JET PROPULSION LABORATORY INTEROFFICE MEMORANDUM

IOM 343R-11-003

14 September 2011

To: Tomas Martin-Mur

From: W. M. Folkner

Subject: Planetary ephemeris DE424 for Mars Science Laboratory early cruise navigation

1. Introduction

The planetary ephemeris DE424 has been fit to the most recently available measurements of the position of Mars, including ranging data from Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter, and Mars Express through July 2011 and VLBI (delta-DOR) observations of Mars Global Surveyor, Odyssey, and MRO through August 2011. The latest VLBI observations from 2011 agree very well with observations from 2010. This agreement gives confidence that the orientation of ephemeris to the International Celestial Reference Frame is now stable to the expected uncertainty. DE424 is recommended for use by the Mars Science Laboratory mission for use in early cruise operation. An updated planetary ephemeris is planned for May 2012 prior to MSL arrival at Mars.

DE424 is also suitable for use by missions to other planets. DE424 was fit to a full set of planetary observations. The orbit of the Moon for DE424 is consistent with the orbit on DE421 at the meter level, while the lunar libration angles are consistent at the 0.01 arcsecond level, which is adequate for many purposes including MSL navigation. Use of DE421 is recommended for the most accurate lunar data analysis.

2. Solar system model parameters

The dynamical models used for the integration of DE424 are similar to those used for the integration of DE421 (Folkner et al. 2009). The mass parameters of the Sun and planets used are given in Table 1. The mass parameters for the planets other than Earth are best estimated by planetary missions. The GM for Mars is consistent with Mars gravity field 095C, which is presently used by the MSL navigation team. A later estimate of GM is available for use with Mars gravity field 110 (Konopliv et al. 2011). The orbits of the planets are not sensitive to the difference in these Mars GM estimates. The mass of the Earth-Moon system has been held fixed to the value used in DE421, with the Earth/Moon mass ratio estimated from the full Mars spacecraft ranging data set used for DE424. The resulting Earth and Moon GM values are given in Table 1. The mass parameter of the Sun is also estimated from the Mars spacecraft range data as indicated from the table.

The mass parameters (GM) of 20 asteroids which perturb the orbit of Mars were estimated with the current Mars spacecraft ranging data set as described in Konopliv et al. (2011) except that the mass parameter of Vesta was taken from a preliminary analysis of the DAWN tracking data (Konopliv, private communication). The mass parameters of the 46 asteroids that most perturb the orbit of Mars were held to nominal values as for DE421 except that the mass parameter of Lutetia was taken from a preliminary analysis of tracking data from Rosetta (Morley, private communication). The mass parameters for 276 other asteroids were estimated using radii and taxonomic classes as used in DE421 with the densities of three taxonomic classes estimated from the Mars spacecraft range data.

Table 1: Mass parameters for major solar system bodies

Body/System	GM (km^3/s^2)	Uncertainty (km^3/s^2)	Reference
Mercury	22031.855000	0.9	Taylor [2010]
Venus	324858.592000	0.006	Konopliv et al. [1999]
Earth	398600.436296	0.0043	fit parameter
Mars	42828.375214	0.00028	Konopliv et al. [2006]
Jupiter	126712764.800000	1.5	Jacobson [2005]
Saturn	37940585.200000	1.1	Jacobson et al. [2006]
Uranus	5794548.600000	7.0	Jacobson et al. [1992]
Neptune	6836527.1005800	10.	Jacobson [2009]
Pluto	977.000000	1.38	Jacobson [2007]
Sun	132712440040.944600	10.	fit parameter
Moon	4902.800013	0.00005	fit parameter

3. Mars spacecraft VLBI observations

The orientation of the planetary ephemeris with respect to the International Celestial Reference Frame (Fey at al. 2009) by VLBI observations of spacecraft. VLBI observations on Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter have been made relative to extragalactic radio sources using delta-differential one-way ranging (ΔDOR) using either the Goldstone-Madrid or the Goldstone-California baselines of the NASA Deep Space Network (DSN). The observations on the Goldstone-Madrid baseline are essentially measurements of right ascension since the Goldstone and Madrid DSN complexes are at almost the same latitudes. Observations on the Goldstone-Canberra baseline measure a linear combination of right ascension and declination.

