NUMERICAL PLANETARY AND LUNAR EPHEMERIDES : PRESENT STATUS, PRECISION AND ACCURACIES

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ABSTRACT. The Ephemeris Development Program has been in existence for nearly 20 years at JPL, providing high precision present-day knowledge of the positions of the moon and major planets. The resultant ephemerides are used extensively in the navigation of spacecraft and in the reduction of astrometric observations. They also provide a key element in the testing of various theories of gravitation and a means for the determination of various relevant astronomical constants. The ephemerides and the process of creating them are both shown to be viable tools for the measurement of various gravitational effects which govern the motions of the objects in the solar system.

This paper gives an outline of the least-squares adjustment of the ephemerides to the observations, the present physical (dynamical) model, the present observations to which the ephemerides are fit, the expected accuracies of various ephemeris elements, recent and future observations and features of the solar system which are poorly determined (and thereby place limits upon the accuracies). Recent comparisons with similar work at the Center for Astrophysics (formerly at MIT) are serving as valuable independent checks on formulations and procedures used at each institution; they also lend insight toward what are the realistic accuracies being attained. The export procedure, by which an outside user may obtain and use the JPL ephemerides, is described.

I. INTRODUCTION

The primary purpose of the Ephemeris Development Program at JPL is to provide high-precision lunar and planetary ephemerides in support of spacecraft navigation. The ephemerides result from the fitting of numerically integrated dynamical models of the solar system to the relevant observational data. The past 20 years have seen a dramatic increase in both the accuracy and in the variety of the observational data, necessitating continued refinement and analyses of the data reduction processes. The dynamics of the solar system are sensitive to many astronomical features (asteroids, relativity, etc.) at

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a level which is now detectable by modern astronomical measurements. The whole process of creating high-precision ephemerides has, therefore, become almost an art in which various testing methods and qualitative judgments play an important role.

Over the years, an extensive amount of rather versatile software has been developed which aids in the testing and analyses of the ephemerides and related subjects. One may view this capability as an investigative tool which may be used in a variety of astronomical research projects. It is the purpose of this paper not only to describe the accuracy of the ephemerides, but also to mention some of the various capabilities and techniques which are used in the creation of the ephemerides themselves. Many of these features are found to be useful when using the ephemerides as part of a broader investigation.

Section II describes features of the ephemeris creation process, including the equations of motion, the numerical integration and the least-squares fitting process. Section III describes the various sets of observational data; Section IV, the estimated realistic accuracies of the different elements of the ephemerides. Further possible observations are described in Section V. Section VI discusses the probable sources for the greatest uncertainties in the ephemerides and Section VII shows where the relativistic factors enter into the ephemerides. Finally, reference for exporting the JPL Ephemerides is mentioned in Section VIII. The reader is referred to the paper by Newhall et al. (1983) for many of the details.

II. EPHEMERIS CREATION PROCESS

The basic flow of the ephemeris creation process is that of a least-squares iteration. The observational data is reduced against an existing "initial ephemeris" in order to produce a set of residuals to which the relevant parameters of the system are adjusted by means of a least-squares solution. These parameters include 1) initial conditions: positions and velocities at an epoch, analogous to orbital elements; 2) dynamical parameters: other constants directly involved in the equations of motion, e.g., planetary masses; and 3) various reduction constants: quantities used in reducing the observational data, e.g., station locations, precession correction, etc. With new values for 1) and 2) above, the equations of motion are integrated to produce a new ephemeris which may then be used to iterate the whole process. There is also the capability of integrating the variational equations in order to produce the partial derviatives used in the least-squares adjustment.

There are a number of features of this process which make it attractive for the testing of various gravitational theories as well as for the determination of certain astronomical constants and for the creation of high-precision ephemerides. These are presented here.

A. Equations of Motion

The equations of motion used in the JPL ephemerides are given explicitly by Newhall et al.(1983). They represent physics "as we believe it to be"; i.e., they include all of the forces which are known to exert a presently measurable effect upon the motions of the moon and the planets. We use the isotropic, Parameterized Post-Newtonian (PPN) n-body metric with Newtonian gravitational perturbations from the major asteroids. Also included are effects upon the earth-moon motion due to non-sphericity of these bodies, earth-tides and lunar librations. The lunar librations are integrated simultaneously with the ephemerides.

