THE EPHEMERIDES OF THE INNER PLANETS FROM SPACECRAFT RANGE DATA AND RADAR OBSERVATIONS 1961–1995

E. V. PITJEVA
Institute of Applied Astronomy, Russian Academy of Sciences
St. Petersburg, Russia

Abstract. A numerical theory of motion of the inner planets and Jupiter is presented. The numerical ephemerides were compared with the set of American and Russian radar observations of planets, obtained during 1961–1995 (nearly 60 000 observations), together with range measurements of Martian landers Viking-1,-2 and Mariner-9 tracking data.

The main fitted parameters were the elements of Mercury, Venus, Earth, Mars, the Astronomical Unit, the scale corrections to the reference surface of planets and variability of the gravitational constant. The parameters of Mars rotation, coordinates of Viking landers, elements and the mass of Jupiter, the masses of the three asteroids were evaluated from Viking landers observations.

1. Mathematical Model of Planet Motion and Observational Data

A numerical theory of motion of the major planets, which is the current stage of a project of constructing new planetary ephemerides (EPM) is presented. This project also includes a new lunar theory, developed as well in the Laboratory for Ephemeris Astronomy of IAA RAN (Aleshkina *et al.*, 1996). These papers continue our investigation of the motion of major planets and the Moon and the improvement of astronomical constants from observations XVIII–XX centuries (Krasinsky *et al.*, 1993). Now a possibility to substantially improve the theory has evolved because a large new set of American spacecraft range data and radar observations of planets became available to us. In addition, the new dynamical theory is constructed under a different instrumental base: with the help of programming system ERA (Ephemeris Researches in Astronomy), developed at the IAA RAN (Krasinsky and Vasilyev, 1996). This system makes it is possible to construct

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dynamic theories for celestial bodies, to process high-accuracy astrometrical data of many types (classical and modern), and to determine and improve astronomical constants and parameters of the theories employed.

Numerical integration of the equations of motion of 9 major planets, the Sun and the Moon in the solar-system barycentric coordinate frame at epoch J2000.0 was made by the Everhart (1974) method of 11^{th} order with a constant 1-day step. The perturbations due to the influence of the five largest minor planets was taken into account. A mathematical model and provisional initial conditions for the numerical integration coincided with JPL ephemerides DE200/LE200. A procedure for numerical integration of the motion of celestial bodies was developed by M. Vasilyev. After the completion of the integration process, a set of Chebyshev polynomials for positions and velocities of the objects is constructed at preassigned times over the interval 1960–2000. Intervals of approximation and degree of the polynomials were taken so that errors of polynomial approximation do not surpass fractions of a meter. For example, an interval of approximation is 40 days for the Earth's orbit and 400 days for the orbit of Jupiter if polynomials of 15^{th} degree are used.

At this stage of investigation only range measurements were used for adjustment of parameters of the theory. The set consists of American and Russian observations discussed earlier (Krasinsky *et al.,* 1993) and of the new data that became available to us by the courtesy of Dr. A.L. Zaitsev (1995) from the Institute of Radioengineering and Electronics of RAN (*viz.* range observations 1991–1995 made in Eupatortia, Crimea), and of Dr. E.M. Standish (1994) from JPL (*viz.* radar observations of planets, ranges to Martian landers Viking-1, -2 and to spacecraft Mariner-9). The complete set of 57886 observations of time delay during 1961–1995 includes 714 observations of Mercury, 2324 of Venus and 54 848 of Mars.

Reductions of measurements included relativistic corrections, effects of propagation of electromagnetic signals in the Earth troposphere and in the solar corona with simultaneous evaluation of parameters of the corona model from general fitting. Great attention was given to the reduction of radar observations for topography of planets, which for Mars and Venus was carried out with the help of hypsometric maps.

2. Ephemeris and Improvement of Astronomical Constants

The main parameters which have been adjusted are the elements of Mercury, Venus, Earth, Mars, the Astronomical Unit and the scale corrections to the reference surface of planets. The values of Mars' orientation and rotation parameters, and Viking lander coordinates have been obtained from Viking lander observations as described in the paper by Pitjeva (1996).

