GPS DATA, ACQUISITION, ENVIRONMENTAL EFFECTS

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INTRODUCTION

Precise geodesy with the Global Positioning System (GPS) emerged in the early 1990s from a decade-long incubation to find vigorous application worldwide. The transition was symbolically inaugurated in January 1991 with the first truly global campaign in scientific GPS geodesy, known as GIG'91. Sixteen satellites were then in service, and geodetic receivers were still scarce and expensive. Today we enjoy a full 24-satellite constellation, much improved receivers at about one-third the 1991 cost, a growing permanent global network and a vital international GPS Service to support GPS geodesy worldwide. In addition, dedicated regional GPS networks are springing up on every continent. The period has been marked less by conceptual advance than by disciplined application and refinement. Here we review the key developments in receivers and networks, and in understanding the environmental factors that limit GPS geodetic performance.

RECEIVERS & ANTENNAS

Since 1992, four manufacturers have introduced advanced GPS field receivers. These include the Z 12 from Ashtech (Ashjaee and Lorenz, 1992), the SNR-8000 (TurboRogue) from Allen Osborne Associates (Meehan et al, 1992), the 4000-SSE from Trimble (Talbot, 1992), and the SR-299 from Leica (Becker et al, 1993). Each model tracks the precise dual frequency (L1 and L2) ranging codes (P-codes) when they are not encrypted for "anti-spoofing" (AS), and each produces dual frequency carrier phase and one-way range ("pseudorange"), though of lower quality, when they are. The GPS observing environment changed abruptly on 31 Jan 1994 when AS encryption came on full time. The new receivers have helped meet that challenge with minimal effect on operations or data products.

While the early "codeless" receivers employed simple. squaring techniques to recover the L2 carrier during AS encryption, no current model does. In the 1980s, Magnavox devised a novel way to exploit the P-code (which is present, though disguised, during AS) to boost the performance of a squaring receiver (Hatch et al, 1992), an approach now employed in the SR-299. At about the same time, the Jet Propulsion Laboratory (JPL) introduced cross-correlation of the L1 and L2 signals rather than squaring to recover the second frequency (preserving full carrier wavelength); this is used in both the SNR-8000 and the 4000-SSE. Ashtech then combined a novel form of code enhancement and cross-correlation in its Z 12. While the various approaches differ somewhat

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While the earliest "codeless" receivers employed simple squaring techniques to recover the L2 carrier during AS encryption (in fact, always), no current model does. In the 1980s, Magnavox devised a novel way to exploit the underlying P-code (which is present, though disguised, during AS) to boost the performance of a squaring receiver (Hatch et al, 1992), an approach now employed in the SR-299. At about the same time, JPL introduced L1/L2 cross-correlation for its Rogue receiver (preserving full carrier wavelength), which is used in both the SNR-8000 and the 4000-SSE. Ashtech then combined code enhancement and cross-correlation in its Z12. While the various approaches differ somewhat in theoretical performance (Ashjaee and Lorenz, 1992), for the all-important carrier phase measurement, atmospheric effects and multipath tend to mask those differences.

A related development is the so-called narrow correlator spacing for C/A-code tracking, Under AS, all current geodetic receivers revert to C/A-tracking on the L1 frequency. Most have adopted for C/A-tracking the same wideband (-20 MHz) filtering and sample rates, and narrow (-50 ns) early-late correlator lag offsets used in P-code tracking. This reduces the maximum multipath error for C/A pseudorange to that of P-code, and improves 1.1 pseudorange precision to near P-code levels (Van Dierendonck et al, 1992; van Nee, 1992). A comprehensive receiver comparison is now being conducted under the auspices of NASA and the University Navstar Consortium (UNAVCO). [Results of that comparison should be available for the final draft of this paper,]

Although antennas for GPS geodesy have evolved little, popular models differ in distinct ways. Schupler et al (1994) have performed detailed measurements of eight antenna models in an anechoic chamber, while Braun et al (1993) have studied the effect of mixing antennas in controlled short-baseline tests. Both groups find that phase center offsets and azimuthal phase dependencies can cause measurement variations of several centimeters. Knowledge of the phase center location, the 3-D alignment and the detailed phase-vs-viewing angle pattern of each antenna is therefore crucial where millimeter accuracy is sought. These studies suggest that while different receiver models may be mixed without harm, care must be taken to orient, calibrate and preferably standardize antennas in high precision geodetic networks.

