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Improved Treatment of Global Positioning System Force Parameters in Precise Orbit Determination Applications

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Data collected from a worldwide 1992 experiment have been processed at JPL to determine precise orbits for the satellites of the Global Positioning System (GPS). A filtering technique has been tested to improve modeling of solar-radiation pressure force parameters for GPS satellites. The new approach improves orbit quality for eclipsing satellites by a factor of two, with typical results in the 25- to 50-cm range. The resultant GPS-based estimates for geocentric coordinates of the tracking sites, which include the three DSN sites, are accurate to 2 to 8 cm, roughly equivalent to 3 to 10 nrad of angular measure.

I. Introduction

The satellites of the Global Positioning System (GPS) are maintained by the U.S. Department of Defense for navigational purposes. These satellites are distributed in six evenly spaced orbit planes, at an orbit altitude of 20,000 km and with an orbit period of approximately 12 hr. GPS measurements collected from globally distributed ground receivers are also being used to estimate Earth rotation, polar motion, and station coordinates. Estimation of the geocenter, or Earth's center of mass, has geophysical and scientific implications. GPS estimates of the geocenter can be used for precise reference-frame calibration and alignment and to eliminate a bias-type error in DSN site coordinates. Over time intervals of weeks to months, the GPS measurements can be used to precisely monitor variations in tracking site coordinates due to crustal motion and continental drift. The data used in this analysis are taken from the International Global Positioning System Geodynamics Service 1992 (IGS'92) campaign. IGS'92 consisted of approximately 30 globally distributed Rogue receiver sites tracking the 18 GPS satellites active during this time. The focus of this analysis was to assess the effects of mismodeling satellite force parameters due to solar radiation on the estimation of other parameters, such as GPS orbits and geocentric DSN coordinates.

II. Estimation Strategy

A unique strength of GPS measurements is that the satellites are sensitive to the geocenter, yet relatively insensitive to errors in the gravity field because of their high orbit altitude and the relatively short data arcs (30 hr) needed for the solution. Mismodeling of satellite force parameters, however, can have a significant effect on satellite orbits, especially in orbit prediction [1]. The goal of this study was to improve satellite modeling in order to achieve centimeter-level accuracy for global geocentric coordinates. To achieve this level of accuracy, it is essential to include corrections for numerous potential errors, including Earth's rotation and orientation, atmospheric distortion of the radio signals from the satellites, gravitational and nongravitational forces acting on the satellites, and various geophysical effects.

The data used in this analysis were taken from GPS week 660, which ran from August 30 through September 5, 1992. In general, the data contain carrier phase and pseudo-range measurements from 18 available GPS satellites tracked by approximately 30 globally distributed JPL Rogue receivers. These tracking sites are shown in Fig. 1 and listed in Table 1. The data were processed using the GPS Inferred Positioning SYstem/Orbit Analysis and Software Integration System, (GIPSY/OASIS II) software [2,3].[1] All nonfiducial station locations were estimated, as well as Earth orientation parameters, GPS carrier phase biases, and random-walk zenith troposphere delays for each tracking site; all transmitter/receiver clocks but one were treated as white noise parameters. X and Y polar motion, pole rate, and UT1–UTC rate are estimated as constant parameters (reset every 24 hr).

One of the most important recent innovations is a new approach to modeling the effects of solar radiation pressure on the satellite orbits. The solar radiation environment of the GPS satellites is generally constant except when a satellite's orbit is in eclipse season. When this occurs, the satellites pass through Earth's shadow, changing the amount of solar radiation the satellite receives. In general, three body-fixed solar-radiation pressure parameters are estimated for all GPS satellite orbits, regardless of whether or not those satellites are in eclipsing orbits. For this analysis however, the GPS orbits were estimated with five solar pressure parameters, which are shown in Table 2. Two solar radiation pressure parameters were estimated as constant: GYC and GX/GZ, where X, Y, and Z represent spacecraft body-fixed coordinates and GYC is the "Y-bias" parameter [4]. GX/GZ represents a single combined scale factor for the ROCK4[2] solar radiation parameter [4], while GX and GZ are independent scale factors for the X and Z directions. The three remaining solar pressure parameters are estimated as stochastic corrections to the constant solar pressure parameters, modeled as a first-order Gauss–Markov process [5]. This technique has enabled the achievement of few-centimeter geocentric coordinate accuracy [6].

III. Results and Discussion

The GPS constellation consists of satellites in Earth orbit configured in six evenly spaced orbit planes. At times, satellites in certain orbit planes experience what will be referred to in this article as eclipsing, or shadowing. Figure 2 shows a satellite in an eclipsing orbit plane. GPS satellites eclipsing during GPS week 660 were PRN02, PRN14, PRN16, PRN20, PRN21, and PRN23.

