JET PROPULSION LABORATORY **INTEROFFICE MEMORANDUM**

IOM 312.F-00-107b

November 1, 2000

TO : P B Esposito and J B Jones

FROM : E M Standish

SUBJECT : Recommendation of DE405 for 2001 Mars Surveyor and for Cassini

The ephemeris DE405 (Standish, 1998) is recommended for the 2001 Mars Surveyor Mission and for current use by the Cassini Mission.

1. Introduction

The latest JPL Planetary and Lunar Ephemeris, DE405/LE405, was created in May 1997. Since that time, there have been some significant additions to the observational data sets to which the ephemerides are adjusted, including in particular, position measurements of Mars and Saturn. However, analyses of these data show that DE405 does not require any significant improvement.

Since the creation of DE405/LE405, three sets of observational data have been obtained which are directly relevant to the ephemerides of Mars and Saturn:

ranging and doppler measurements from Mars Pathfinder

ranging normal points from Mars Global Surveyor

astrographic CCD positions of Saturnian satellites

The assessment of DE405 is done using these data in three ways:

1. residuals of the recent data are computed against DE405, indicating its extrapolation accuracy;
2. the complete set of observational data is used for a full least squares ephemeris adjustment, and the resultant (linearly-predicted) ephemeris is compared to DE405; and
3. DE405 is compared directly with EPM2000, the recent planetary and lunar ephemeris from the Institute of Applied Astronomy in St. Petersburg, Russia.

These three analyses are described in the rest of this memo. They will show that no significant corrections are indicated for DE405.

2. Recent Observations w.r.t. DE405

2.1. Observations of Mars

The ranging and doppler measurements of the Pathfinder Spacecraft at Mars from July to October, 1997, have *a priori* uncertainties of about 10 m and 0.05 mm/sec, respectively (Folkner, 1998). The ranging normal points from Mars Global Surveyor, March 1998 - February 2000, have a reported uncertainty of only a few meters (Konopliv, 2000). Both of these data sets have been computed against DE405, and their residuals are shown in Figures 1 and 2. While the fit for DE405 did include the Viking ranges (1976-82), neither Pathfinder nor MGS was available at that time. Consequently, these more recent data provide a good indication of the extrapolation abilities of DE405 itself.

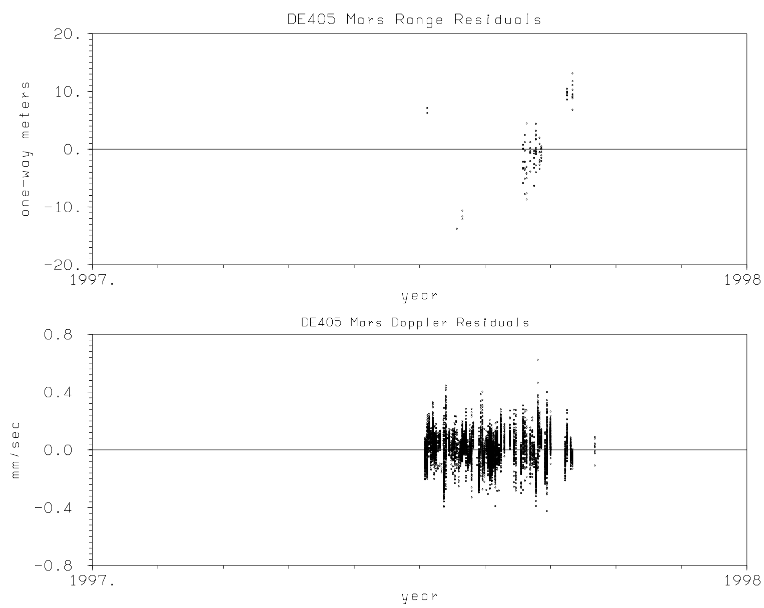

Figure 1. Pathfinder range and doppler residuals: 1997–1998.

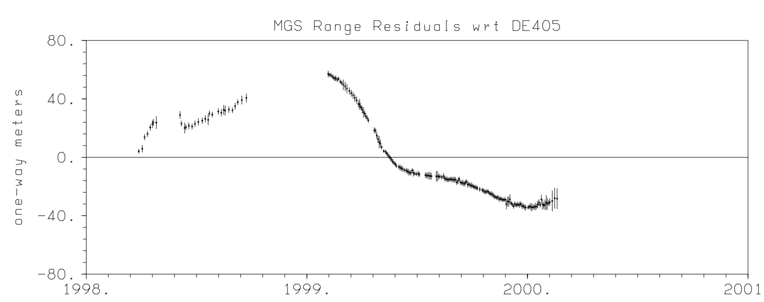

Figure 2. Mars Global Surveyor range and doppler residuals: 1998–2000.

