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Improved GPS Solar Radiation Pressure Modeling for Precise Orbit Determination

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Data collected from a worldwide 1992 experiment have been processed at the Jet Propulsion Laboratory to determine precise orbits for the satellites of the Global Positioning System (GPS). The goal of this study was to improve satellite force modeling in order to achieve centimeter-level accuracy for global geocentric coordinates. A filtering technique has been tested to improve modeling of solar radiation pressure parameters for GPS satellites. The new approach improves orbit quality for eclipsing GPS satellites by a factor of 2, with typical results in the range of 25–50 cm.

Nomenclature

d^2_{jkt} = three-dimensional distance between corresponding points on two overlapping segments
GX = solar radiation pressure scale factor for X direction, spacecraft body-fixed coordinates
GYC = ROCK4 Y-bias solar radiation pressure parameter
GZ = solar radiation pressure scale factor for Z direction, spacecraft body-fixed coordinates
j = GPS satellite pseudoroman noise number
k = orbit overlap segment number
t = time index
T = number of epochs within both orbit overlap segments

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, with an orbit period of approximately 12 h. GPS measurements collected from globally distributed ground receivers are also being used by many in the scientific community for applications that include estimating earth rotation, polar motion, and geocentric station coordinates. Estimation of such parameters as the geocenter, or Earth center of mass, has geophysical and scientific implications as well. Also, the GPS estimates of the geocenter can be used for precise reference-frame calibration and alignment. 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 campaign. IGS'92 consisted of dozens of globally distributed sites tracking the 18 GPS satellites active during this time. The data were collected from approximately 30 tracking sites using the high-precision Rogue receivers developed at the Jet Propulsion Laboratory (JPL). The focus of this analysis was to assess the effects of mismodeling satellite force parameters due to solar radiation, and how other parameters are influenced, such as estimates of the geocenter.

Estimation Strategy

A unique strength of GPS measurements is that the satellites are sensitive to the geocenter, yet relatively insensitive to errors in gravity field because of their high orbit altitude and the relatively short data arcs (30 h) needed for the solution. Mismodeling of satellite force parameters, however, can have a significant effect on satellite orbits, especially in orbit prediction.[1] Since the goal of this study was to improve satellite force modeling in order to achieve centimeter-level accuracy for global geocentric coordinates, it was essential to include corrections for numerous potential errors, including Earth 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 consists of data from August 30, 1992 through September 5, 1992. This week was chosen specifically because antispoofing was not on during this period. In general, the data contain carrier phase and pseudorange 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 GIPSY/OASIS II software.[2,3] All nonfiducial station locations were estimated, as well as Earth orientation parameters, GPS carrier phase biases, random-walk zenith troposphere delays for each tracking site; all transmitter and receiver clocks but one were treated as white-noise parameters. X and Y polar motion, pole rate, and UT1-UTC rate were estimated as constant parameters (reset every 24 h).

One of the most important recent innovations is a new approach to modeling the effects of solar radiation pressure on the satellite orbits.

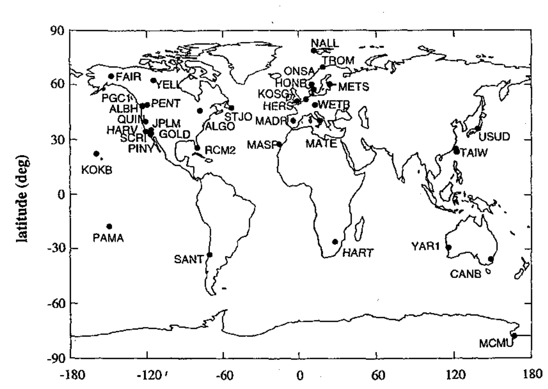

Fig. 1 1992 GPS tracking sites from IGS'92 campaign.

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Table 1 IGS'92 GPS Rogue receiver sites

ALBH—Albert Head, B. C., Canada	NALL—Ny Alesund, Norway
ALGO—Algonquin, 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, Netherlands	TAIW—Taiwan
MADR—Madrid, Spain	TROM—Tromso, Norway
MASP—Maspalomas, Grand Canary Is., Africa	WETB—Wettzell, Germany
MATE—Matera, Italy	USUD—Usuda, Japan
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 σ
GX/GZ	Constant[a]	100%
GYC	Constant[a]	2 nm/s^2
GX	First-order G-M[b]	10%
GY	First-order G-M[b]	0.1 nm/s^2
GZ	First-order G-M[b]	10%

[a]Estimated as constant parameter with no process noise.
[b]Gauss-Markov with time constant of 4 h and steady-state σ of 0.1 nm/s^2. Typical magnitude of GX and GZ accelerations is 100 nm/s^2.

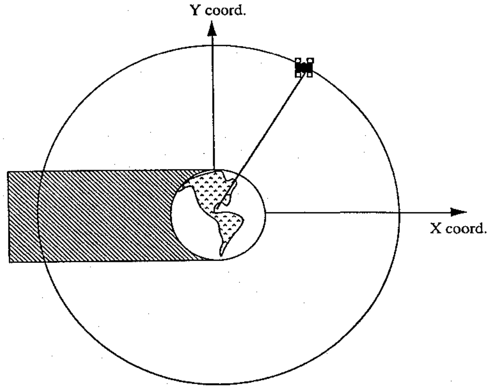

Fig. 2 Satellite in earth orbit with simple cylindrical shadow model.

Table 3 3DRSS orbit repeatability for GPS week 660

PRN no.	Repeatability, m: With stoch. SRP	Repeatability, m: Without stoch. SRP
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.

