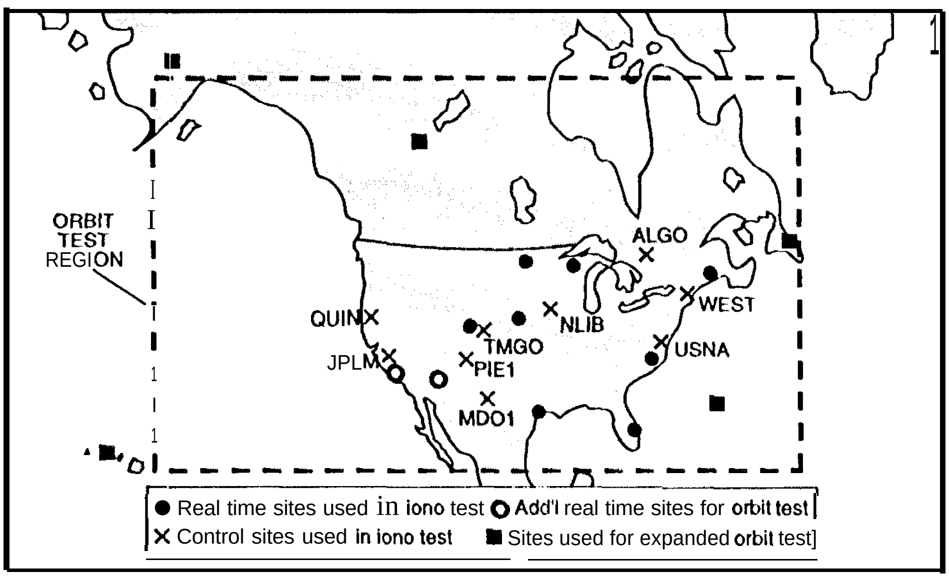

Fig. 4. Map of sites used in tests of the real time ionospheric and GPS orbit corrections.

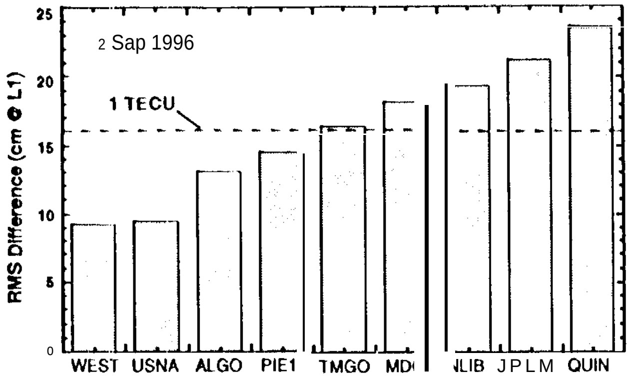

Fig. 5. Ionosphere calibration discrepancies at 9 test sites.

sites across the US, represented by the crosses, The test data were used to compute the zenith ionospheric delays near the test sites using a precise post processing technique for maximum accuracy. The real time maps were then evaluated at the ionospheric pierce points of the test observations and compared directl y with those observations. Figure. 5 shows the RMS difference over 24 hours bet wccn the real time maps and the direct test measurements for all nine test sites. The RMS differences range from 9.5 cm to 23.5 cm. Note that the two worst cases (JPI ,M and QUIN) arc the two sites farthest outside the 8-site real time network. With a 16-site real time network uniformly distributed, wc can expect typical zenith accuracies of 1 S cm or better, except during magnetic storms, when they may degrade by a factor of 2 or 3.

Real Time Orbit Accuracy

In a recent test, real time GPS orbits were computed over a 39-hr period from 6 Scp 96 to 8 Scp 96 using data from a 10-sitc real time North American network. (The commercial real time net work was just being installed and the number of sites operating fluctuated somewhat from day to day.) The two additional real time sites arc indicated by the open circles in Fig. 4. The orbit solutions were propagated forward at 5-rein intervals and updated every hour. The real time orbit solutions were then compared against precise (~1 S-cm) orbits computed after-the-facl with data from the full global network. The orbit comparison was performed over an area considerably greater than that spanned by the real time network, extending from Cuba (20° N) to Anchorage (60° N) and nearly from Hawaii (1 50° W) to St Johns, Newfoundland (50° W).