PERMANENT NETWORKS

Perhaps the most visible development in the 1990s has been the rapid emergence of permanent, continuously operating GPS networks. Through much of the 1980s the guiding concept for GPS geodesy was to deploy a relatively few permanent fiducial sites to provide reference control for episodic regional campaigns, Many factors have since combined to alter if not entirely overturn that model, among them the great cost of mounting campaigns; the declining cost of receivers; the expansion of the Internet; the lower reliability inherent in returning to sites after long intervals, often with different equipment; the greater precision available from averaging continuous data; and the lure of catching a large earthquake. in the act (accomplished twice now--Landers and Northridge--though distantly, in southern California), Most critical may have been the precipitous drop in the cost of data analysis.

GPS geodesy in the 1980s was notable for the grinding toil needed to edit and analyze the usually ragged data; investigation strategies that minimized data volume were a necessity. By 1990, improved receivers and analysis techniques (Blewitt, 1993) had set the stage for a revolution. Four events in 1991 set it in motion: the massive. 3-week GIG'91 campaign (Melbourne et al, 1991), which deployed more than 100 receivers around the world; installation of a S-site permanent GPS geodetic array (PGGA) in southern California (Bock, 1991, 1994; Lindqwister et al, 1991); operation and expansion of a permanent global GPS network following GIG'91; and the arrival of low-cost RISC workstations running at warp speed. By mid-1991 teams in the U.S. and Europe were laboring to mold existing analysis tools into engines of high-volume production. Meanwhile, the newly formed International GPS Service for Geodynamics (Mueller, 1992; Mueller and Beutler, 1992), in cooperation with the international Earth Rotation Service, began planning a 3-month test campaign that would be the pilot for an operational service to provide archived data, continuous GPS orbits, and daily global geodetic parameters. When the IGS/IERS test campaign began in June of 1992 with more than 25 permanent global sites, the transition was largely completed. Seven analysis centers employing six independent analysis software systems were able to process the 3-month data set as it came in (Beutler and Brockmann, 1993; Kouba, 1993). Today seven full time IGS analysis centers produce daily global solutions for the IGS.

The success of the IGS and the PGGA inspired a general movement towards permanent networks. At this writing the formal global network monitored at JPI. numbers about 60 sites; the PGGA now serves as the framework for a dense Southern California Integrated GPS Network (SCIGN) numbering nearly 40 sites [expected by 9/94], with a goal of 250 in 2 years; Japan is installing two networks totaling more than 100 sites; Australia has put in 15 new sites including 5 in Antarctica. The. global complement of permanent geodetic sites may pass 1000 in 1996.

ENVIRONMENTAL EFFECTS

The environment for GPS geodesy extends from the foundation monuments seated firmly in the earth to the transmitting satellites more than 20,000 km overhead, At those points and at al l points between, environmental elements alter the pure geometrical information in the passing signal. Technology development for GPS geodesy today consists largely in searching for better ways to reduce those contaminants, Here we review recent advances and discuss briefly some new science disciplines that have grown out of those efforts.

Multipath and Phase Windup

Although a popular subject for worry, multipath error is of generally little consequence in GPS geodesy, The phase observable is subject to relatively small effects, revealed by typical postfit residuals of ≤ 5 mm (RMS) for dual frequency phase at permanent sites (e.g., Yunck et al, 1994), though peaks can reach 3 cm or more in hostile settings. The regular oscillation of the multipath signature together with long integration times can reduce the error to insignificance. Genrich and Bock (1992) note that an occupation time of 30 min is usually adequate for sub-millimeter multipath error and that 10 min will typically suffice for 1 mm performance even in difficult environments. Most vulnerable are rapid static and kinematic applications that require short-interval solutions in reflective settings.