The Mars spacecraft VLBI measurements on the Goldstone-Canberra baseline in the past have exhibited some internal inconsistency that is thought to be caused by difficulty in calibration of the Earth ionosphere at the low elevations at which Goldstone and Canberra can simultaneously view Mars. In 2010 and 2011 more care has been taken to observations of multiple radio sources near Mars made from the same tracking stations. The improved observation method has led to an improved consistency of the measurements. Figure 1 shows the VLBI measurements residuals for DE424.

With the longer set of improved VLBI measurements, the estimated orientation of the solar system with respect to the ICRF has changed from previous ephemerides by about twice the expected 1-sigma uncertainty (Folkner 2010a). Figure 2 shows the difference in the position of Mars with respect to Earth as estimated in DE423 and DE424. A significant change in orientation from DE423, evident in the difference in right ascension and declination of Mars, is shown in Figure 2. Some change was expected since in the analysis of the Mars orbit uncertainty it was found that systematic effects in the reduction of VLBI observations of the Cassini spacecraft at Saturn were causing unexpected effects on the solar system orientation. The improved VLBI observations for Mars and improvements in the reduction of the VLBI observations of Cassini give consistent results. Thus the DE424 fit is considered to be consistent with the previous Mars orbit uncertainty analysis and future changes are expected to be smaller than one sigma.

More VLBI observations of Mars spacecraft are planned through MSL arrival at Mars in August 2012 and will provide confirmation of the ephemeris orientation estimation.