The results presented here illustrate recent improvements in GPS orbit accuracy. The three-dimensional root-sum-square (*3DRSS*) orbit repeatability for each GPS satellite (j) is defined as [7]

$$3DRSS(j) = \sqrt{\frac{1}{T}\sum_{t=1}^{T} d_{jkt}^2} \qquad (1)$$

where j is the satellite PRN number, T is the number of epochs within both overlap segments, t is the time index, k indicates which overlap segment, and d_{jkt}^2 is the three-dimensional distance between corresponding points on the two overlapping segments. In other words, the orbit quality of a single day is quantified as the rms difference between the ephemerides computed over the corresponding 3 hr of orbit overlap at both ends of that day. This concept is illustrated in Fig. 3.[3]

Figure 4 shows the *3DRSS* orbit repeatability for all GPS satellites active during GPS week 660. The improvement in the orbits with stochastic solar pressure parameters is approximately 25 percent overall for all the GPS satellites (averaged), with a 44 percent improvement in the eclipsing orbits and only an 8 percent improvement in the noneclipsing orbits. This demonstrates how mismodeling of satellite force parameters due to solar radiation can have a significant effect on GPS orbit accuracy, especially for an eclipsing satellite. In an eclipsing orbit, a satellite does not experience constant solar radiation forces throughout the entire orbit arc.

The orbit repeatability for each satellite using both strategies is shown in Table 3. These values represent

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[1] S. C. Wu, Y. Bar-Sever, S. Bassiri, W. I. Bertiger, G. A. Hajj, S. M. Lichten, R. P. Malla, B. K. Trinkle, and J. T. Wu, *TOPEX/POSEIDON Project: Global Positioning System (GPS) Precison Orbit Determination (POD) Software Design*, JPL D-7275 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 1990.

[2] ROCK4 is a solar radiation pressure model provided by Rockwell Corp. for GPS satellites.

[3] J. F. Zumberge, "Regular Analysis of Global Positioning System Data from a Globally-Distributed Network of Rogue Receivers," Interoffice Memorandum 335.4-92-012 (internal document), Jet Propulsion Laboratory, Pasadena, California.

the average orbit repeatability over the 7 days in GPS week 660, with the eclipsing satellites indicated. This table shows the improvement in orbit accuracy due to estimating stochastic corrections to the GPS solar radiation parameters (srp). The table also shows how the eclipsing satellites benefit more from improved estimation strategy.

IV. Concluding Remarks

This analysis shows that GPS orbit accuracy can be improved by estimating stochastic corrections to the GPS dynamic parameters. This new approach improves orbit quality for eclipsing satellites from 85 to 47 cm. This level of orbit accuracy is in agreement with results given by Zumberge et al. [7], where routine processing of GPS data shows orbit accuracy in the range of 25 to 50 cm. A direct result of the improvements in orbit accuracy can be seen in the improvement of the geocentric station coordinate accuracy [6]. The goal of the analysis described in [6] was to achieve centimeter-level accuracy for global geocentric coordinates. Those GPS results were obtained with 3 months of GPS measurements and compared to satellite laser ranging (SLR) solutions from many years of repeated observations. It was demonstrated that the geocenter estimates from GPS are accurate to better than 2 cm in the X and Y components and to approximately 8 cm in the Z (where Z is parallel to the axis of rotation). This capability has important benefits for DSN tracking and for geophysical research, such as geocentric crustal motion studies, and for understanding the magnitude and time scale of geocenter variations and their origin. Precise tracking of interplanetary spacecraft and Earth orbiters requires that DSN geocentric station coordinates be determined to high accuracy. The accuracy for geocentric DSN coordinates determined from the GPS data is approximately 3 to 10 nrad in angular measure.

Figure 5 shows a history of the improvements in the GPS determination of the geocenter. Most of the recent improvements can be attributed to the changes in the technique used for modeling solar radiation pressure, changes that have been described in this article. These new results enable the tracking sites to be precisely specified in a reference frame whose origin is at the geocenter, and will enable precise alignment of different reference frames used for Earth-based tracking, interplanetary navigation, and geophysical measurements. Some future work in this area will examine systematic error sources, further improve the orbit modeling, study fixing phase ambiguities, and incorporate data from low Earth orbiters, such as TOPEX/POSEIDON, to look for time-varying signatures of the geocenter.