Attempts to reduce the instantaneous multipath error often center on suppressing reflections with stealthy site designs and stopping reflected signals with sharp rolloffs in antenna gain. Some groups are attempting to devise signal processing techniques to minimize tracking loop sensitivity to reflected components that reach the receiver. Meehan et al (1992) describe a technique, now used in the Osborne SNR-8000, that exploits the differing multipath effects in the early and late correlator channels to partly cancel multipath in the prompt channel, and thus in the measured observables. They report that their fixed-gain technique can reduce RMS multipath by a factor of 2 or 3. Coenen and Devos (1992) describe an FFT-based approach to detecting (and potentially reducing) multipath in the receiver. A more ambitious adaptive technique reported by van Nee and Siereveld (1993) shows promise but has yet to be demonstrated in an operational setting. Yet another approach is to remove multipath errors after the fact, during data analysis. Bishop et al (1994) report success exploiting the repeating daily multipath signature in fixed settings to form calibration templates. As yet they have applied the technique only to pseudorange.

Wu et al (1993) noted that antennas having different spatial orientations (inevitable on long baselines) will measure different relative phases at the same transmit time (i.e., when sampling the same wavefront) that can persist at the level of 1 cm or more after double differencing. They provide a model of this “phase windup” which, when incorporated into network analysis, eliminates the anomaly and modestly improves residuals and solution stability. Young et al (1994) investigated the magnitude and effect of phase variations in the GPS transmit antenna. They find that such variations are apparently inconsequential in precise geodesy.

Atmospheric Errors

Brunner and Welsch (1993) and Yunck (1993) present general overviews of atmospheric effects on geodetic measurements and means of dealing with them. Tropospheric water vapor is the principal offender, and the water vapor radiometer (WVR) has been a traditional tool for calibrating its effect. Elgered et al (1992) present a detailed overview of WVRS; Puliafito and Buerki (1991) offer evidence that a well-tuned dual frequency WVR can recover the zenith delay to 8 mm or better, which is consistent with earlier claims. A now standard alternative is to dispense with

WVRs and estimate the zenith delay from the GPS data as part of the geodetic solution. This has the virtue of absorbing residual errors in the dry delay model as well. 'l'he most sophisticated variation is to model the zenith delay as a stochastic process and estimate a constrained adjustment every few minutes. Tralli et al (1992) confirm reports from the late 1980s that stochastic delay estimates made with GPS and VLBI data agree with one another, and with WVR measurements, at the 8-15 mm level. Mendes and Langley (1994) compare 14 zenith delay mapping functions (central to delay estimation) and find notable discrepancies below 20° elevation. Further study is needed identify preferred mapping functions for different sites and seasons.

Early evidence hinted that the power of stochastic zenith delay estimation all but nullified the value of WVR data (e.g., Dixon et al, 1991). Ware et al (1993), however, describe a careful study in which data from WVRs pointed towards the GPS satellites improve the vertical precision of a 50-km baseline measurement by 40% (to 2.6 mm) over that from stochastic estimation alone. The advent of dense regional arrays promises a further advance in atmospheric calibration. Wdowinski et al (1994) show that data from a regional network can help identify slow variations in apparent site position duc to local atmospheric changes; those trends can then be exploited in a "spatial filtering" to improve the stability of the absolute position estimates. Other forms of water also pose a problem. Tranquilly and Alrizzo (1993) demonstrate that the spatial irregularity of snowstorms can cause significant variation in the height component of baseline solutions. In another twist on atmospheric influences, VanDam et al (1994) report that variable atmospheric loading can cause as much as 5 mm of variation in actual vertical site positions and present observational evidence from the global network.