The Pathfinder residuals are less than 20 m in 1997. Most of the residuals are only a few meters; the few outlers of 10 m or so surely contain observational errors; otherwise, they would indicate sudden changes to the ephemeris of Earth or Mars, happening over the time-span of only a few weeks – a fully unrealistic situation. More probably, they indicate calibration uncertainties due to instrumentation or to the solar corona, similar to those known to exist in the Viking range data. The MGS residuals are as large as 60 m in 1998–2000, but, here also, there is reason to believe that these data contain a systematic error; if this should be the case, the actual residuals are significantly less than those shown. This question is addressed in the next section.

2.2. Observations of Saturn

In 1999, the Flagstaff Station of the US Naval Observatory began to provide astrographic CCD observations of the Saturnian satellites (Stone and Harris, 2000). These routinely show *a priori* single observation uncertainties of about 0.2 arcseconds (which projects to about 1300 km at Saturn's opposition). Figure 3 shows the residuals of these data up through the end of September 2000. The fit is good. There is a slight apparent signature in the declination residuals, seen in the 1999-2000 opposition, yet the residuals of the next opposition show no offset at all. Thus, the drift is most certainly an observational problem. In fact, as noted in the next section, the small drift persists through a linearized ephemeris correction.

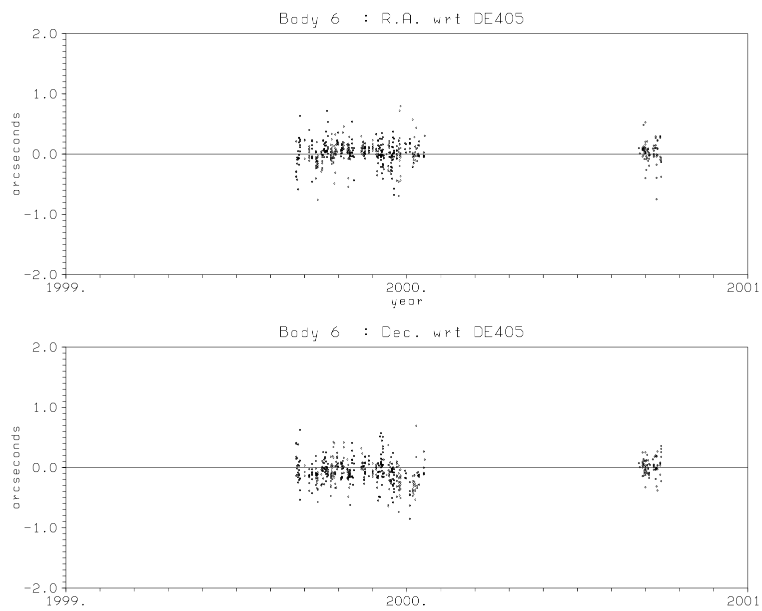

Figure 3. Saturn CCD residuals from the US Naval Observatory at Flagstaff

3. Linearized Adjustment of DE405 to Recent Observations

The complete set of ephemeris observational data for all planets was used for a least squares adjustment for corrections with respect to DE405; i.e., this is the same process that would be used for the creation of a new ephemeris. The parameter corrections from the solution itself are listed and discussed in Appendix A. The relevant parameter corrections seem to be reasonable; all of the data sets seem to be comfortably fit by the adjustment with one exception: the MGS normal range points of Mars. For the MGS points, a parameter representing a scale factor proportional to the Earth-Mars range was introduced into the least squares solution. The resulting value of about 11 m/au seems to remove any inconsistency between all of the data sets. The cause of the systematic error, however, is unknown.

3.1. Solution for the ephemeris of Mars

It is then possible to linearly predict the changes to the geocentric position of Mars, resulting from the adjustment; such differences in r.a., dec., and distance, respectively, are plotted on the left side of Figure 4. It is evident that a sizable part of the differences is due to an overall frame rotation. Solving for such a rotation gives 1.0,-1.5, and 0.9 milliarcseconds for rotations on the x-, y-, and z-axes, respectively (for a geocentric distance of Mars, a rotation of 1 mas can be from 0.5 km to 2.0 km). After removal of the rotation, the differences are greatly reduced, as shown on the right side of Figure 4. This rotation is no larger than what has long been estimated as the uncertainty in the orientation of DE405 w.r.t. the ICRF (International Celestial Reference Frame).

