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VIKING RADIO SCIENCE DATA ANALYSIS AND SYNTHESIS

Grant NAGW-411

Semiannual Status Report No. 3

For the period 30 December 1983 through 30 June 1984

Principal Investigator

Irwin I. Shapiro

September 1984

Prepared for
National Aeronautics and Space Administration
Washington, DC 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Mr. Henry C. Brinton, Code EL-4, Solar System Exploration Division, NASA Headquarters, Washington, D. C. 20546.

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During the reporting period, we made progress toward our primary objectives: (a) an investigation of the rotational motion of Mars and its geophysical ramifications, and (b) the study of solar-system dynamics and the laws of gravitation. We obtained a new bound on the rate of change of the constant of gravity G measured in atomic units

$$|\dot{G}/G| < 2 \times 10^{-11} \text{ per year}$$

and our studies continue to show that we can expect to reduce the uncertainty to 10^{-11} per year or less. This and other new results were presented at the May 1984 meeting of the AAS, Division of Dynamical Astronomy (DDA).

In the remainder of this report, we consider the recent technical progress which made possible our new results and which will be the basis of additional scientific results in the near future. This discussion is divided into three parts: A. Solar System Model and Data Set; B. Rotation of Mars; and C. Solar System Constants and Tests of Relativity. The last part includes the planetary masses and relativity results that were presented at the DDA Meeting.

A. Solar System Model and Data Set

The central element in our data analysis is the Planetary Ephemeris Program (PEP) which embodies our mathematical models of the solar system and observables. It functions as a weighted-least-squares fitting (and Kalman filtering) facility for observations related to the positions, velocities, rotations, etc. of solar-system bodies, natural and manmade. PEP contains approximately 10^5 lines of code, which is written mostly in Fortran with a small part in assembly language. It was originally developed at the MIT Lincoln Laboratory where it is still in use. Over most of the past 17 years, the principal center of development has been the MIT Dept. of Earth and Planetary Sciences; at the beginning of CY1983, that center shifted to the Harvard-Smithsonian Center for Astrophysics. During the past few years, PEP has been systematically upgraded to take advantage of changes in computing and software-development techniques.

During CY83, the asteroid model in PEP was changed. We had been able to estimate the mass of a fictitious uniform ring and the masses of eight separate asteroids. (In an earlier modification, the latter had been increased from four.) During the reporting period, the model was enhanced so that it is now also possible to estimate the densities of asteroids in up to five classes. This new model serves to include, at least approximately, the effects of up to 200 asteroids which are too small to consider individually but which may be important collectively. For each, the mass is the product of the density estimated for its class and an externally provided volume. Although this model has serious shortcomings, the dearth of applicable auxiliary data makes it a reasonable compromise. In our recent numerical experiments with the data, we have made use of the ability to estimate the larger number of individual asteroid masses and densities for the different asteroid classes.

Shortly before the start of the reporting period, we iterated the estimator a total of four times to obtain a stable, converged solution. During the first iteration, we added some new terms associated with the orientation of the planetary orbits. At the last iteration, we reintegrated all of the variational equations and included all of the new "cross partial" terms. At this time, we also increased the number of outer-planet orbital elements that could be estimated by including the required additional variational equations. Finally, we recalculated the entire sensitivity matrix and recomputed the prefit residuals.

To investigate the results of the iterations, we performed a series of numerical experiments during the reporting period; we found our solutions to show more stability and the postfit residuals to show less systematic signature than before. Before the iteration, we had been unsuccessful in including in our solutions the Viking Lander delay data taken after 5 August 1980: When included, these data showed, and caused the other Lander delay data to show, a large systematic signature; their prefit residuals had a systematic signature with about a 5 μs peak. (The same problem was encountered at JPL.) After the iteration, the postfit systematic signature was found to be reduced by roughly one-third. By increasing the number of estimated asteroid masses, we were able to remove about half of the remaining systematic signature. Finally, we included the outer-planet NPs (Earth-planet time-delay pseudo-data derived from the Doppler and ranging observations of spacecraft at encounter with the planet) and optical observations which permitted us to estimate an enlarged set of outer-planet orbital elements; the systematic signature became lost in the noise.

Our present, recently enlarged working set of data is listed in Table 1. For discussion, we divide the Viking Lander delay data into two groups: those taken through 5 August 1980, when the last dual-band calibration data were received from the Orbiter; and those taken between 6 August 1980 and November 1982, when the last Viking failed. Although the latter set lacks corrections for the effects of the solar plasma, the data that we use from this set are restricted to those taken at a time when the Sun-Earth-Mars angle was large and thus the plasma-induced errors in the measurement of the vacuum delay can be corrected approximately in the mean by use of a simple model. Thus, we have discarded the data taken near the time of the Mars superior conjunction of 2 April 1981; they require large plasma corrections that cannot be made usefully with a model. The errors assigned to the remaining data range from 2.5 to 5 times those that are assigned to data for which there are plasma density estimates from the Orbiter dual-band tracking.