Orbit accuracy was assessed by computing the RMS difference between the real time and precise solutions over a 15-min interval past the end of the 39-hr data arc, for the altitude (h), cross-track (c), and in-track (l) orbit components. The RMS differences for all 24 GPS satellites were then averaged to give a single measure of orbit accuracy. The component errors were 81 cm (h), 75 cm (c) and 88 cm (l). 'l'his is somewhat above our goal of 50 cm for real time orbits with a full global network, illustrating the limitations of a US-only network in serving a more extended region.

In a second test, simulated real time orbits were computed after adding data from five NASA sites to the 10-site real time network. The NASA sites included Fairbanks, Alaska; Yellowknife, in northern Canada; Kokcc, Hawaii; St. Johns, Newfoundland; and Bermuda (indicated by the squares in Fig. 4). The same comparison was then performed. Component errors fell to 42, 54, and 55 cm.

In a final test, a well-distributed 18-site global network was selected from the larger IGS network (Fig. 1). The da(a were processed off-line but in exactly the real-time mode. None of the actual real-time sites were included, The orbit solutions were updated every hour and propagated 1 hr beyond the last data point. The predicted values were then compared with precise (filtered and smoothed) orbits made with a 38-site global network. This time the comparison was made over 22 days and over the entire globe, not just in the test region in Fig. 4. All component RMS differences fell below 40 cm, illustrating tbc power of global observation. Real-time orbit results arc summarized in Fig. 6. With further tuning of the estimation strategy and introduction of the cycle ambiguity resolution procedure currently used in daily GIPSY solutions, some additional improvement, perhaps reaching 30 cm pcr component, can bc expected with global data.

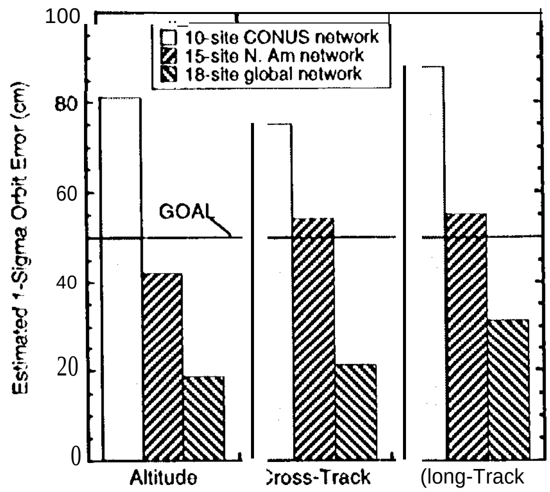

Fig. 6. Summary of real time orbit accuracy tests.

Fast Correction Results

Although the prototype NASA system is generating fast pseudorange corrections once per second using the full simultaneous estimation technique described above, no specific accuracy tests on those corrections have yet been performed. in 1994, however, wc performed covariancc studies and simulated real time fast corrections (with actual data), the results of which have been reported in Ref. [5]. The expected (1-sigma) error of the fast correction before propagation is about 15 cm, Additional error is incurred, primarily owing to selective availability dither, when the fast correction is predicted forward several seconds to compensate for system latency. '10 test this, the 1994 studies predicted the corrections ahead 6 see using a quadratic fit to the last six 1-SCC estimates. The predicted corrections were compared with precise, smoothed corrections computed after the fact, Over several thousand trials, the 1-sigma prediction error was 4.3 cm. Combined with the estimation error, this gives a total expcctcd 1-sigma error for the predicted fast corrections of less than 16 cm.

User Differential Range Error (UDRE)

Though definitions differ, the UDRE is typically made up of the residual orbit error---aflcr the direct range error is scaled down by the fast correction-and the fast correction error itself. For a typical WADGPS user, the direct orbit error reduction induced by the. fast correction will be more than a factor of 5 (see [5] for more discussion). l'bus, for an operational system providing slow orbit corrections accurate to 40 cm (1-sigma), the orbit contribution to UDRE will be less than 8 cm. To this wc add in quadrature the ~15 cm fast correction error to arrive at a 1-sigma UDRE of 17 cm. 1 'or a typical PDOP of 2.5, this gives a 1-sigma 3D user error of 43 cm from the slow and fast corrections.