The accuracy of the least squares estimation of parameters is rather high. For example, standard deviations of the Astronomical Unit and semi-major axis of planets are of about 1 m or even better. It should be mentioned that here and in the following, the errors given are formal statistical errors, the real accuracy is conceivably several times lower. For the Astronomical Unit the following estimate is obtained:

$$AU_{EPM} = (149\,597\,870\,687.7 \pm 1.5)\ \mathrm{m} \tag{1}$$

which is in good agreement with the value of the Astronomical Unit

$$AU_{DE403} = 149\,597\,870\,691\ \mathrm{m},$$

adopted in the new ephemerides DE403/LE403 (Standish *et al.,* 1995), from analysis of slightly different observational data.

Because the orbit of Mars is strongly perturbed by Jupiter, the observations of Martian landers provide valuable information concerning the mass of Jupiter (including masses of satellites of Jupiter) as well as the elements of its orbit. For Sun-Jupiter mass ratio the following estimate is obtained:

$$\mu_{Jupiter} = 1047.34830 \pm 0.00017,$$

which is in accordance with the value $\mu_{Jupiter}$ derived from Pioneer and Voyager tracking data (Campbell and Synnott, 1985),

$$\mu_{Jupiter} = 1047.3486 \pm 0.0008.$$

It appears that for a good fit to the Viking data it is also necessary to evaluate the masses of at least three largest asteroids which perturb the orbit of Mars (*i.e.,* Ceres, Pallas and Vesta). Their determined masses are

$$m_{Ceres} = (0.1745 \pm 0.0024) \cdot 10^{-12}\ \mathrm{au^3/day^2},$$

$$m_{Pallas} = (0.2862 \pm 0.0124) \cdot 10^{-13}\ \mathrm{au^3/day^2},$$

$$m_{Vesta} = (0.4875 \pm 0.0073) \cdot 10^{-13}\ \mathrm{au^3/day^2}.$$

A rather unexpected result of the investigation is that the analysis of the Viking data proves it necessary to correct the DE200 elements of the orbit of Jupiter. While these data are practically not sensitive to corrections to the node and inclinations, corrections to other elements may be evaluated with an accuracy which is better than the accuracy provided by direct optical observations of Jupiter. The formal standard deviations of the adjustment of orbital parameters of Jupiter are given in Table 1.

The findings are illustrated by Figures 1–4. In Figure 1 are presented residuals of Viking data after adjusting just the coordinates of landers and

TABLE 1. The formal deviations of the adjustment of orbital parameters of Jupiter.

$\Delta a/a$	$\Delta(e\cos\pi)$	$\Delta(e\sin\pi)$	$\Delta\lambda$
$0''.0080$	$0''.0088$	$0''.0085$	$0''.0662$

parameters of orientation of the equator of Mars. In Figure 2 the residuals correspond to the solutions in which elements of the Earth and Mars are also adjusted. The values of the residuals are diminished but some systematic components are still present. Figure 3 corresponds to the case where the masses of Jupiter and three asteroids are evaluated, and Figure 4 where the elements of Jupiter are also included in the set of estimated parameters. The residuals of Figure 4 agree closely with the values obtained from new ephemerides DE403/LE403 (Standish *et al.*, 1995).

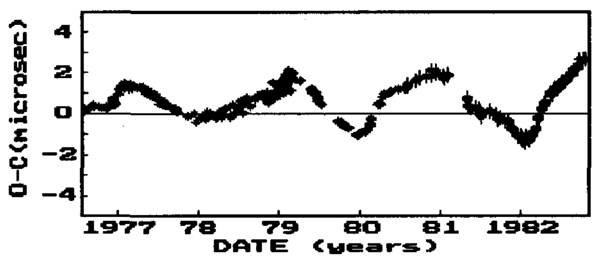

Figure 1. Viking residuals after correction of coordinates of landers and parameters of orientation of the equator of Mars.