Acknowledgments

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[7] J. F. Zumberge, D. Jefferson, G. Blewitt, F. Webb, and M. Heflin, "Processing IGS Data at JPL," paper presented at the American Geophysical Union, Fall Meeting, San Francisco, California, 1992.

Table 1. GPS Rogue receiver sites.

ALBH	Albert Head, B.C., Canada	NALL	Ny Ålesund, Norway
ALGO	Algonquin, Ontario, Canada	ONSA	Onsala, Sweden
CANB	Canberra, Australia	PAMA	Pamatai, Tahiti
FAIR	Fairbanks, Alaska (USA)	PENT	Penticton, B.C., Canada
GOLD	Goldstone, California (USA)	PGC1	Victoria, Canada
HART	Hartebeesthoek, South Africa	PINY	Pinyon, California (USA)
HARV	Harvest Platform, California (USA)	QUIN	Quincy, California (USA)
HERS	Herstmonceux, Great Britain	RCM2	Richmond, Florida (USA)
HONE	Honefoss, Norway	SANT	Santiago, Chile
JPLM	Pasadena, California (USA)	SCRI	La Jolla, California (USA)
KOKB	Kokee, Hawaii (USA)	STJO	St. Johns, Canada
KOSG	Kootwijk, The Netherlands	TAIW	Taiwan
MADR	Madrid, Spain	TROM	Tromso, Norway
MASP	Maspalomas, Grand Canary Is., Africa	USUD	Usuda, Japan
MATE	Matera, Italy	WETB	Wettzell, Germany
MCMU	McMurdo Station, Ross Is., Antarctica	YAR1	Yarragadee, Australia
METS	Metsahovi, Finland	YELL	Yellowknife, Canada

Table 2. Estimated solar radiation parameters.

Parameter	Model	A priori sigma
GX/GZ	Constant[a]	100%
GYC	Constant[a]	2 nm/sec^2
GX	First-order G-M[b]	10%
GY	First-order G-M[b]	0.1 nm/sec^2
GZ	First-order G-M[b]	10%

[a] Estimated as constant parameter with no process noise.

[b] Gauss-Markov (G-M) with time constant of 4 hr and steady-state sigma of 0.1 nm/sec^2. Typical magnitude of GX and GZ accelerations is 100 nm/sec^2.

Table 3. *3DRSS* orbit repeatability for GPS week 660.

PRN number	With stochastic srp, m	Without stochastic srp, m
2[a]	0.76	0.64
3	0.70	0.28
11	0.38	0.32
12	0.43	0.45
13	0.32	0.56
14[a]	0.48	0.94
15	0.51	0.58
16[a]	0.28	1.02
17	0.52	0.56
18	0.43	0.60
19	0.66	0.44
20[a]	0.72	1.19
21[a]	0.30	0.75
23[a]	0.29	0.54
24	0.45	0.56
25	0.42	0.47
26	0.30	0.83
28	0.48	0.43

[a] Eclipsing satellites.

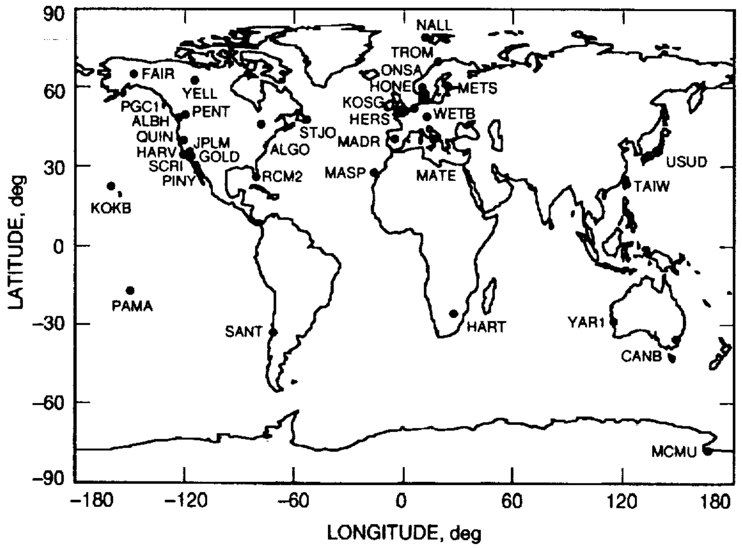

Fig. 1. 1992 GPS tracking sites.