Discussion and Plans

Its operational simplicity and high performance will quickly make WA1)GPS a familiar part of the GPS landscape. When such services arc openly available, manufacturers will offer WADGPS in even the most basic consumer receivers, and the distinction between GPS and WADGPS will begin to fade..

Many current WADGPS system designs, however, fall shot-l of the possibilities inherent in the WADGPS concept, Those designs tend to be straightforward extensions of conventional pseudorange-based GPS and local area DGPS, with no attention to the more precise phase-based methods devised for science and geodesy over the past 15 years. Our own WADGPS experiments confirm that such techniques can be readily embedded in a global WADGPS offering performance exceeding that of existing and planned systems.

In view of the clear benefits to its programs and the readiness of the technology, NASA is now proceeding with the first step in a phased deployment of a global high- performance WADGPS. The planned phases arc summarized below.

•Dec 96: ***Pilot Startup*** — In Ott of 1996, JPL will begin producing the slow orbit and fast clock corrections using the real t ime data stream from a North American WADGPS network. Special hard ware has been installed for that purpose. By 1 November, the ionospheric computation will be brought online, together with real time Internet links to 20 of NASA's global sites. By December, the system will begin generating the full set of global real time WADGPS corrections and should provide sub-meter accuracy for single-frequency users and sub-SO cm accuracy for dual-frequency users.

•Mar 97: ***Full Pilot Operation*** -- Between Dec 96 and Mar 97, ten additional global sites will be equipped with real time Internet links and integrated into the pilot WADGPS operation. Computing facilities at JPL will be augmented and several integrity monitoring and validation functions will be incorporated. The system will then produce fully global real time orbit, clock, and ionospheric corrections. The corrections will be made available in real time over the Internet and by frame relay to White Sands, NM, for possible broadcast by TDRSS to selected NASA users. They could also be communicated by phone, radio, and numerous other real time links to potential users around the world,

•Mar 98: ***Enhanced operation*** --- In FY 97, JPL will begin testing system enhancements intended to improve real time GPS orbit accuracy to 30 cm and to provide real time subdecimeter positioning accuracy to dual-frequency users worldwide.. The first of these enhancements will be introduced into the operational pilot system by early 1998. Further refinements will be added regularly thereafter, and will eventually require some departures from WAAS data formats and message content,

•Date TBD: ***Global Broadcast Operation*** —-- NASA is considering developing new L-band transponders for the next generation TDRSS satellites to enable continuous real time broadcast of the WADGPS message to most of the inhabited world, The earliest these could be in operation would be late 1998. Should this phase go forward, the entire system will be upgraded, with dedicated real time links to the monitor sites and rigorous real time system validation.

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References

1. Kee, C., Parkinson, B. W., Axelrad, A., Wide area differential GPS, *Navigation*, Journal of the Institute of Navigation, *38*, #2, pp. 123-146, 1991.

2. VanDierendonck, A. J. and P. Enge, RTCA special committee 159 definition of the GNSS integrity channel (GIC) and wide area differential GNSS (WADGNSS), Proc. ION GPS'93, Salt Lake City, UT, Scpt 1993, pp. 495-505.

3. Federal Aviation Administration, ***Wide Area Augmentation System (WAAS) Specification***, Document FAA-E-2892, U.S. Department of Transportation, 9 May 1994.

4. Ceva, J., W. Bertiger, R. Muellerschoen, 'I'. Yunck and B. Parkinson, Incorporation of orbital dynamics to improve wide-area differential GPS, Proc. institute of Navigation GPS-95, Palm Springs, CA, pp 647-659, Scp 1995.

5. Yunck, T. P., W. 1. Bertiger, S. M. Lichten, A. J. Mannucci, R. J. Muellerschoen and S. C. Wu, A robust and efficient new approach to real time wide area differential GPS navigation for civil aviation, JPL Report D- 12584, 1 April 1995.

6. Mannucci, A. J., B. D. Wilson and D.-N. Yuan, An improved ionospheric correction method for wide-area augmentation systems, Proc. Institute of Navigation GPS-95, Palm Springs, CA, pp 1199-1208, Sep 1995.