The flip side of error removal is error source observation, and the earth's atmosphere is a particularly rich source to observe. A nascent industry is now seeking to apply in practical ways the enveloping atmospheric grasp of GPS. Objectives range from regional mapping of tropospheric water vapor for weather prediction to global recovery of stratospheric temperatures for studying long term climate change. Bevis et al (1992, 1994) discuss the conversion of GPS-inferred zenith wet delays from ground data into estimates of precipitable water vapor (PWV) and suggest that GPS may yield PWV accuracies of 1% or better. Rocken et al (1993) show agreement between GPS estimates and WVR measurements to better than 1 mm of PWV (not to be confused with 1 mm of delay), Space based techniques take a quite different approach: An orbiting receiver can minutely trace the changing carrier phase from GPS satellites rising and setting through the atmosphere to obtain high resolution profiles of atmospheric density, pressure and either temperature (in the upper troposphere and stratosphere) or water vapor (in the lower troposphere). This occultation technique is described by Kursinski et al (1994), Hajj et al (1994a) and Melbourne et al (1994). Yuan et al (1993) consider how ground and space based techniques may complement one another in the long term study of climate change.

ionospheric Effects

Klobuchar (1991) and Yunck (1993) review the major ionosphere effects on GPS positioning and standard techniques of calibration. While dual frequency delay correction has been practiced for decades, a few new twists have emerged. Wu and Melbourne (1993) describe an efficient method of combining dual frequency phase and pseudorange to achieve a slight noise improvement and a factor of two reduction of data volume when both data types are used. Of chief research interest today are the higher order effects that remain in the dual frequency ("ionosphere-free") observables. These can be traced to the interaction between the ionosphere and the earth's magnetic field, and to the differential bending of the L1 and L2 signals by the ionosphere. Brunner and Gu (1991) and Bassiri and Hajj (1993) note that higher order effects can exceed 1 cm under some conditions, though more typical values are 1-3 mm. They offer modified dual frequency calibration techniques which may remove as much as 90% of the higher order error. An old technique of single-frequency ionosphere calibration. accomplished by combining L1 phase and pseudorange data, was revived by Gold et al (1994) for orbit determination of the Extreme Ultraviolet Explorer. The technique sharply reduced postfit residuals and yielded altitude accuracies of 30-40 cm for a satellite carrying a single-frequency receiver at an altitude of 500 km.

The data bonanza from the GPS global network is stimulating new advances in ionospheric mapping. Until recently GPS ion mapping has relied on local observations of total electron content (TEC) from individual receivers as they sweep out a band of the ionosphere each day. Wilson et al (1992) and Mannucci et al (1993) introduced a globally simultaneous technique that features a gridded TEC model with stochastic local TEC adjustment and can produce images of the evolving global ionosphere with arbitrary time resolution. Such techniques may soon provide precise global ionospheric corrections in real time for single-frequency GPS users. The addition of space based measurements will improve the fidelity and resolution of ionospheric images. Hajj et al (1993, 1994) examine through simulation and singular value decomposition the feasibility of 2-D and 3-D tomographic imaging by combining ground and flight GPS data. They conclude that measurements from space are better suited to imaging both horizontal and vertical features,

Ionospheric mapping depends on absolute one-way measurements rather than differenced data, imposing a requirement to calibrate the relative L1/L2 instrumental delay biases that would appear as biases in estimated TEC. This is typically accomplished by first calibrating each L1/L2 receiver bias, then solving for the individual satellite biases while estimating TEC (Coco et al, 1991; Wilson et al, 1992; Gaposchkin and Coster; 1993). The global estimation technique permits the solution for individual receiver biases as well. Wilson and Mannucci (1993) report bias estimates with a day-to-day consistency of 0.2-0.4 ns, or about 3 times the precision of previous techniques.