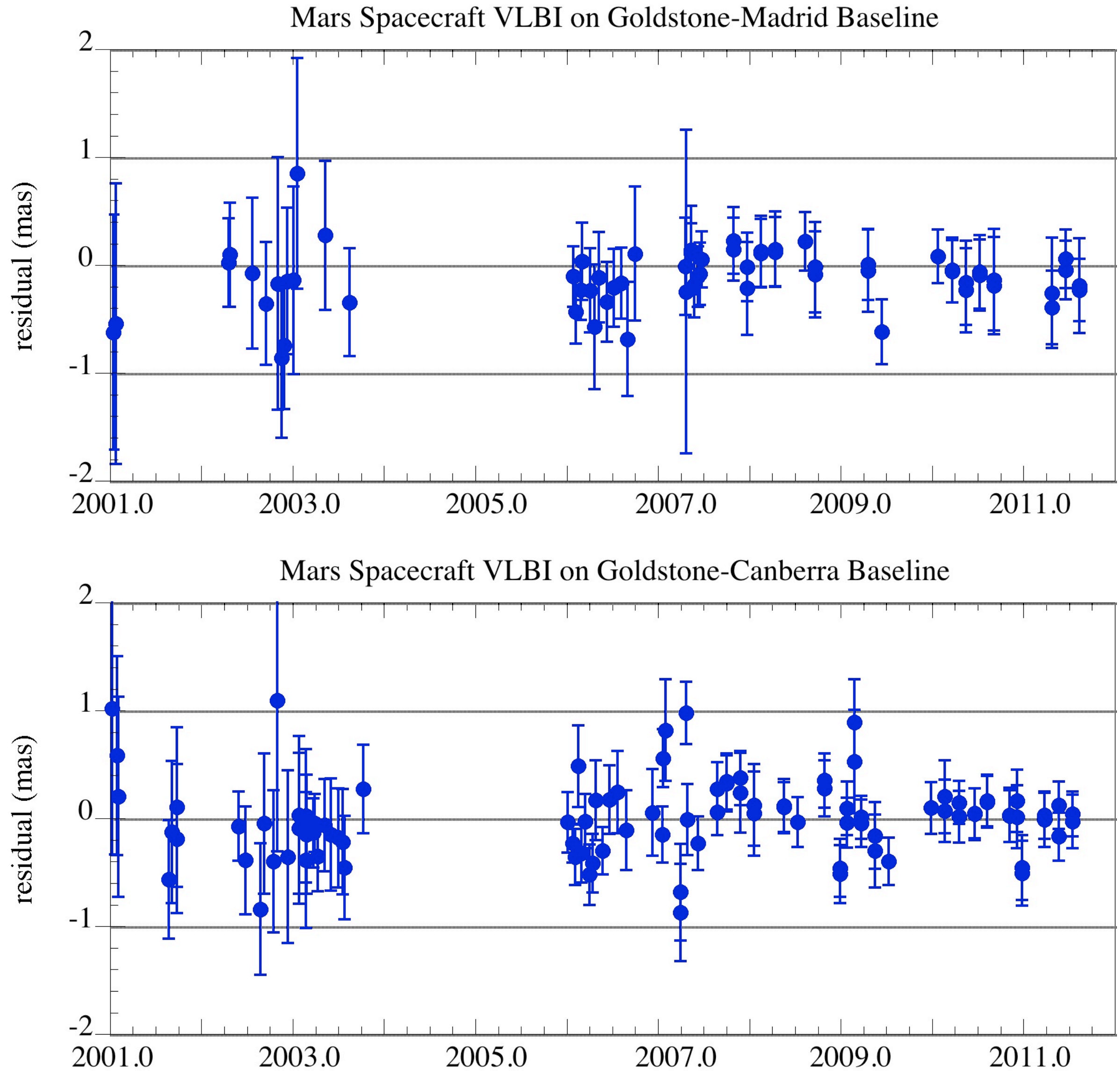

Figure 1: VLBI measurement residuals for MGS, Odyssey, and MRO

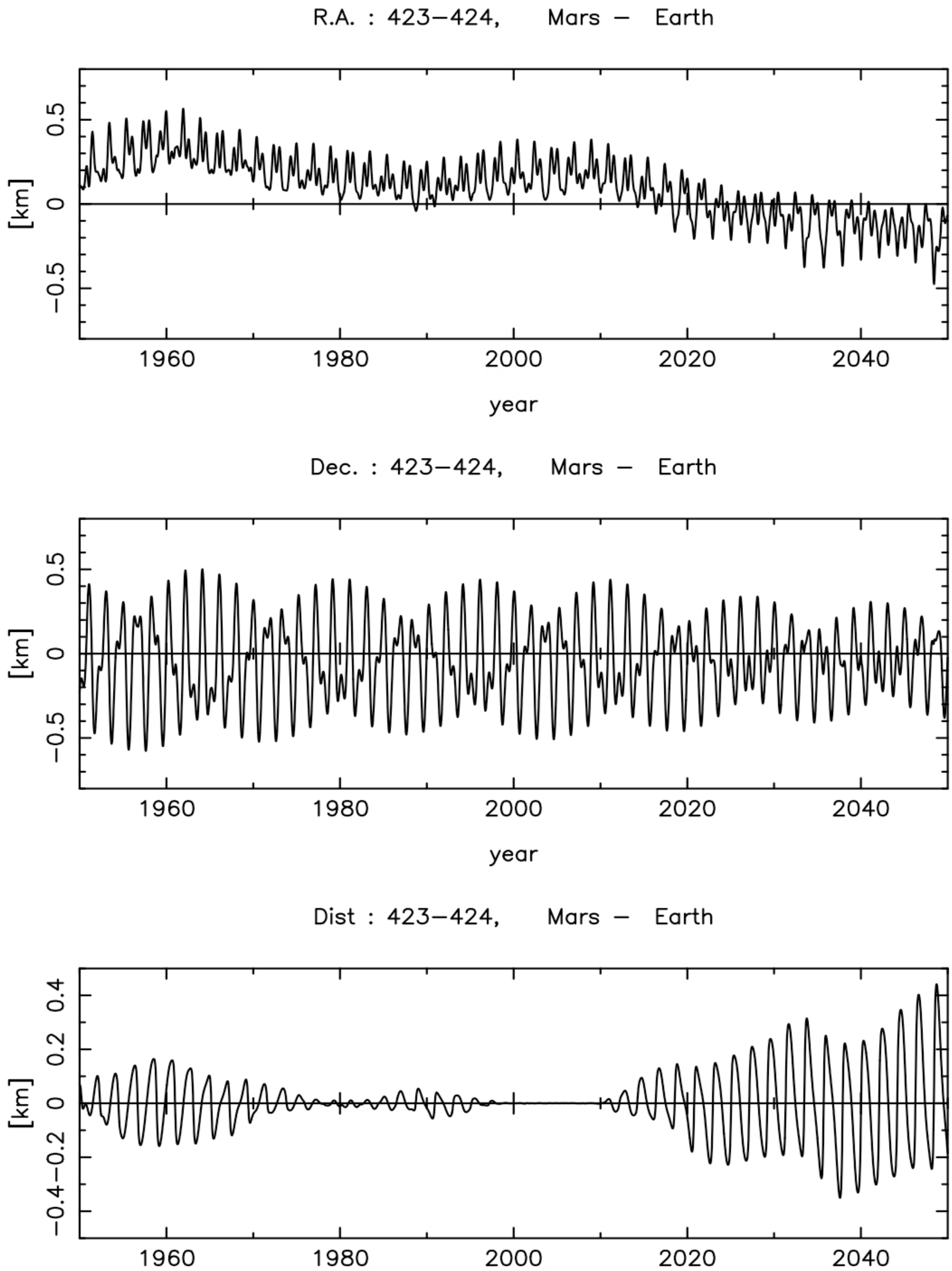

Figure 2: Difference in position of Mars relative to Earth from DE423 and DE423 in right ascension, declination, and range (distance).

4. Mars spacecraft range data

The orbit of Mars is significantly disturbed by the gravitational effects of asteroids whose mass parameters are mostly unknown. This results in an uncertainty in the distance from Earth to Mars which increases with time from the last range measurements to which the ephemeris has been fit. The difference in the range from Earth to Mars between DE423 and DE424, as shown in Figure 2 ,is very small over the 1997-2009 time span within which range data were available when DE423 was created, and increases as a roughly linear envelope thereafter. The period where ranging data from the Viking landers were made, 1976-1982, is also evident by a smaller difference in estimated Earth-Mar range between DE423 and DE424.

Figure 3 shows the residuals for range measurements to Viking and Mars Pathfinder landers for DE424. Figure 4 shows residuals for ranging measurements from spacecraft orbiting Mars; MGS, Odyssey, MRO, and Mars Express. These data allow the estimation of about 20 asteroid mass parameters with useful accuracy. However the number of asteroids with unknown mass parameters is sufficient to cause errors in prediction at about the level of difference seen between DE423 and DE424.

Range measurements to Mars spacecraft are expected to continue and will be incorporated into the next planetary ephemeris delivery.