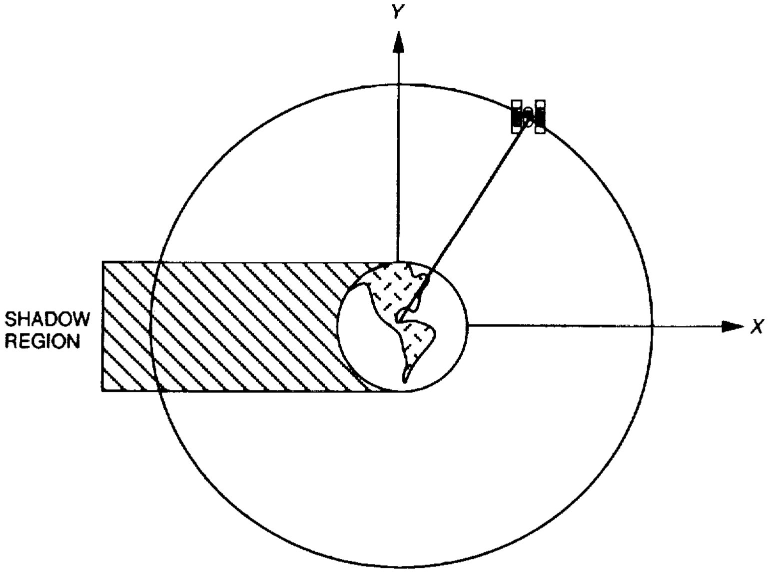

Fig. 2. Satellite in Earth orbit with simple cylindrical shadow model.

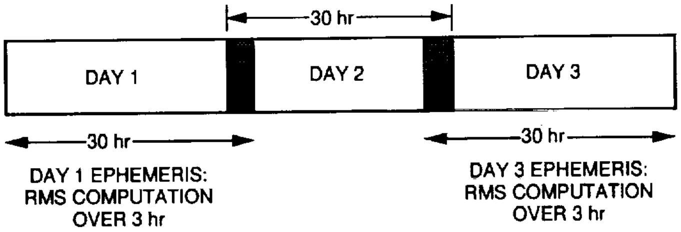

Fig. 3. Assessment of GPS orbit accuracy.

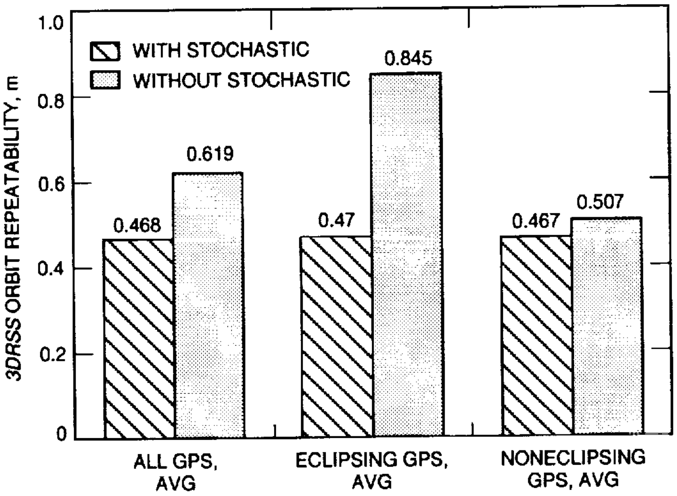

Fig. 4. *3DRSS* GPS orbit repeatability—7 days, GPS week 660.

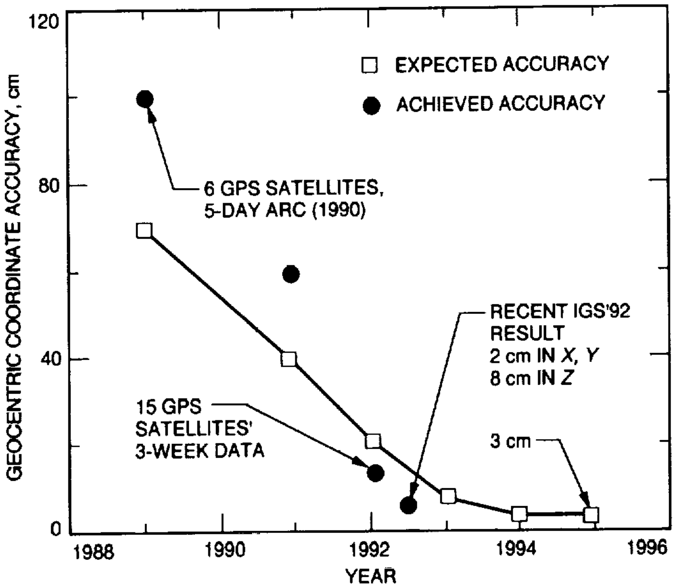

Fig. 5. Recent improvements in GPS geocentric coordinate accuracy.