Use of Reference Frames for Interplanetary Navigation at JPL

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Abstract. Navigation of interplanetary spacecraft is typically based on range, Doppler, and differential interferometric measurements made by ground-based telescopes. Acquisition and interpretation of these observations requires accurate knowledge of the terrestrial reference frame and its orientation with respect to the celestial frame. Work is underway at JPL to reprocess historical VLBI and GPS data to improve realizations of the terrestrial and celestial frames. Improvements include minimal constraint alignment, improved tropospheric modeling, better orbit determination, and corrections for antenna phase center patterns.

Keywords. Reference Frames, Navigation, VLBI, GPS, ITRF, ICRF

1 Introduction

Interplanetary navigation is typically accomplished with some combination of range and Doppler measurements. Range to the spacecraft is determined from light travel time measurements. Range velocity information is provided by Doppler shift measurements of the spacecraft signal.

Delta-differential one-way range (DDOR) measurements provide complementary information about the remaining two angular dimensions. Spacecraft move against a background of extra-galactic radio sources. We measure differences in arrival time of a

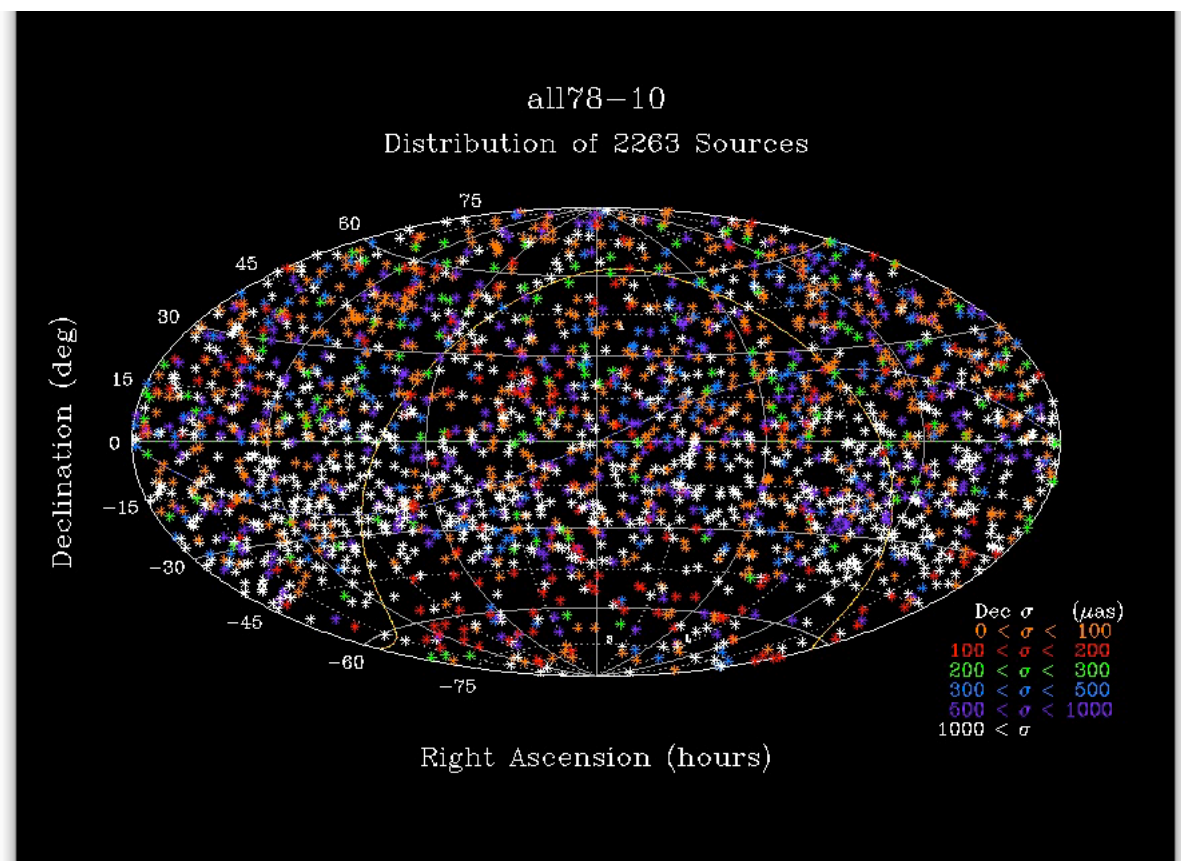

Figure 1. Updated VLBI celestial reference frame realization.

spacecraft signal at several ground antennas. We measure differences in arrival time of a radio source signal which is close to the spacecraft line of sight at the same antennas. These arrival time differences tell us the angle between the spacecraft and radio source on the sky. Knowledge of the radio source position then gives us precise celestial coordinates for the spacecraft.