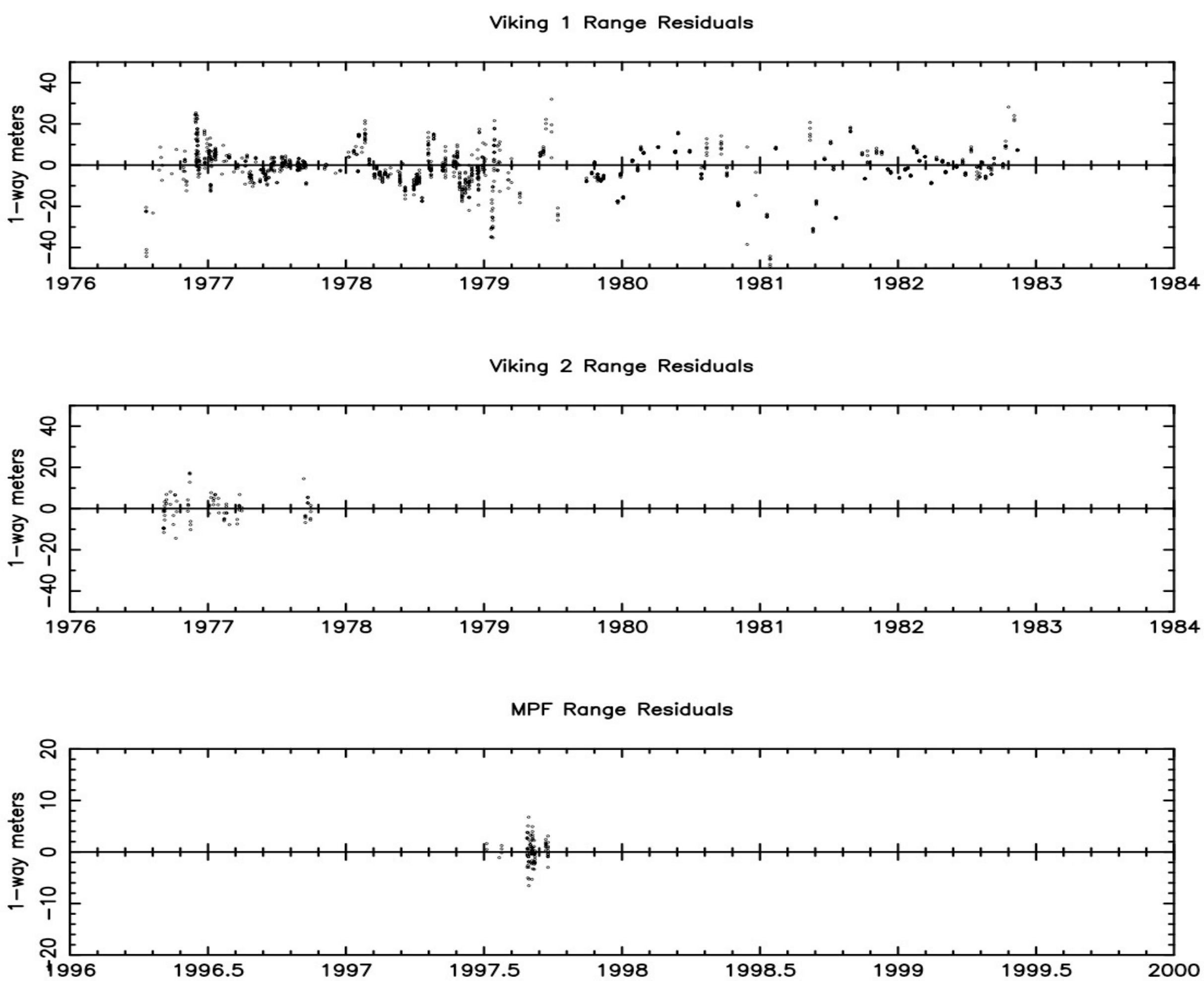

Figure 3: Range measurement residuals for Viking lander 1, Viking lander2, and Mars Pathfinder