B. Numerical Integration

The JPL ephemerides are the result of numerically integrating the equations of motion. The integration process has been tested sufficiently so that it is believed that the equations of motion are represented with an accuracy well below that of the observational data. Further, considering the propagation of the uncertainties of the initial conditions, it is quite safe to say that inaccuracies in the numerical integration are not a concern; certainly not over the time-span covered by all of the observational data. We do not have to concern ourselves with the solutions to the equations of motion; we can concentrate on the equations of motion themselves and on the fits to the observational data.

C. Variational Equations, Partial Derivatives

We have the capability of integrating variational equations in order to produce the partial derivatives necessary for the least-squares adjustment to the ephemeris parameters. One wishes, in general, to find the quantity, $\partial p(t)/\partial q(t_0)$, showing how much the observed quantity, p (e.g., right ascension), is varied at time t due to a change in the ephemeris parameter, q (e.g., mass of Jupiter, initial y-coordinate of Mars, etc.) at time t_0. The partial derivative is computed from

$$\frac{\partial p(t)}{\partial s(t)} \quad \frac{\partial s(t)}{\partial q(t_0)},$$

where the vector s may represent the position or velocity of any member of the solar-system. The first term is obtained by differentiating the equations of the observational reduction, and the second comes from integrating the variational equation, $\partial \ddot{s}/\partial q$, obtained by differentiating the equations of motion. Thus it may be seen that in the least-squares adjustment one has the capability of solving for any dynamical parameter in the equations of motion as well as for any of the initial conditions. Furtermore, the present ephemerides have had good success in modeling the existing observations. Any realistic change to either the initial conditions or to the dynamical parameters will be small and of a linear nature. I.e., the ephemerides are well-converged and the partial derivatives are well within the linear range. They need not be re-computed for each new ephemeris.

D. Least-Squares Adjustment

Assuming that the equations of motion are correct and that the accuracy of the numerical integration is adequate, one may state that the quality of the ephemerides is completely dependent upon the accuracy of the initial conditions and dynamical constants. These, in turn, are determined by the least-squares fit to the observational data. Experience with this procedure tends to lend insight into the quality of the ephemerides. Some features of this procees are given here.

i) Normal Equations. Each observational equation (residual and associated partial derivatives) is normalized by the factor, $1/\sigma$, where the σ is the apriori standard deviation assigned to that particular observation and which may depend upon a number of different factors (data type, observer, technique, etc.). The normalized observational equations are then accumulated into sets of normal equations, a different set for each data type. These sets are added together and solved for the ephemeris parameters in question. One may create additional sets of normal equations to be included in the sum for the purpose of providing apriori constraints and correlations among the various parameters. One may also assign different weights to each of the sets of normal equations when they are being summed.

ii) Sensitivity Analyses. Sensitiviy analyses are often useful in determining the effect of certain parameters upon a sloution. The behavior of the various solutions produced by "forcing in" differing values of a given parameter can be highly informative. One may change beforehand the nominal value of any of the parameters, constrain it at the new value, either permanently or with an apriori sigma, and then solve the resulting modified system.

iii) Solution. The solution of the normal equations employs a singular value analysis in which the original set of n parameters is transformed into a set of n orthogonal vectors (the eigenvectors), each being a linear combination of the original set of parameters. The n eigenvectors are then eliminated, one at a time, in the order of the strength of their determination. The results of each elimination (rank) may be displayed, thereby showing the progressive values of the original parameters, the successive improvements of the fit, and the uncertainty associated with each eigenvector. Inspection of the last few ranks of the analysis shows the degree of singularity in the solution, the amount of correlation between the parameters, and the stability of the determination of each of the parameters.

iv) Covariances. A least-squares solution provides a covariance matrix associated with the parameters of the solution, giving the standard deviations and pair correlations. These are the formal covariances, which are often overly optimistic. Formal covariances are realistic only if the residuals of the observational equations are uncorrelated, contain no systematic errors, and are normally distributed about the mean. Such is seldom the case. One may augment the covariance matrix by adding to it the effect of the uncertainties of *known* parameters not included in the solution ("consider covariances"). However, the systematic errors usually come from *unknown* sources and therefore cannot be accounted for. A more viable alternative for determining realistic uncertainties is to check the consistency between the different data sets by successively eliminating different sets from the solution and by then comparing the differences of the results. I.e., "how well is a particular data set fit by the ephemerides when it has not been included in the solution?"

