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Linking the planetary ephemeris to the International Celestial Reference Frame

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Abstract. The largest uncertainty in the ephemerides for the inner planets is in the orientation of the dynamical system to the celestial reference frame. A program of VLBI measurements of spacecraft in orbit about Venus and Mars has been performed to reduce the orientation uncertainty to 0.2 milliarcseconds.

Keywords. celestial mechanics, ephemerides, solar system: general

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The dynamical orbits of the inner planets (Mercury, Venus, Earth, and Mars) have been determined through planetary radar ranging starting in the 1960's, and have been determined with increasing accuracy by radio range measurements to spacecraft in orbit about them and, in the case of Mars, landers on the surface (e.g. Reasenberg *et al.* 1979; Fienga *et al.* 2009; Konopliv *et al.* 2011; Smith *et al.*, 2012). The largest uncertainty in planetary positions comes from the determination of the overall orientation of the solar system with respect to the celestial reference frame, now defined by the positions of extragalactic radio sources (Ma *et al.* 2009). The earliest link between the dynamical solar system frame and the radio reference frame, with accuracy of $0.020''$, was obtained by use of narrow-band very-long-baseline interferometry (VLBI) measurements of the Mariner 9 spacecraft in orbit about Mars (Newhall *et al.* 1986). The accuracy was improved to $0.003''$ by a comparison of Earth orientation estimates from lunar laser ranging (LLR) and VLBI (Folkner *et al.* 1994).

In order to improve the accuracy of the orientation of the inner solar system to the ICRF, a series of measurements of the angular positions of planets using spacecraft in orbit about Venus and Mars has been performed, starting with observations of the Magellan spacecraft in orbit about Venus in 1990, continuing through 2012 with observations of Mars Odyssey and Mars Reconnaissance Orbiter. The measurements are based on VLBI instrumentation using a technique called delta differential one-way range (ΔDOR) (Thornton & Border 2000) to measure one component of the direction to a planet relative to radio sources. Measurements are made using pairs of tracking stations (baselines) from the NASA Deep Space Network, with one station near Goldstone, California, and a second station from near Madrid, Spain, or near Canberra, Australia.

The accuracy of the ΔDOR measurements has continued to improve. Early measurements were limited by several factors. Limited recording bandwidth required use of bright radio sources, which are more likely be be resolved. With resolved sources the position of the center of brightness varies depending on the observation geometry. The limited bandwidth also limited the measurement signal-to-noise ratio (SNR). Non-linearity of the phase response of the analog radio down-conversion electronics introduced significant errors in the determination of group delay. The delay due to the Earth's ionosphere was calibrated using Faraday rotation measurements from a small set of satellites.

Improved data transmission technology now allows the use of much wider signal band-

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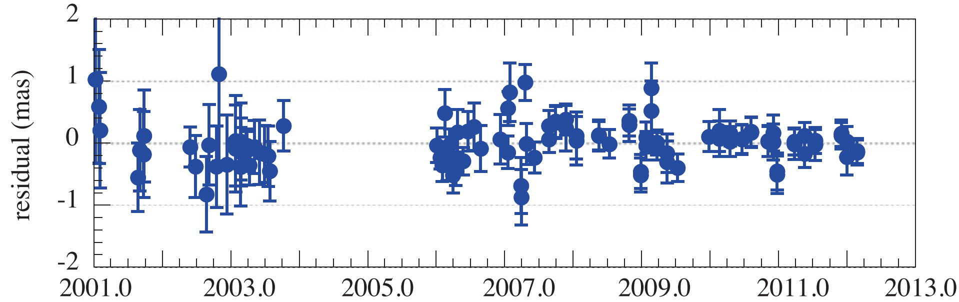

Figure 1. Residuals (milliarcseconds) of VLBI measurements of Mars-orbiting spacecraft on Goldstone-Madrid baseline

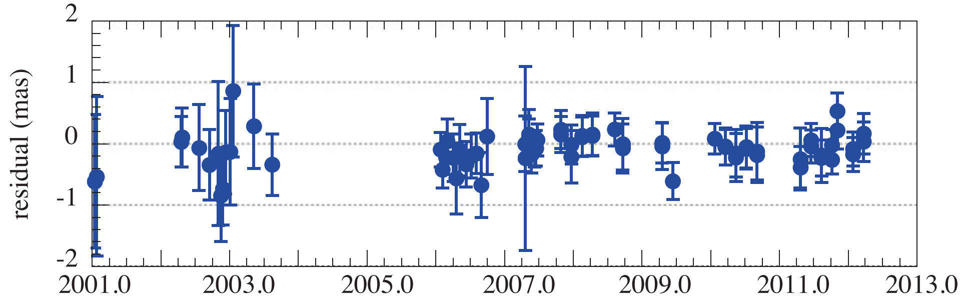

Figure 2. Residuals (milliarcseconds) of VLBI measurements of Mars-orbiting spacecraft on Goldstone-Canberra baseline

widths giving better SNR on more point-like radio sources. Digitization of radio signals at higher intermediate frequencies has reduced instrumental phase response errors. Measurements of dual-frequency radio signals from the Global Position System has improved the ionosphere calibration. As a result, measurements of the direction from Earth to Mars taken since early 2010 show residuals, after adjustment of the ephemerides of the inner planets, of less than 0.2 milliarcsecond, as shown in Figures 1 and 2. This improvement in accuracy enables increasingly precise targeting of planetary science missions.

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