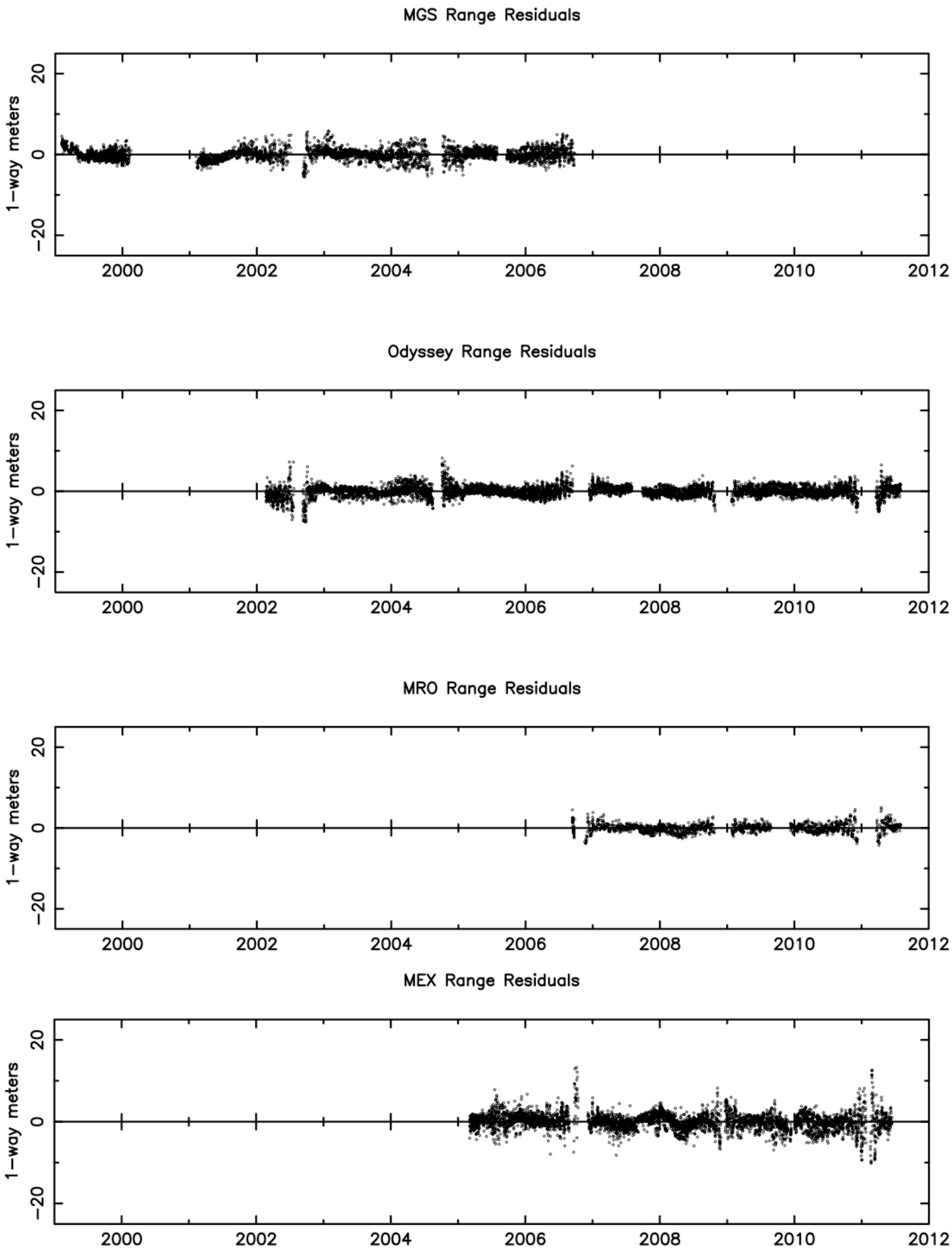

Figure 4: Range measurement residuals from Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter, and Mars Express

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Acknowledgements

The improvement in the planetary ephemeris relies on the continual improvement in data provided for the estimation. Jim Border of JPL provided the VLBI observations of the Mars spacecraft. Alex Konopliv of JPL provided range measurements of MGS, Odyssey, and MRO reduced to the center of Mars through estimation of the spacecraft orbits and Mars gravity field. Trevor Morley and colleagues at ESOC provided range measurements to Mars Express.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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