III. OBSERVATIONAL DATA

Since the quality of the ephemerides depends upon the accuracy of the initial conditions and dynamical parameters which, in turn, are determined by the least-squares fits to the observational data, it is the inherent quality of the observational data which ultimately determines the accuracy of the final ephemerides. Table 1 presents a list of the sets of observational data to which the JPL ephemerides are presently being fit. Various features of the USNO optical transits, radar ranges and Mariner 9 observations are discussed by Newhall et al. (1983) ; the Lunar Laser Ranging data is discussed by Dickey et al.(1983). Since that time we have added a number of new data sets which are briefly mentioned here.

A. RGO Transit Circle. Transit observations, taken with the Cooke Transit Circle at the Royal Greenwich Observatory in Herstmonceux, cover the time span 1957-82 (see Swift et al., 1984). They are handled in a way similar to those from the USNO and exhibit similar accuracies. Conveniently, these observations bridge the years during which the USNO Transit Circle was being overhauled (1972-75) and provide an important consistency check.

B. Satellite Astrometry. If one has a sufficiently accurate ephemeris for a planetary satellite, one may derive a position of the planet itself from an astrometric position of the satellite. Many observations of this type are found in the literature, a list of which is obtainable from the author. However, it has been found that the astrometric positions which have been reduced with respect to the referenece stars of the SAO Catalogue, especially in the southern half of the sky, were subject to extreme systematics errors (up to 1."0). This was especially apparent with some recent observations of the Uranian system taken and measured for JPL by Ianna(1984), where a plate overlap program at JPL revealed unrealistic ephemeris offsets. However, Klemola(1985) kindly reduced the field stars for us with respect to the Perth 70 Catalogue using plates which he had taken with the Lick double-astrograph. The resulting improvement has now shown consistent agreement with the other optical sources.

Table I. Observational data for the lunar and planetary ephemerides.

SOURCE	TYPE	DATES	BODIES	S.D.
Transit Circle, USNO	RA,Dec	1911-	Sun,Mer,Ven Mars,...,Nep	1″.0 0″.5
Transit Circle, RGO	RA,Dec	1957-	Sun,Mer,Ven Mars,...,Nep	1″.0 0″.5
Satellite Astrometry	RA,Dec	19	Jup,...,Nep	0″.3
Astrolabe	RA,Dec	1967-	Mars,...Nep	0″.3
Ring Occultation	RA,Dec	1977-	Uranus	0″.1
Lunar Laser	Range	1969-	Moon	18 cm.
Radar Echo	Range	1964-68 1969-	Mer,Ven,Mars Mer,Ven,Mars	10 km. 1.5 km.
Radar Closure	Diff'd Range	1971-	Mars	150 m.
Mariner 9 Orbiter	Range	1971-72	Mars,near conj. away from conj.	300 m. 40 m.
Mariner 10 Fly-bys	Range	1974,75	Mercury	150 m.
Viking Landers	Range	1976-80 1980-82	Mars	7 m. 12 m.
Pio X,XI; Voy I,II spacecraft tracking	RA,Dec Range	1973-80	Jupiter	0″.03 100 km.
Pio XI; Voy I,II spacecraft tracking	RA,Dec Range	1979,80	Saturn	0″.03 200 km.

C. Astrolabes. Astrolabe observations of the planets have been taken at many observatories and have been published in the Astronomy and Astrophysics Supplement Series, yielding an r.m.s. resiual of about 0"3. A list of the sources is available from the author.

D. Uranus Ring Occultations. Timing of an occultation of a star by the Uranian ring system, coupled with a model for the rings themselves, yields an offset of the planet's ephemeris. A series of seven occultations, most recently reduced by French(1985), shows a scatter of about 0"1 in both right ascension and declination.