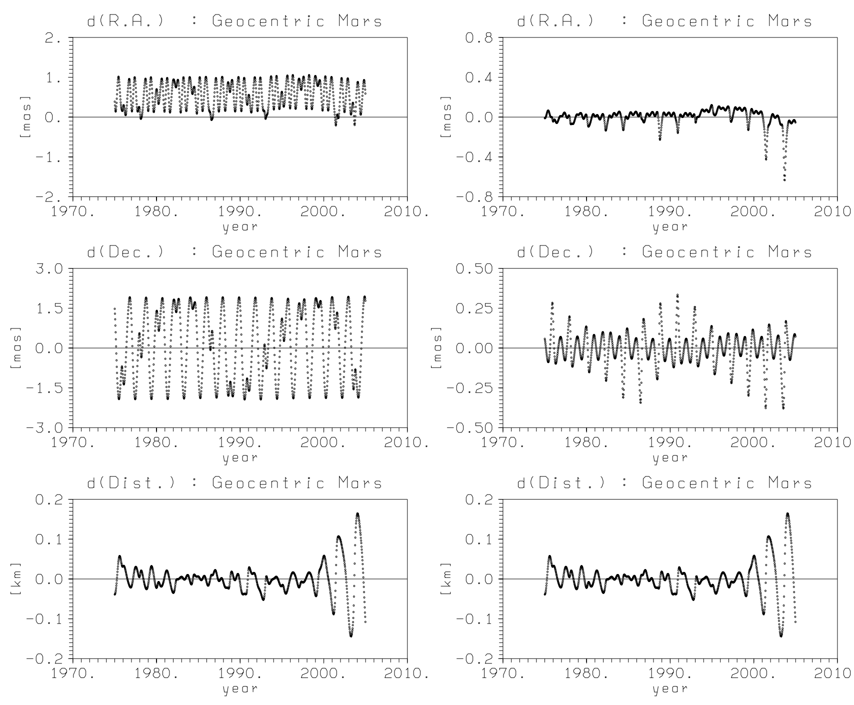

Figure 4. Linearized corrections for Mars from adjustments to the total set of observational data. Left-hand side: full correction; right-hand side: correction after removal of frame rotation. (Note the changes in the ordinate scales.

3.2. Solution for the ephemeris of Saturn

The corrections from the least squares solution are plotted in Figure 5 for the ephemeris of Saturn. As seen, the new solution differs by less than 100 mas (650 *km*) from DE405. Furthermore, the new solution has been used to plot the new linearized residuals of Saturn, comparable to those plotted in Figure 3. The two plots are virtually identical. The small signature remains, indicating that is most probably an observational effect.

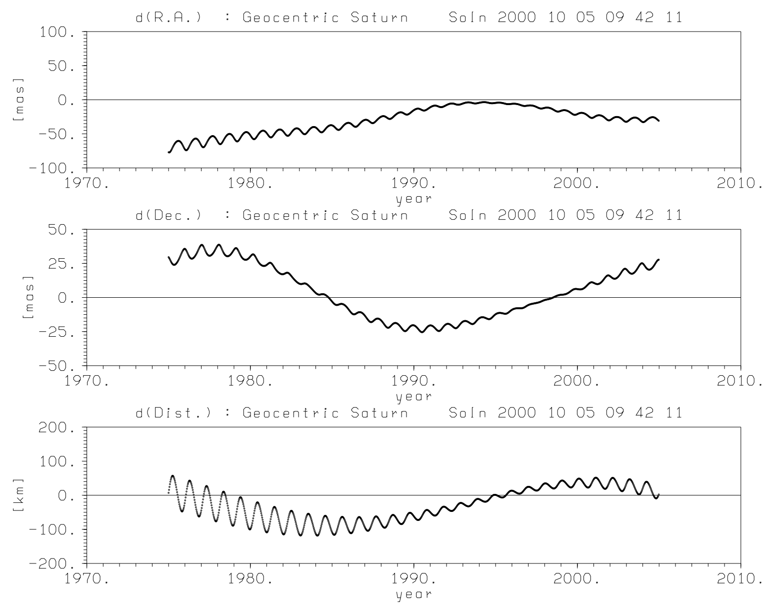

Figure 5. Linearized corrections for Saturn from adjustments to the total set of observational data.

4. Comparison of DE405 vs. EPM2000

For the first time in nearly two decades, there is a modern planetary ephemeris which has been created independently from ephemerides produced here at JPL. Members from the Institute of Applied Astronomy (IAA) in St. Petersburg have developed their own software, reduction routines, and integration programs for the complete process of creating planetary and lunar ephemerides (Krasinsky and Vasilyev, 1997; Pitjeva, 2000). They have also kindly supplied a portion of their ephemerides in order to make a comparison possible with JPL's DE405 (Krasinsky and Pitjeva, 2000).