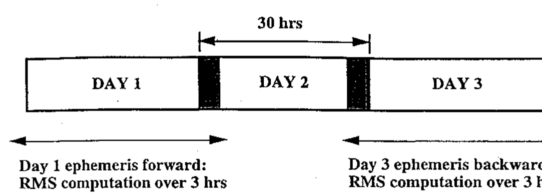

Fig. 3 Assessment of GPS orbit accuracy.

The solar radiation environment of the GPS satellites is generally constant except for the period during which a satellite's orbit is in eclipse season. When this occurs, the satellites pass through Earth's shadow, changing the amount of solar radiation that 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. For this purpose, X, Y, and Z are defined as spacecraft body-fixed coordinates, and GYC is the Y-bias parameter.[4] GX/GZ represents a single combined scale factor for the ROCK4 solar radiation force parameter,[5] while GX and GZ are scale factors for the X and Z directions independently. 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.[6] This technique has enabled the achievement of few-centimeter geocentric coordinate accuracy.[7]

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 paper as eclipsing, or shadowing. Figure 2 shows a satellite in an eclipsing orbit plane. GPS satellites that were 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 orbit repeatability for each GPS satellite (j) is defined as[8]

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

The orbit quality of a single day is quantified as the root mean square (RMS) difference between the ephemerides computed over the corresponding 3 h of orbit overlap at both ends of that day.[8] This concept is illustrated in Fig. 3.

Figure 4 shows the three-dimensional root sum square (3DRSS) orbit repeatability for all GPS satellites during GPS week 660. In the cases where stochastic solar radiation parameters were not

Table 4 Eclipse durations for GPS week 660

	Duration, min:s						
PRN no.	92aug30	92aug31	92sep01	92sep02	92sep03	92sep04	92sep05
2	56:27	56:05	55:38	55:05	54:22	53:42	52:50
14	39:47	43:17	46:12	48:38	50:40	52:20	53:40
16	35:42	39:59	45:01	47:41	49:55	51:46	53:15
20	56:09	55:52	55:31	55:02	54:29	53:49	53:05
21	43:26	46:17	48:39	50:38	52:15	53:33	54:34
23	38:04	41:52	45:00	47:37	49:48	51:36	53:04

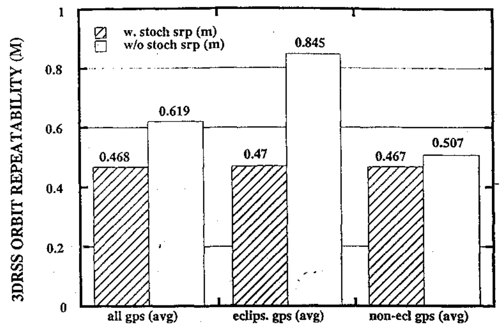

Fig. 4 3DRSS GPS orbit repeatability—7 days, GPS week 660.

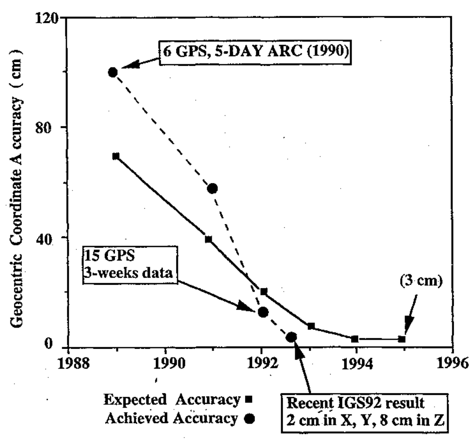

Fig. 5 Recent improvements in GPS geocentric coordinate accuracy.

estimated, the ROCK4 solar radiation force model was used as nominal,[5] with a nominal Y bias of zero. The improvement in the orbits with stochastic solar pressure parameters is approximately 25% overall for all the GPS satellites (averaged), with a 44% improvement in the eclipsing orbits and only an 8% 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. Also, this is in agreement with the physical environment of an eclipsing satellite. In an eclipsing orbit, the solar radiation forces acting on a satellite vary dramatically over the orbit arc.

The orbit repeatability for each satellite using both strategies is shown on Table 3. These values represent the average orbit repeatability over the 7 days in GPS week 660, with the eclipsing satellites marked with a footnote. This table shows the improvement in orbit accuracy due to estimating stochastic corrections to the GPS solar radiation parameters. Table 3 also shows how the six eclipsing GPS satellites benefit more from the improved estimation strategy. During GPS week 660, all six eclipsing satellites were oriented in their orbit planes in such a way that their orbits crossed centrally through the shadow regions. The eclipse durations for all eclipsing GPS satellites are given in Table 4.

Concluding Remarks

In this analysis, we have shown how GPS orbit accuracy can be improved by estimating stochastic corrections to the GPS dynamical parameters. This new approach improves the 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.,[8] where routine processing of GPS data shows orbit accuracy in the range of 25–50 cm. A direct result of the improvements in orbit accuracy can be seen in the improvement of the geocentric station coordinate accuracy.[7] The goal of the analysis described by Vigue et al. was to achieve centimeter-level accuracy for global geocentric coordinates.[7] Those GPS results were obtained with 3 months of GPS measurements, and compared with 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 approximately 8 cm in Z (where Z is parallel to the axis of rotation). This capability has important benefits for NASA Deep Space Network (DSN) tracking and for geophysical research such as geocentric crustal motion studies and the study of the magnitude and time scale of geocenter variations and their origin. Precise tracking of interplanetary spacecraft and Earth orbiters requires that NASA DSN geocentric station coordinates be determined to high accuracy. This will also have an effect on precise DSN geocentric coordinates and precise reference-frame calibration and alignment.

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 that have been described in this paper. 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.

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