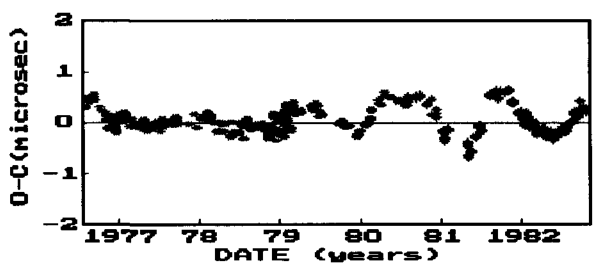

Figure 2. Viking residuals after adjustment of elements of the Earth and Mars.

With radar observations of high accuracy, which cover a time interval of 30 years, one may estimate the time derivative of the gravitational constant,

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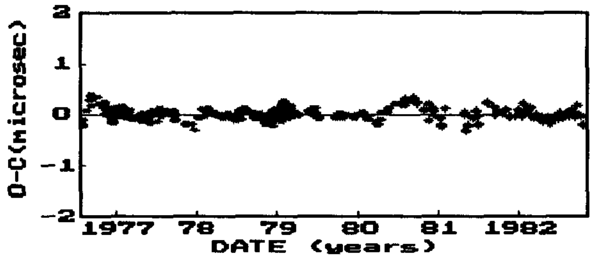

Figure 3. Viking residuals after fitting also the masses of Jupiter and asteroids.

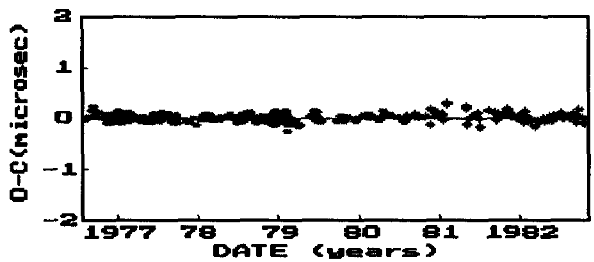

Figure 4. Post-fit Viking residuals when the elements of Jupiter are also included in the solution.

which characterizes the fundamental properties of our physical time-space. The value $\dot{G}/G$ may be obtained from the analysis of the time variations in the difference of the longitudes $l_i - l_3$ (where i is the number of a planet). One can estimate either the common value $\dot{G}/G$ or three values obtained from radar data of Mercury, Venus, Mars and after that check the results for their consistency. The results obtained are given in Table 2.

TABLE 2. The variability of the gravitational constant $\dot{G}/G$ (10^{-11}yr^{-1}).

	1986	1993	This work
Mercury	-0.9 ± 5.2	-0.50 ± 1.29	0.012 ± 0.023
Venus	3.7 ± 0.8	2.37 ± 0.59	0.221 ± 0.613
Mars	16.1 ± 2.4	-2.65 ± 0.72	-0.011 ± 0.055
Weighted	4.8 ± 2.7	0.25 ± 1.65	0.009 ± 0.008
Total solution	4.1 ± 0.8	0.37 ± 0.45	0.009 ± 0.020

In the first two columns of the table are reproduced our earlier results from the papers by Krasinsky *et al.* (1986, 1993), and in the last column our new estimates. One can see that the accuracy of the new results increased by an order of magnitude as a consequence of a considerable amount of new Mercury and Mars radar data included in the analysis.

The main result is that the deflection of $\dot{G}/G$ from zero is statistically insignificant, as derived both from radar observations for each planet and from the general solution of the complete set of ranging data for the inner planets. It means that the secular trend between the atomic and dynamic time scales (according to Canuto, 1979) cannot be larger than 10^{-12} yr^{-1} (5σ). Our result is in good agreement with a null result for $\dot{G}/G$ with a standard error of $\pm 2.0 \cdot 10^{-12}$ yr^{-1}, which was yielded from Pioneer Venus and Galileo spacecraft data (Anderson *et al.,* 1992).

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