2 VLBI Celestial Frame Analyses

An updated VLBI source catalog was derived from 5.7 million delay measurements and an equal number of delay rates. Data were collected by 71 ground stations in the S/X band between October 28, 1978 and August 24, 2010. The wrms of delay residuals is 34 picoseconds and the wrms of delay rate residuals is 100 femtoseconds/second.

Estimated parameters in the least squares fit included radio source positions, station locations, station clocks, wet tropospheric zenith delays, and tropospheric gradients. A no net rotation constraint was placed on the radio source positions relative to ICRF2 (Ma et al. 2009) using a subset of 295 defining sources. Kinematic station positions were estimated daily for each site relative to ITRF08 (Altamimi et al. 2011) a priori values and rates. Station clocks were estimated using a linear model reset about every six hours. Wet zenith tropospheric delays were estimated roughly once per hour based on the VMF1 mapping function. Tropospheric gradients were estimated about once per day relative to a priori values from the Steigenberger equation (N-S = -0.5*sin(2*lat) mm) with 100 mm level a priori sigmas. The COMB2009 earth orientation solution (Ratcliff and Gross 2010) was used to fix UTPM values. Precession and nutation models were from MHB2000 (Matthews, Herring, and Buffet 2002). Constant offsets for the PSIA and EPSA model parameters were estimated in order to avoid over constraint with respect to ICRF2.

The resulting celestial catalog contains 2263 radio source locations. Alignment with ICRF2 is achieved at the level of 0.2-1.7 μas. Agreement of source positions is at the 49-87 μas level. Celestial frame results are illustrated in Figure 1 and summarized in Table 1.

3 GPS Terrestrial Frame Analyses

An updated GPS station catalog was derived from 3.1 million station-days of data from 1015

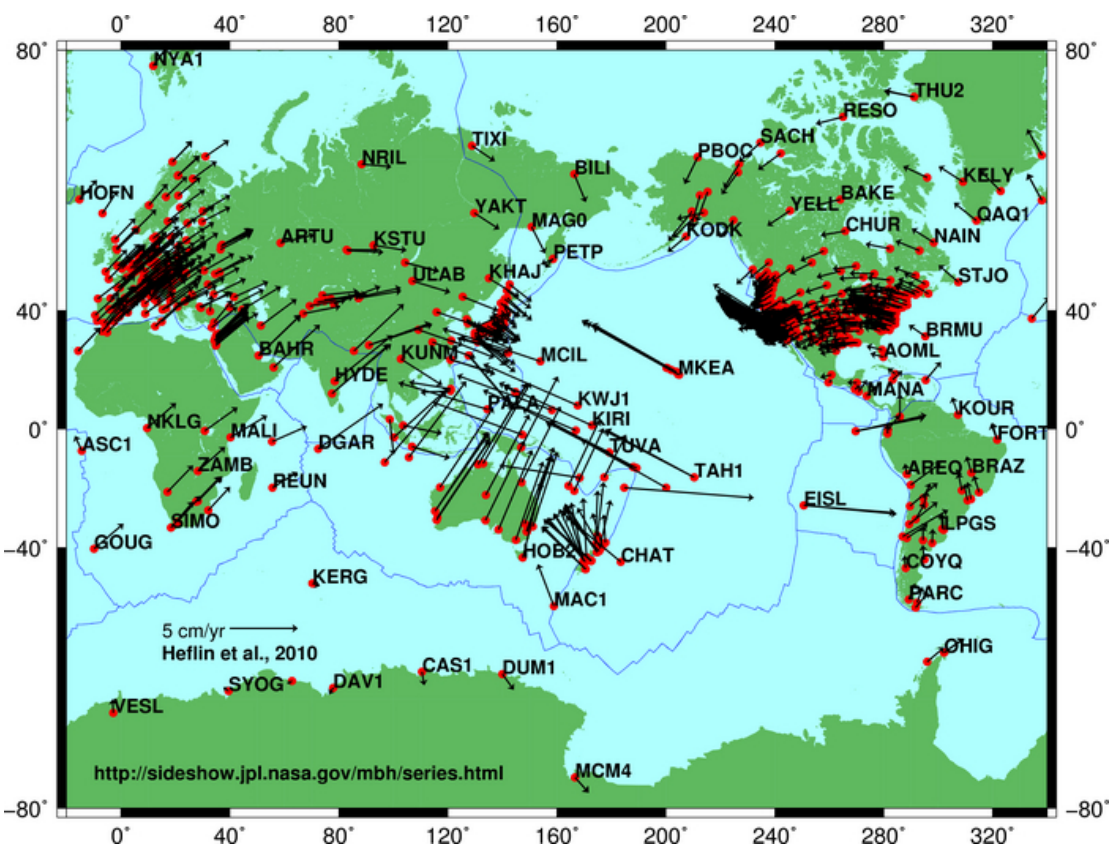

Figure 2. Updated GPS terrestrial reference frame realization.

sites. Daily GPS orbits and clocks were provided by separate reanalyses based on a network of 80 stations, 30-hour arcs, a 7-degree elevation cutoff, and standard IGS phase center maps. Seven daily transformation parameters for alignment with IGS05/ITRF2005 (Altamimi et al. 2007) were derived as part of the orbit analysis. These orbit products go back in time to January 7, 1996 so the time span of analysis starts there and ends on November 6, 2010.