The data sets fit by both DE405 and EPM2000 were quite similar. Neither was fit to the MGS range points. However, EPM2000 was fit to the Pathfinder ranging and doppler from 1997 while that data set was *not* in the fit for DE405. For this reason, the comparison is a most significant one.

The comparison is shown in Figure 6. For Mars, the differences in all 3 components are below 200 meters; for range, it is below 80 meters.

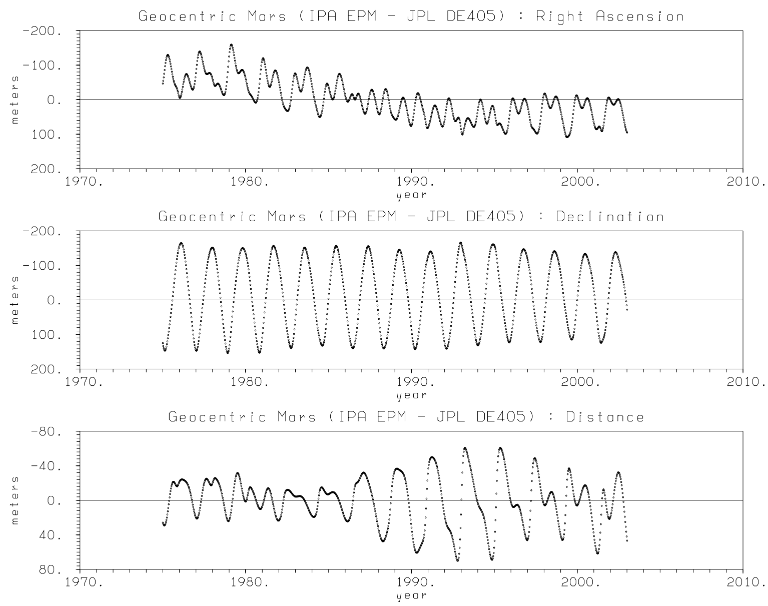

Figure 6. EPM2000–DE405: Geocentric differences in right ascension, declination, and distance; 1970-2000.

5. Conclusions

Three different methods have each shown that DE405 remains an accurate ephemeris, even when extrapolated a number of years past the time-span of the observational data to which it was fit.

Residuals of recent data, not included in the fit of DE405, are small;

an updated solution fitting to all data shows no significant changes to the ephemerides; and

a comparison with an independently created ephemeris shows insignificant differences.

The DE405 ephemeris for Mars shows no significant extrapolation errors since its creation in 1997. It is recommended for use by present-day spacecraft missions.

6. Acknowledgements

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Appendix A

The most recent ephemeris solution, fit to all relevant existing observational data, indicates the corrections that would be made to DE405, if a new ephemeris were to be created at the present time. Overall, there were 103 explicit unknowns and 59412 observations. Most of the data sets have been described in Standish *et al.* (1995) and in Standish (1998). The additional observational data are those already discussed (Pathfinder, MGS, and USNO Flagstaff CCD observations). Table I presents values for a few of the more interesting parameters from that solution.

Table I. Some of the parameters from the least squares solution.

parameter	value	*formal* uncertainty
m/au	149597870689.7	0.4
$\mathcal{M}_{Ceres}/\mathcal{M}_{Sun}$	4.76 x 10^{-10}	0.01 x 10^{-10}
$\mathcal{M}_{Pallas}/\mathcal{M}_{Sun}$	1.08 x 10^{-10}	0.01 x 10^{-10}
$\mathcal{M}_{Vesta}/\mathcal{M}_{Sun}$	1.35 x 10^{-10}	0.01 x 10^{-10}
ρ_C	1.29	0.06
ρ_S	2.71	0.04
ρ_M	5.29	0.53

The length of the AU is now estimated to be 1.3 m shorter than its value in DE405. The masses of Ceres, Pallas, and Vesta are fully consistent with *most* modern determinations. The ones here are a bit unique, however, for the others are derived from asteroid-asteroid encounters, while these estimations are derived principally from the asteroids' perturbations upon the accurately measured Earth–Mars range. Also of note are the estimations of the densities of the three major taxonomic asteroid classes. In particular, the seemingly low value of 1.29 for the carbonaceous class agrees remarkably well with the determination of Mathilde's density by Yeomans *et al.* (1997).