E. Mariner 10 Fly-bys. The Mariner 10 spacecraft flew by the planet Mercury three times in its mission, providing usable range fixes during the first and third encounters of about 1 microsecond accuracy (±150 m).

F. Viking Landers. Round-trip ranging measurements to the Viking landers on the surface of Mars were obtained during the lifetimes of these spacecraft, 1976-1982. While the orbiting spacecraft were also active, the dual frequencies from the orbiters were used to calibrate the delay in the signal due to the ionized electron content of the solar corona. These data show mean errors of ±7m. After the orbiters had ceased functioning, the corona could be only approximated using an average model, yielding errors of about ±12 m.

G. Pioneer and Voyager Spacecraft Tracking. Extended doppler tracking of the Pioneer and Voyager Spacecraft through their encounters with the outer planets provide accurate three-dimensional determinations of the planets' positions with respect to the tracking stations of the Deep Space Network. The locations of the stations have been previously tied to the planetary reference system using the tracking of encounters with the inner planets. Campbell and Synnott(1985) discuss the data which have now been combined into the ephemeris data sets.

H. Millisecond Pulsar. The millisecond pulsar, PSR1937+21, emits pulses which seem to be of a highly regular nature and which can be measured to a high degree of accuracy. Presently, over a two-year period, the residuals fall below 1 microsecond (see Backer et al., 1985; Davis et al., 1985). Hopefully, with the use of more accurate clocks and improved detection equipment, the residuals could be reduced much further.

IV. EPHEMERIS ACCURACIES

It is evident from the preceding section that the ephemerides are fit to a wide range of observational data types, each affecting the ephemeris adjustments in differing ways. Qualitative and quantitative descriptions of the various elements of the ephemerides and how they are determined by the observations are given by Standish(1986) and by Newhall et al.(1983). They are summarized here.

Relative orbits and the inertial mean motions of the four innermost planets and the moon are determined by the ranging measurements. The orientation of this system to the earth's instantaneous equatorial plane is determined by the lunar ranging, which is sensitive to both the earth's rotation (equator) and to the solar motion (ecliptic). The spacecraft tracking of the Jupiter and Saturn encounters orient these planets to the inner system via the locations of the tracking stations, which themselves, have been determined from spacecraft encounters of the inner planets. The orientation of the whole system onto the equinox of the FK4 stellar catalogue is provided by the optical observations, which also provide the only data presently available for the outermost planets. Finally, one may locate the dynamical equinox at some given epoch by an analysis of the ephemerides themselves (Standish, 1982; Chapront-Touze and Chapront, 1983).

Table II gives the approximate accuracies for the mean epoch of the modern observational data, about 1975. For times removed from this epoch, the errors are expected to grow at a rate consistent with the uncertainties of the mean motions.

Table II. Approximate accuracies with respect to the mean epoch of the modern observational data (1975). These are for the present ephemerides, DE118 and DE200. The values in parentheses show values for expected accuracies in the near future.

Body	Longitude relative to Earth	Latitude w.r.t. ecliptic	Inertial mean motion	Longitude w.r.t. (FK4)	Longitude w.r.t. (Dyn)
Mercury	0".010	0".030	0".14/cty	0".05	0".03
Venus	.003	.010	.06	.05	.02
Earth	---	---	.03	.05	.01
Mars	.003	.003	.03	.05	.01
Jupiter	.2 (.05)	.1 (.05)	.5 (.2)	.25 (.07)	.25 (.05)
Saturn	.3 (.1)	.2 (.1)	1.0 (.5)	.25 (.1)	.25 (.1)
Uranus	.3 (.1)	.3 (.1)	1.0 (.5)	.3 (.1)	.3 (.1)
Neptune	.3 (.2)	.3 (.2)	1.0 (.5)	.3 (.2)	.3 (.2)
Pluto	1.0	.5	4.0	1.0	1.0
Moon	0.005	0.005	0".65/cty^2	.05	.01

V. FUTURE OBSERVATIONS

Most of the observational programs producing the data sets mentioned in Section III are of a continuing nature, thereby extending the time spans over which the data exists. The spans of the spacecraft, of course, are limited. However, there are also some newer data sets which can be expected in the near future which will further improve the ephemerides.

