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Present and Future Ephemerides: Requirements and Limitations

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Introduction

JPL continues to develop planetary and lunar ephemerides in support of its spacecraft navigation. Over the years, the requirements for increasingly sophisticated navigation have called for higher and higher accuracy; that trend is expected to continue into the future. It is therefore mandatory that JPL maintains a state-of-the-art program for the maintenance and improvement of its ephemerides. This paper discusses various aspects of the planetary and lunar ephemerides at JPL. First, the question of the independent variable of the ephemerides is reviewed: JPL's long-time use of “T_{eph}” vs. the IAU's newly-defined “TCB”. Next, the paper mentions the navigational requirements of past missions and those expected in the future. A brief description follows of modern observational accuracies, of present-day ephemeris uncertainties, and of the effects of the asteroids upon the ephemerides. Lastly, the plans for future ephemerides are presented.

Independent Variable of the Ephemerides

Since the mid-1960's, JPL navigation, including the ephemeris creation effort, has included general relativity in all of its dynamical calculations as well as in the reductions of the observational data. Even though the IAU defined both the variables, ET and TDB, the JPL ephemerides have never used either as they were defined; the strict IAU definitions of give variables that are not physically real. On the other hand, as shown by Standish (1998), the time argument used in the JPL ephemerides since the mid-1960's, “T_{eph}”, is a true relativistic coordinate time, rigorously equivalent to TCB, which is the time variable most recently defined by the IAU and which differs from T_{eph} only by a rate and an offset.

Contrary to what has been said in the literature, a conversion to TCB would not allow an increase in accuracy for the JPL ephemerides. One can show that working in T_{eph} is equivalent to working in TCB; the resultant ephemerides would be equivalent.

There has been an immense amount of sophisticated and detailed software produced over the past number of decades throughout the astronomical community and within the aerospace industry. The mere suggestion that this software be converted from the present T_{eph} into TCB is unacceptable: a conversion to TCB would involve a tremendous cost, time, and effort, and the chance of significant error involved with such a conversion would be virtually guaranteed and unavoidable. There are many applications which don't even have to consider the difference between TT and T_{eph}, since those two time scales never differ by more than 2 milliseconds of time; in contrast, the difference between TT and TCB grows at 0.5 seconds per year!

What is the benefit in converting to TCB? Absolutely nothing. Furthermore, it is a trivial matter to convert T_{eph} units provided by the JPL ephemerides into SI units using TCB. This involves simply the scale factor, $1-L_B = d(T_{eph})/d(TCB)$, applied to T_{eph}, the independent argument of the ephemerides, to the distances, and to the GM values.

Spacecraft Navigation : Accuracy Requirements

Planetary spacecraft navigation continues to become more and more sophisticated, requiring ever higher accuracy. For example, the numbers and sizes of necessary mid-course corrections are significantly reduced with accurate navigation, leading to significant savings in the onboard thruster propellant. Accurate navigation also allows the immediate entry of a spacecraft into a planet's atmosphere, a process which requires an extremely accurate entry angle, thereby taking advantage of aerobraking, and avoiding the fuel-consuming process of orbit insertion. Even greater accuracy is demanded when a small landing area on the surface of planet is specified, as will undoubtedly be the case in the future as the planetary terrains become better known.

One of the major contributing sources of navigation uncertainty has been and continues to be the uncertainties associated with the planetary ephemerides. For this reason, JPL has been supporting the maintenance and improvement of the ephemerides since the mid-1960's and is expected to continue to do so into the future, as the navigational requirements become even more demanding. For the Viking mission in 1976, the ephemeris requirements for going into Mars orbit were on the level of 50 km; by the time of the direct entry (and subsequent use of a parachute) of Pathfinder, the requirements had shrunk below 5 km; for the future Mars Exploration Rovers, launching in 2003, the demand is for no more than a 1 km error.

Observations, Ephemeris Accuracies and Effect of Asteroids

The planets may be split into two groups when discussing the observational data and the resultant accuracies.

For the four inner planets, the ephemerides are dominated by two types of data:

- ranging measurements, whether radar reflections from a planetary surface or return signals from a transponder aboard a landed or orbiting spacecraft, and
- ΔVLBI measurements of an orbiting or landed spacecraft, taken with respect to the International Celestial Reference Frame (ICRF).

The ranging measurements provide all relative angles and distances between the earth and the other three innermost planets, thus locking the whole system together. The ranging measurements also provide accurate mean motions of the planets with respect to inertial space. The ΔVLBI are angular measurements which serve to orient the whole inner system onto the background ICRF.

Typically, radar-ranging has in inherent accuracy of 100 meters or less, though topography tends to add signatures to the observations. The uncertainties of spacecraft-ranging can be as low as 2–3 meters when the solar corona is calibrated using dual frequency signals or when the single frequency is high enough or when the planet is not near to solar conjunction. VLBI to an orbiting or landed spacecraft relate the planet to the background radio sources at a level of a few milliarcseconds.

No matter how good the observational data are, the planetary motions can not be perfectly known, for the planets are perturbed by many asteroids whose masses are quite poorly known. It is not possible to solve for the individual asteroid masses, other than for the biggest few, because there are too many for their relatively minor signatures to be uniquely recognizable in the observational data. Consequently, as shown by Williams (1984) and by Standish and Fienga (2002), the ephemerides of the inner planets, especially Mars, will deteriorate over time. If, as in the case of Mars, the most accurate observations are separated by long stretches of time (15 years between Viking and Pathfinder), then the attempts to fit all of the observational data, at the level of its inherent accuracy, result in effectively smoothing out the perturbations. The result is that the ephemerides are no more accurate than 1–2 km over the span of the observations and that the uncertainties grow at a rate of a few km/decade outside that span.

There has been a great deal of effort to model the asteroid perturbations as well as possible. The orbits are sufficiently known; the masses are not. Studies of the estimations of the masses for the most relevant 300 or so asteroids have been made by Fienga (2001) and by Krasinsky *et al.* (2001); modeling of a ring to represent the perturbations from the remaining thousands of small asteroids is described by Krasinsky *et al.* (2002).

Certainly, any improvement in our knowledge of asteroid masses in general will provide a corresponding improvement in the computed dynamics of the planetary motions.

For Jupiter, a number of spacecraft observations exist, allowing Jupiter's ephemeris to be known at the level of about 50 km ($0.''01 - 0.''02$). For the outermost four planets, the problem is not the asteroids; it is the fact that the observations are only optical and the planets have not gone through a full orbital period since the most modern optical techniques were developed. Consequently, these ephemerides are accurate to only about $0.''1 - 0.''2$.

Future JPL Ephemerides

There is a choice to be made in creating ephemerides; the choice involves mainly the ephemerides of Mars and the Earth and is due to the uncertainties imposed by the perturbations of the asteroids.

- One may fit all of the observations as well as possible, thereby smoothing out the perturbations and creating a "long-term" ephemeris which is as accurate as possible over extended periods of time. However, some of the perturbations have periods exceeding the time-spans of the modern observations. The result can be biases, especially in the mean motions.

- One may concentrate on fitting only the most recent observations so that present-day accuracy is as high as possible. Hopefully, extrapolation into the near future (a year or two) will be good enough for these "accurate now" ephemerides, but certainly, the accuracy will decline over longer time spans.

For future JPL planetary ephemerides, the independent variable will continue to be T_{eph}. The "long-term" ephemerides will continue to be available to the general public, while the "accurate now" ephemerides will be created for navigational purposes and for specific scientific studies.

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