A comparison of Table 1 with Table 2 of Reasenberg [1983], which is reproduced in the Appendix, shows four recently enlarged sets of data. The extra plasma-corrected Lander delays are the result of the "discovery" in November 1983 of 150 lost data, an improved plasma correction method, and a re-evaluation of previously discarded data made fruitful in part by the improved solar-system model. The increased number of Lunar Laser NPs were obtained from our MIT colleagues (R. W. King, private communication). The two sets of radar data show a dramatic increase in the number of observations. This is the result of an implementation at Arecibo of a technique (Shapiro et al., 1972) by which simultaneous observations are made of a contiguous series of small regions along the planet's Doppler equator.

B. Rotation of Mars

In addition to precession and nutation [Reasenberg and King, 1979], our model of the rotation of Mars includes a secular rate of change of the period and both annual and semiannual variations in the phase of rotation [Williams, 1977, private communication; Philip, 1979; Reasenberg and King, 1979]. Our preliminary investigation with a 400-day set of Lander delay data provided a marginal detection of the semiannual terms [Reasenberg et al., 1979] and showed that these could not be clearly distinguished from the annual terms with such a small span of data. A better result was provided by our initial study with an 800-day data set to which we applied the improved plasma estimates and data weights: The annual terms are found to be small and only moderately correlated in the estimator with the semiannual terms. The semiannual terms have an amplitude (expressed as an equatorial surface displacement) and a phase (11.5 $\pm$5 m, -2° $\pm$25°) consistent with the model of Davies et al. [1977] (10.5 m, -36°), but not so consistent with the model of Philip [1979] (9.6 m, -58°). The published measurements of atmospheric pressure [Hess et al., 1979] cover a time span insufficient for a meaningful comparison. The results of an analysis of a much longer span of Lander pressure measurements have been supplied to us by James Tillman who is preparing this material for publication [private communication, 1983, 1984] and distributed through the NSSDC. These data show that the general features of the annual and semiannual pressure fluctuations at the Landers repeat from year to year. The use of the Viking data to determine the amplitude and phase of the annual and semiannual terms in the rotation of Mars will provide one of the few independent constraints on global models of the circulation and condensation of the atmosphere of Mars. (See, for example, Shimazaki and Shimizu [1979] and references therein.)

During the reporting period, we modified our model of the rotation of Mars. In the old model, the seasonal irregularities were added to a spin rate that was constant in ephemeris time. In the new model, that spin rate is constant in Mars proper time, and therefore varies by about $\pm 10^{-9}$ in ephemeris time. The associated rotational phase shift is of the same order and phase as the predicted annual effect of the atmospheric condensation at the poles. The new relativistic correction is thus critical for the accurate determination of the amplitudes and phases of the proposed meteorological effects.

C. Solar System Constants and Tests of Relativity

At the June 1984 meeting of the AAS, Division of Dynamical Astronomy, Babcock [1984] and Chandler [1984] presented some of our recent results. Table 2 contains the values of planetary masses from Babcock's presentation. In general, our results agree well with the latest values published in the Astronomical Almanac. Other results that they presented were improved estimates of the relativistic parameters; these are listed in Table 3.

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Table 1. Combined Sets of Data

Source[1]	Number of Data	Approximate Time Span of Observations From	To
VIKING			
Lander delay (plasma corrected)	1041	July 1976	Aug. 1980
Lander delay (not plasma corrected)	239	Aug. 1980	Nov. 1982
Orbiter NP[2]	4060	June 1976	Aug. 1977
Lander Doppler	1075	Sept.1979	Aug. 1980
LLR			
Observing session NP[3]	3074		
MARINER 9			
Orbiter NP[2]	185	Nov. 1971	Oct. 1972
RADAR			
Mercury	4339	1969	1982
Venus	5464		
MERIDIAN CIRCLE[4]		1970	1978
Sun	1023		
Moon	212		
Inner planets (M,V,M)	1518		
Outer planets (J,S,U,N)	1643		
OUTER PLANET NP[2]	6	see note 5	

[1] All observables are time delays except for the Viking Lander Doppler and for the meridian circle data.

[2] The spacecraft Normal Point (NP) is a compressed datum: the equivalent Earth-planet time delay that would have been measured between the centers of mass of the planets. All spacecraft NPs were obtained from the Jet Propulsion Lab where they were derived from the tracking data.

[3] The Lunar Laser Ranging (LLR) Normal Point (NP) is a single estimate of the round trip propagation time between a tracking station and a single lunar retroreflector. The estimate is an average based on all photons received during an observing sequence. Under good conditions, there are as many as three sequences per day.