A. Milliseconds Pulsars. With improved detection equipment and with future searching, it is entirely possible that more of these objects will be found in various parts of the sky. Thus, the doppler-like projections of the earth's orbit will be established in complimentary directions. Futhermore, the seemingly consistent nature of the pulses may be checked by measuring each pulsar against the others. With three or more such pulsars, the long-term behavior of the pulsars could be monitored for any unpredictable variations, thereby establishing a type of celestial clock.

B. Radio Measurements. Positional measurements of the Galilean satellites have been made using the Very Large Array in New Mexico (Muhleman et al., 1985) with highly encouraging results. The center of the apparent thermal emission appears to coincide quite closely with the body's center of mass. The measurements, coupled with satellite ephemerides, yield planetary positions with respect to the Radio Source Catalogue. These, in turn, seem to be fairly closely aligned to the ephemeris reference system (FK4-FK5) as shown by Newhall(1986). The same technique is presently being used to provide a positional measurement of Uranus where there seems to be no asymmetry of the radio emission over the planetary disk.

C. VLBI. In principle, spacecraft in the vicinity of a planet may be used as a means of measuring the planet's position with respect to the Radio Source Catalogue, using VLBI techniques coupled with an accurate ephemeris for the spacecraft with respect to the planet. This has been done by Newhall (1986) with the Viking Orbiters and with the Venus Orbiter. Future missions where this may be possible include Voyager at Uranus (1986) and Neptune(1989), Galileo orbiting Jupiter(1988-1990+), the Venus Radar Mapper(1988-1989+) and the Mars Observer (1990-1991+).

D. Occultations. The timing of an occultation of a catalogue source (stellar, radio, etc.) by a solar system object (planet, satellite, etc.) would yield an observation of high accuracy in the direction along the track of the moving body. Searches for such possible events are currently being made.

E. Space Telescope and Hipparcos. Astrometric measurements of planetary satellites made with Space Telescope hold promise of being accurate to the order of 0″.01 or less. Coupled with an improved stellar catalogue provided by the Hipparcos Astrometry Satellite, such observations could bring the outer planet ephemerides down to an angular accuracy comparable to that of the inner planets. Of course, the Hipparcos catalogue alone will be of great benefit for the classical astrometric observations.

VI. LIMITATIONS TO ACCURACY

A few of the most prominent contributors to the uncertainties of the ephemerides are briefly mentioned in this section.

A. Asteroid Masses. Williams (1984) discusses the general problem of determining asteroid masses from perturbations on the motion of Mars. This is an area of vital concern to the construction of planetary ephemerides for it is most probably the greatest contributor to the uncertainties in the positions and motions of the whole inner planetary system. The most accurately measured feature of the planetary system (excluding the lunar ranges) is the Earth-Mars distance using the Mariner 9 and Viking lander range data. As mentioned above in Section IV, the fitting of this data is what determines the inertial motions of the inner planets. In turn, this data is sensitive to the perturbative effects of a number of asteroids whose masses are not well known. Futhermore, the present length of the data span is inadequate to allow satisfactory mass determinations for most of these objects. Williams estimates that the remaining uncertainties in the masses contribute an uncertainty of about $0''\!.025/\mathrm{cty}$ to the inertial motions of the four inner planets. Our numerical experience tends to confirm this estimate.

B. Lunar Secular Acceleration. Tidal forces between the Earth and Moon lead to a secular (negative) acceleration of the lunar longitude. At present, this can be measured only empirically, the value being determined as $n = -25''\!.1 \pm 1''\!.3/\mathrm{cty}^2$, leading to an uncertainty in longitude of $\pm 0''\!.65/\mathrm{cty}^2$ (see Dickey and Williams, 1982).

C. Solar Corona. The density of ionized electrons in the solar corona produces a delay in the transmission time of an electromagnetic signal passing through such a medium. Since the delay is frequency-dependent, it can be calibrated by using multiple-frequency signals. However, in cases when only a single frequency exists, the density of the corona must be approximated by a constant analytical model. This delay can reach many hundreds of microseconds when the signal passes close to the solar surface. However, at times away from solar conjunction, the total delay is less than one microsecond with an uncertainty falling below 0.1 microsecond. This is reflected, especially in the Viking Lander residuals, whose errors increase from ±7 meters to ±12 meters when the dual-frequency calibration of the orbiting spacecraft ceased to be available.