Reference Frame Errors

The IGS disseminates all data from the global network, globally consistent GPS orbits, and precise site coordinates. This has freed regional investigators from having to deploy fiducial networks or compute their own orbits, and has relieved concern about changing reference frames as fiducial sites change. Heflin et al (1994) now report daily global site position repeatabilities of about 14 mm (-2 parts in 10A9). The published global reference frame is accurate absolutely to about 1 cm. There is nevertheless room for reference frame improvement as GPS moves towards sub-centimeter global geodesy, Analysts have long noted that orbit accuracy degrades when the satellites pass through the earth's shadow (e.g., Yunck et al, 1994) and have suspected a problem with the modeling of GPS thermal radiation (Blewitt, 1993). Bar-Sever et al (1994) uncovered a different and possibly root cause: rapid, unpredictable yaw variations when the satellite loses its sun sensor. As a remedy, they proposed inserting a 0.5 deg yaw bias in the satellite attitude control subsystem, which was adopted and instituted by the Air Force in June of 1994, To realize a benefit from this, orbit analysts must now estimate yaw rate parameters during eclipse periods.

Monument instability threatens the integrity of the reference frame and the authenticity of perceived geophysical signals. While of only modest concern for global measurements, site stability is a top priority for the SCIGN array in the LA Basin, which will feature 5-10 km site spacing and should detect strain rates of 0.2 mm/yr within one year, The SCIGN science team has set a provisional goal of 0.5 mm for long term monument stability, though whether that can be attained is not yet clear. Such local effects as soil expansion from rainfall and slow churning can in principle perturb even robust monuments by millimeters over months or years (D. Agnew, personal communication). Broader scale effects are also a concern, Ikehara (1991) and Blodgett and Galloway (199 1) report land subsidence on the order of 2-4 cm/yr due to intensive water pumping in California's Sacramento and Antelope Valleys. Even relatively benign areas may exhibit nontectonic subsidence at the millimeter level over a period of years from fluid extraction or as a result of drought (Sylvester, 1992; Van Hasselt, 1992), A focused effort is needed to probe site stability at the levels required by dense networks, and GPS may offer a solution. Elosegui et al (1993) report measurement precisions of about 0.1 mm on baselines of less than 100 m with just a few hours of data, which is consistent with results from JPL in the late 1980s and with the work of Genrich and Bock (1992). Long term GPS measurements on closely spaced monuments could answer some of the questions now being raised for the LA array,

Selective Availability and Anti-Spoofing

Selective Availability, which involves destabilizing the satellite oscillators and altering broadcast ephemeris and clock parameters, should have no effect on precise GPS geodesy since the differential solution removes oscillator errors and either estimates the orbits and clocks or obtains them from a separate source, This has indeed proved true, so long as care is taken to ensure that the data samples at different receivers are taken within 10 or 20 msec of a common transmit time. Where that is not the case in the original data it can often be attained by later adjustment, Wu et al (1992) describe a simple interpolation scheme that is effective under a wide range of conditions. Feigl et al (199 1) describe a somewhat more laborious scheme that accomplishes the same thing.

AS is a different matter. All current geodetic receivers produce a degraded L2 phase observable under AS, which in theory could lead to degraded geodetic solutions. In many applications, however, atmospheric variation, not instrumental precision, is the limiting factor and data corruption under AS has little or no effect. Lindqwister and Meehan (1992), for example, achieved 2-3 mm horizontal repeatability over a 50-km baseline with SNR-8000 receivers in AS mode, or about the same as in code mode, Results with modern receivers in the PGGA show little loss of precision since AS went on full time in early 1994. In contrast, the daily repeatability of site coordinates in the global network has degraded by roughly 30% (J. Zumberge, unpublished results), primarily because many older receivers with poorer AS performance are still in place. Like multipath, AS will most directly affect kinematic, rapid static, and other users employing short (<30 rein) averaging times. Even then, however, multipath and atmospheric effects (which are comparable to the AS data noise) will cushion the AS error.

Conclusions

Completion of the GPS constellation, improved receiver quality and a steady reduction of environmental errors have pushed GPS geodesy to levels few had foreseen even five years ago. While the discipline has attained a measure of maturity, progress continues on many fronts, including atmospheric and higher order ionospheric calibration, GPS orbit modeling, AS mitigation and network estimation techniques. At the millennium we will see still better and less costly receivers, a vast global network supporting perhaps hundreds of permanent regional arrays, 10 cm GPS orbits, and daily global site repeatability below 1 cm,

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