Orbits, clocks, and transformation parameters were fixed to compute precise point positions (Zumberge et al. 1997) in the IGS05 terrestrial frame for each station-day based on 24 hours of phase and range data. Positions were estimated along with tropospheric zenith delays, tropospheric gradients, clocks, and unresolved phase ambiguity parameters. A segmented linear fit was computed for the position time series of each site. Mean repeatability after subtracting the fit from each time series is 2.4 mm N, 3.5 mm E, and 7.0 mm V. Position and velocity estimates for the last segment of data from each site were computed with an epoch of January 1, 2011.

The resulting terrestrial catalog contains 1015 sites. Alignment with IGS05 is achieved at the level of 0.1-2.2 mm and 0.07-0.20 mm/yr for all 14 frame parameters. Agreement of site positions is at the 2.9-4.4 mm level. Agreement of site velocities is at the 0.3-1.0 mm/yr level. Terrestrial frame results are illustrated in Figure 2 and summarized in Table 2.

4 Conclusions

Historical VLBI and GPS data have been reanalyzed. The updated celestial frame contains 2263 sources and agrees with ICRF2 defining coordinates at the 49-87 μas level. The updated terrestrial frame contains 1015 stations and agrees with IGS05 defining coordinates at the 2.9-4.4 mm level for positions and at the 0.3-1.0 mm/yr level for velocities.

5 Acknowledgements

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Parameter	Value	Sigma
Rx	0.2 μas	4.5 μas
Ry	1.7 μas	4.5 μas
Rz	1.2 μas	3.9 μas
Ra cos(dec) WRMS	49 μas	
Dec WRMS	87 μas	

Table 1. VLBI celestial frame alignment and residuals with respect to ICRF2

Parameter	Value	Sigma
Rx	1.3 mm	0.2 mm
Ry	0.9 mm	0.2 mm
Rz	0.1 mm	0.3 mm
Tx	0.2 mm	0.2 mm
Ty	0.5 mm	0.2 mm
Tz	2.2 mm	0.2 mm
Scale	0.6 mm	0.2 mm
N WRMS	2.9 mm	
E WRMS	3.1 mm	
V WRMS	4.4 mm	
Rx Rate	0.19 mm/yr	0.03 mm/yr
Ry Rate	0.20 mm/yr	0.03 mm/yr
Rz Rate	0.11 mm/yr	0.03 mm/yr
Tx Rate	-0.12 mm/yr	0.02 mm/yr
Ty Rate	0.07 mm/yr	0.02 mm/yr
Tz Rate	0.10 mm/yr	0.02 mm/yr
Scale Rate	0.19 mm/yr	0.03 mm/yr
N Rate WRMS	0.4 mm/yr	
E Rate WRMS	0.3 mm/yr	
V Rate WRMS	1.0 mm/yr	

Table 2. GPS terrestrial frame alignment and residuals with respect to IGS05.

References

Altamimi, Z., X. Collileux, and L. Metivier (2011). ITRF2008: an improved solution of the international yerrestrial reference frame. Journal of Geodesy, doi:10.1007/s00190-011-0444-4.

Altamimi, Z., X. Collileux, J. Legrand, B. Garayt, and C. Boucher (2007). ITRF2005: A new release of the International Terrestrial Reference Frame based on the time series of station positions and Earth Orientation Parameters. Journal of Geophysical Research, VOL. 112, B09401, doi:10.1029/2007JB004949.

Ma, C., et al. (2009), editors: A.L. Fey, D. Gordon & C.S. Jacobs. The 2nd Realization of the ICRF by VLBI. IERS Tech Note 35: IERS, Frankfurt, Germany.

Matthews, P. M., T. A. Herring, and B. A. Buffet (2002). Modeling of Nutation and Precession: New nutation series for Nonrigid Earth and Insights into the Earth's Interior. JGR, 107, B4, 10.1029/2001JB000390.

Ratcliff, J.T., and R.S. Gross, (2010). Combinations of Earth Orientation Measurements: Space 2009, COMB2009, and POLE 2009. JPL Publication 10-22, Pasadena CA.

J. Zumberge, M. Heflin, D. Jefferson, M. Watkins, and F. Webb (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. J. Geophys. Res., 102, B3, doi:10.1029/96JB03860.