D. Planetary Topography. The individual topographic features of the terrestrial planets introduce random-like residuals into the round-trip times of the radar echo data. Even when the surfaces of these planets are modeled as tri-axial ellipsoids, the mean errors reach ±1.5 km (see e.g., Standish, 1973). For Mars, it has been possible to produce differenced ranges when two echos from the same point on the planet are subtracted, one from the other. The result, a measure of ephemeris drift over the time interval between the two points, can be determined to an uncertainty of about ±150 meters.

E. Optical Catalogue Errors. The transit data and the astrolabe data are based on global-type catalogues produced by the instruments themselves. These catalogues are referenced to the FK4 and exhibit only small systematic (zone) errors. On the other hand, the satellite astrometry and ring occultation data employ narrow-field observations, usually reduced to a secondary catalogue. The possibility of existing systematic zone errors, such as those mentioned in Section III for the SAO, is hereby noted.

VII. RELATIVITY FEATURES

There are various features of relativity which enter into the ephemeris creation process in a number of places: into the dynamics through the equations of motion, into the reduction of the observational data, or into the transformation of the different time-scales.

A. Equations of Motion. As mentioned before, we use the isotropic, Parameterized Post-Newtonian (PPN) n-body metric. Though the various parameters are coded as variables, we always integrate with the values required for the validity of general relativity. The formulation is detailed by Newhall et al. (1983). However, for the testing of general relativity, we do integrate the variational equations of these parameters as well as the parameters of other gravitational theories.

B. Observational Data. For ranging data as well as for the pulsar timing data, it is necessary to account both for the time retardation due to a signal passing through a varying potential field and also for the increased path length of the signal. The former effect was noted explicitly by Shapiro(1964) and the latter by Richter and Matzner(1983).

C. Time Transformations. Moyer (1981) gives approximate formulae for the relation between TDB, the independent variable in the equations of motion, and UTC, the time given by an individual atomic clock. These have been found to be accurate enough for all of the observational data with the noted exception of the pulsar timing data. Moyer's formulae show a quasi-periodic error of a number of microseconds over a year's time. They enter directly into the difference of two timing events, which if separated by a long time span, as is the case with the pulsar timings, become significant. We have integrated the exact equation which gives the difference in clock rates and have eliminated the secular rate, averaged over a complete century. In the future, we expect to provide a more complete analysis, eliminating the periodic features in a way similar to the procedure used by Standish (1982) when determining the average equinox offset and obliquity.

VIII. EXPORT PROCEDURES

We have the capability of providing direct, machine-readable, non-formatted tapes of our ephemerides for a number of different types of computers including IBM, Modcomp, CDC Cyber, PDP11, VAX and UNIVAC. We also provide reading and interpolating routines, character-coded in Fielddata, ASCII or EBCDIC. Users wishing a copy are asked to contact E.M.Standish, JPL 264-664, Pasadena, CA 91109, USA.

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DISCUSSION

Alley : could you explain further the meaning of your $\dot{\xi}$ relating to atomic physics ?

Standish : it is the rate at which an atomic clock would drift away from proper time, caused by a change in atomic physics with respect to gravitational physics.

Alley : what is the present value from the J.P.L. ephemerides work for the limit on $\dot{G}/G$?

Standish : we find $\dot{G}/G$ to be not significantly different from zero, with an uncertainty of $\pm 5.10^{-12}$ per year. The major contributors to this uncertainty are the uncertainties of the masses of the asteroids.

Nobili : what is the radar closure ?

Standish : it is when the signal returns to the same point.

Seidelman : how did you test the stability of the solution ?

Standish : by numerical integration forward and back for the same period of time. The errors of the numerical integration were small in both directions and coincided very well.

Tikhonov : it is right that DE-200 is fitted to FK5 ?

Standish : no. It is DE-111 which is fitted to FK5.

Tikhonov : what JPL ephemerides are the best for space flights ?

Standish : there are different JPL ephemerides for different missions. For instance, DE-118 was constructed for Halley comet.