THE PLANETARY EPHEMERIS REFERENCE FRAME

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ABSTRACT. The JPL planetary ephemeris is aligned to the ICRF through use of VLBI observations of spacecraft in orbit about Mars and Venus. VLBI measurements using DSN and ESA tracking stations have been supplemented by use of the Very Long Baseline Array for specific measurement campaigns. Currently the planetary ephemeris is aligned to the ICRF with an accuracy of 0.25 milli-arcseconds, nearing the accuracy of current quasar catalogs. The ephemeris dynamics are most accurately determined by range measurements to spacecraft, including spacecraft currently in orbit about Mars, Venus, and Saturn. Because the orbit of Mars is significantly perturbed by asteroids, a continued program of measurements is planned in order to support increasing ephemeris accuracy needs for Mars landers, including the upcoming Mars Science Laboratory.

1. THE CURRENT JPL PLANETARY EPHEMERIS

The current JPL planetary and lunar ephemeris is DE421 (Folkner et al. 2008). The DE421 ephemeris has been fit to a large number of spacecraft range and very-long- baseline interferometry (VLBI) measurements, most of which were not available for the widely used ephemeris DE405 (Standish et al. 1997).

Most notably the DE405 ephemeris preceded the wave of spacecraft to Mars starting with the Mars Pathfinder lander in 1997, followed by Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter. The dynamics of the Earth and Mars orbits were thus based mainly on range measurements to the Viking landers between 1976 and 1982, with the orbits of Mercury and Venus determined primarily by radar ranging from Earth to the planetary surfaces. The DE405 ephemeris was aligned to the International Celestial Reference Frame mainly through VLBI observations of the Magellan spacecraft in orbit about Venus between 1990 and 1995. Unfortunately the Magellan spacecraft radio system did not support range measurements.

Starting in 1997 range measurement to Mars have been made regularly, with an accuracy about ten times better than the Viking lander range data due to improved radio measurement systems and use of higher radio frequency than used for Viking, reducing the effects of charged particles in the heliosphere. The recent Mars spacecraft also support regular VLBI observations. The VLBI measurement accuracy has improved by a factor of ten from Magellan through improved calibration techniques and changes to the spacecraft radio systems.

The ephemerides of the other planets have also benefited from recent space missions. The Venus Express spacecraft has provided accurate range measurements greatly improving the accuracy of the orbit of Venus. The Galileo and Cassini spacecraft measurements have significantly improved the orbit accuracy for Jupiter and Saturn. The orbit of Mercury will shortly be improved from measurements from the MESSENGER spacecraft. The orbits of Neptune and Uranus have been improved by modern astrometric observations.

2. SPACECRAFT VLBI MEASUREMENTS FOR PLANETARY EPHEMERIDES

Spacecraft VLBI measurements used for planetary ephemeris estimation have primarily been made for spacecraft in orbit about other planets. Measurements of the Doppler shift of the spacecraft radio signal determine the spacecraft positions relative to the planet center of mass with an accuracy as good as $1m$ for spacecraft in low-altitude orbits (e.g. Konopliv et al. 2006) and less accuracy for high-altitude orbits such as Galileo about Jupiter. The VLBI measurements are performed using two or more tracking antennas on Earth. Most measurements to date have been made with the NASA Deep Space Network, with an antenna at Goldstone California used to co-observe with either an antenna in Madrid, Spain or in Canberra, Australia. The measurements are made by determining the difference in arrival time at the Earth tracking antennas of a radio signal transmitted by the spacecraft spanning a wide bandwidth, often two narrow-band tones separated by about $40MHz$. The separation between tracking stations and station clock differences are calibrated by observing the difference in arrival time of the radio signal from an extra-galactic radio source shortly before or after the spacecraft observation. The difference in delay time divided by the baseline length gives a measurement of one component of the direction to the spacecraft. Since the Goldstone and Madrid stations are at nearly the same latitude, VLBI measurement made on the Goldstone-Madrid baseline are largely aligned with right ascension. Measurements on the Goldstone- Canberra baseline are about mid-way between right ascension and declination. (More details on the VLBI measurement technique are given in Thornton and Border, 2000).

Figure 1 shows the differences between measured and estimated angular position of Venus from the ephemeris DE421 on the two DSN baselines from the Magellan spacecraft in orbit about Venus. These measurements were used to align the DE405 ephemeris to the ICRF. The average of the residuals is about 3 mas (milli-arcsecond) and largely represents the errors in the Magellan VLBI measurements and the difference in orientation of DE421 and DE405.

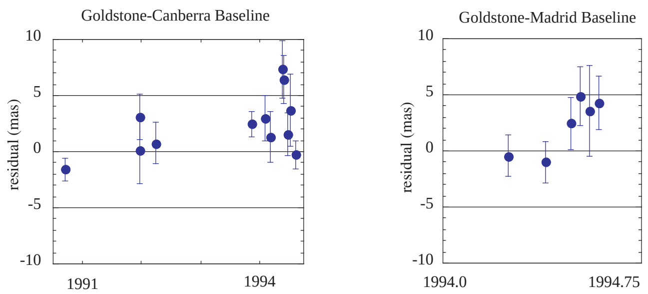

Figure 1: Residuals of VLBI measurements of the Magellan spacecraft in orbit about Venus, relative to the JPL planetary ephemeris DE421.

Figure 2 shows the VLBI measurement residuals of recent Mars-orbiting spacecraft relative to the DE421 ephemeris. The average of the residuals is about 0.25 mas and may be limited by the different quasar catalogs used to reduce the VLBI measurements from different periods. The uncertainty in the Mars ephemeris is thus currently thought to be about 0.25 mas. The orbit uncertainty predicted into the future increases with time since the interaction of asteroids with unknown masses limits the dynamical modeling accuracy. Thus to maintain the ephemeris accuracy requires an on-going measurement campaign, which is required for the upcoming Mars Science Laboratory project.

3. FUTURE PROSPECTS

Since the Mars spacecraft VLBI measurement residuals appear to be limited, at least in part, by changes in quasar catalog, the current measurement set will shortly be adjusted to a common quasar catalog. Further measurements are expected to be acquired at the rate of about one per month at least until the Mars Science Laboratory arrival at Mars.

4. REFERENCES

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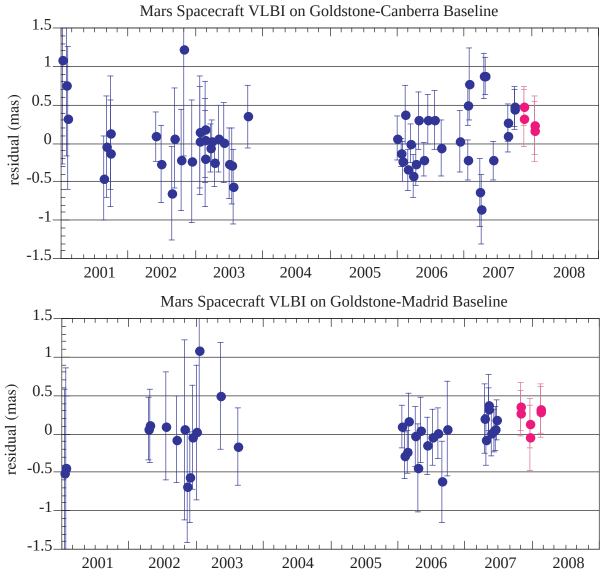

Figure 2: Residuals of VLBI measurements of Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter in orbit about Mars, relative to the JPL planetary ephemeris DE421. Measurements prior to December 2007 (in blue) were included in the estimation process leading to the DE421 ephemeris, measurement taken later (in red) were not used in the estimation process.

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