[4] The data are a mixture of right ascension and declination measurements.

[5] The epochs of the four Jupiter data are 12/4/73, 12/3/74, 3/5/79, and 7/10/79; those of Saturn are 11/13/80 and 8/26/81.

Table 2. Planet Mass Estimates[1]

Planet[2]	Mass Estimates Analysis at CfA	Astron. Almanac(1984)	Differences Between Estimates	Standard Deviation (CfA)
Mercury	6,023,700	6,023,600	100	1000
Venus	408,523.1	408,523.5	0.4	1
Earth + Moon	328,900.554	328,900.550	0.004	0.003
Mars[3]	3,098,750	3,098,710	40	60
Jupiter	1,047.3482	1,047.350	0.0018	0.002
Saturn	3,497.90	3,498	0.10	0.3
Uranus	22,830	22,960	130	300
Neptune	19,480	19,314	166	500
Earth/Moon	81.300565	81.300588	2.3×10^{-5}	1.5×10^{-5}

[1] All planet masses in inverse solar mass units.

[2] The data are not sensitive to the mass of Pluto.

[3] The CfA estimates of the mass of Mars does not use the spacecraft encounter data which dominate the estimate given in the Astronomical Almanac (1984, US Government Printing Office).

Table 3. Relativity Results Presented at the DDA Meeting, May 1984

Quantity	GR Nominal	Estimates[1] #1	#2	#3	Units
J_2	N/A	-3 ± 3			10^{-6}
$\beta-1$	0	-0.025 ± 0.05	-0.01 ± 0.02		
$\gamma-1$	0	$0. \pm 0.002$	$0. \pm 0.0015$		
$\dot{G}/G$	N/A[2]			0 ± 2	10^{-11} per year

[1] Each column represents a summary of results from a large number of solutions of the least-squares normal equations. The errors shown are realistic estimates of the standard deviation.

[2] Although general relativity does not address the possible time dependence of the relation between atomic and gravitational times, one normally assumes $\dot{G}/G = 0$ in classical physics.

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The constancy of G and other gravitational experiments

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Traditionally, theories of gravitation have received their most demanding tests in the solar-system laboratory. Today, electronic observing technology makes possible solar-system tests of substantially increased accuracy. We consider how these technologies are being used to study gravitation with an emphasis on two questions:

(i) Dirac and others have investigated theories in which the constant of gravitation, G, appears to change with time. Recent analyses using the Viking data yield $|\dot{G}/G| < 3 \times 10^{-11}$ per year. With further analysis, the currently available ensemble of data should permit an estimate of $\dot{G}/G$ with an uncertainty of 10^{-11} per year. At this level it will become possible to distinguish among competitive theories.

(ii) Shapiro's time-delay effect has provided the most stringent solar-system test of general relativity. The effect has been measured to be consistent with the predictions of general relativity with a fractional uncertainty of 0.1%. An improved analysis of an enhanced data set should soon permit an even more stringent test.

Technology now permits new kinds of tests to be performed. Among these are some that measure relativistic effects due to the square of the (solar) potential and others that detect the Earth's 'gravitomagnetic' field (the Lense–Thirring effect). These experiments, and the use of astrophysical systems are among the experimental challenges for the coming decades.

Table 2. Combined sets of data

source†	no. of data	approximate range of error assumed in estimator: min	max	unit
Viking				
Lander delay (plasma corrected)	798	20	60	ns
Lander delay (not plasma corrected)	263	50	300	ns
Orbiter n.p.‡	4060	100	900	ns
Lander Doppler	1075	20	40	mHz
l.l.r.				
Observing session n.p.§	2613	6	14	ns
Mariner 9				
Orbiter n.p.‡	185	0.1	10	μs
radar				
Mercury	642	1	15	μs
Venus	784	1	15	μs
meridian circle‖				
Sun	1023	≈ 2		″
Moon	212	≈ 0.5		″
inner planets (M, V, M)	1518	≈ 1		″
outer planets (J, S, U, N)	1643	≈ 1		″
outer planet n.p.	6	25	500	μs

† All observables are time delays except for the Viking Lander Doppler and meridian circle data.

‡ The orbiter normal point (n.p.) is a compressed datum: the equivalent Earth–Mars time delay measured between the centres of mass of the planets.

§ The lunar laser ranging (l.l.r.) normal point (n.p.) is a single estimate of the round trip propagation time between a tracking station and a single lunar retroreflector. The estimate is an average based on all photons received during an observing sequence.

‖ The data are a mixture of right ascension and declination measurements.

¶ The outer planet normal point (n.p.) is a compressed datum from a spacecraft encounter with either Jupiter or Saturn. The n.p. is the equivalent Earth–planet time delay measured between the centres of mass of the planets.