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DETERMINATION OF RADIO-FRAME POSITION FOR EARTH AND JUPITER FROM ULYSSES ENCOUNTER TRACKING

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Radio metric tracking data acquired from the Ulysses spacecraft about its encounter with Jupiter in February 1992 allow an accurate measurement of some components of the orbital elements describing the positions of the Earth and Jupiter with respect to extragalactic radio sources. Range and Doppler data acquired from the Earth while the spacecraft is far from any planet provide an estimate of the spacecraft trajectory relative to the orbit of the Earth. Doppler data near Jupiter provide an accurate position determination of the spacecraft with respect to Jupiter. Very Long Baseline Interferometry observations of the spacecraft with respect to the distant radio sources provide a direct measure of the spacecraft position in the radio reference frame. Combining these measurements provides a means to estimate the locations of the Earth and Jupiter in the radio reference frame. One of the three Euler angles describing the orientation of the Earth's orbit in the radio frame has been determined to an accuracy of 50 nanoradians; the result agrees with other recent determinations of this orientation. The position of Jupiter at the time of Ulysses encounter has been determined to 15 nanoradians in ecliptic latitude and longitude.

INTRODUCTION

Navigation for interplanetary spacecraft is based on measurements of the radio signal from the spacecraft to antennas on Earth. From these data, the trajectory of the spacecraft and its position at encounter with the target plaint are inferred. The accuracy of the prediction of planetary arrival depends largely upon a priori knowledge of the location of the target planet in the inertial reference frame used to reduce the radio metric data. At the time of planetary encounter a large signature on the spacecraft radio signal is imposed by the gravitational field of the planet from which yields an accurate position of the spacecraft with respect to the target planet. The encounter data can be used to improve the accuracy of the planetary ephemeris and reduce approach navigation uncertainty for future missions.

The Ulysses mission is a cooperative project of NASA and the European Space Agency. The Ulysses spacecraft is a science probe designed to measure charged and neutral particles, magnetic fields, electromagnetic waves, and ultraviolet and X-ray

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emissions at high solar latitudes. To achieve an orbit highly inclined to the ecliptic plane, Ulysses made a close approach to Jupiter in February, 1992.

Two-way range and two-way Doppler measurements were made between Ulysses and tracking stations from NASA's Deep Space. Network (I EN) to enable. orbit determination to support mission operations, On a short time scale. (a few days), range and Doppler observations of a spacecraft have signatures due to the rotation of the Earth, allowing determination of the (geocentric) right ascension and declination of the spacecraft. Range observations also have. a signature due to the motion of the Earth and the spacecraft about the sun.

In addition, measurements of Ulysses were made using a Very-Long Baseline Interferometry (VLBI) technique, referred to as delta-differential one-way range (ΔDOR), which measured the angular separation of the spacecraft relative to a reference extragalactic radio source. (quasar).[1] The ΔDOR measurements were made to improve. the orbit determination of Ulysses and allow for an improved ephemeris determination of Jupiter that could be used by the. Galileo spacecraft, which will encounter Jupiter in December, 1995.

The combination of these. measurements allowed an estimate of the orientation of the Earth's orbit and the position of Jupiter with respect to the radio reference frame.. The definition of the radio reference frame, and its relation to other possible celestial frames, is given below, followed by a discussion of the solution technique and results for the planetary position estimates.

REFERENCE FRAME DEFINITIONS

Celestial reference frames have been defined historically by the mean direction of the Earth's pole at a reference. epoch and by the intersection of the. mean equator and man ecliptic at that epoch. The mean pole of epoch differs from the actual pole of epoch by the removal of model for the. periodic. motion of the. pole.[2] This definition has sufficed for optical astrometry, with typical measurement accuracies of ~0.1 seconds of arc (500 nrad) since models of the motion of the Earth's pole direction are accurate at that level. Beginning in 1980 measurements of the Earth's pole direction have been made with accuracy of ~5 nrad by VLBI and by lunar laser ranging. The model of the motion of the Earth's pole direction has been found to be in error by ~100 nrad for periods of time greater than ~10 yr. Thus it is not possible to define a reference frame based on the Earth's mean equator of 2000 (or 1950) with an accuracy comparable to current measurement accuracy.

Since VLBI can be used to measure relative positions of extragalactic radio sources to better than 5 nrad and because the orientation of the Earth can be monitored with respect to the radio sources with comparable accuracy, the International Earth Rotation Service. (IERS) has defined a reference frame in terms of adopted positions for a number of well-observed radio sources.[3] The reference axes of the IERS radio frame are nominally aligned with the Earth's mean pole and equinox of the year 2000 based on measurements of radio source occultation by the moon.[4]

Lunar laser ranging data are. sensitive to the Earth's mean equator and orbit of date; this sensitivity is used to define the orientation of recent JPL planetary ephemerides. With respect to the. mean equator and mean orbit of 1990, the position of the Earth is known to ~15 nrad.[5] However, delivered ephemerides are referred to the Earth mean equator and orbit of the year 2000 based on various models for the. motion of the Earth's pole. direction.[6] Since a different model for the motion of the Earth's pole direction is generally used for each ephemeris, the reference frame of the ephemeris varies at the 100 nrad level.

Aside from a choice of reference frame, the orbit of the Earth about the sun is consistent between various ephemerides at the 5 nrad level, The position of Mars relative to Earth is known at a similar level due to accurate ranging data to the Viking landers from 1976 to 1981. The positions of the. Mercury and Venus relative to Earth are known to -4(I nrad and the outer planets to ~250 nrad.[5] Thus comparing the orbit of the Earth (or Mars) between two ephemerides is the. best means of comparing the relative orientation of the reference frames.

'J'he rotation from one celestial frame to another can be expressed in terms of a rotation vector $\vec{A}$ with components AX, A_y, A_z about the celestial x, y, and z axes. The z axis is nominally aligned with the Earth's mean pole of 20(K) and the x axis is nominally aligned with the equinox of 2.()(K). For small rotations, a vector . in the initial system can be expressed in the rotated system by the vector $\vec{C}'$, where

$$\vec{C}' = \vec{C} - \vec{A} \times \vec{C}$$

The rotation parameters describing the relative orientation of the JPL planetary ephemeris DE200 (based on the orbit of the Earth) relative to the IERS radio frame have been determined previously to an accuracy of 25 nrad.[7] The Ulysses data set has the. potential to confirm and possibly improve on this relative orientation knowledge. The solutions of the Ulysses tracking data below are. done with a more recent planetary ephemeris labeled DE234.[8] The rotation from DE234 to DE200 has been determined by comparison of the Earth's orbit for the two ephemerides in 1990. The a priori rotation for each ephemeris to the IERS radio frame is given in Table 1.

Table 1: A PRIORI **FRAME TIE ROTATION FROM PLANETARY EPHEMERIS 10 IERS RADIO FRAME**

Component	DE200	DE234
AX	s nrad	7 nrad
A_y	-49 nrad	34 nrad
A_z	-19 nrad	-210 nrad

SOLUTION METHOD

The Ulysses spacecraft is spin stabilized and communicates through a high gain antenna with its boresight on the spin axis, The primary spacecraft radio system is an S-band (2.3 GHZ) uplink and X-band (8.4 GHz) downlink, which is used for Doppler and range measurements, as well as for scientific and engineering telemetry. VLBI data can also be derived from the X-band signal when properly configured. Like most spinning spacecraft, Ulysses has a relatively low level of non-gravitational accelerations acting on the. spacecraft (primarily from solar pressure, which is low at Jupiter).

The orbit determination process used to derive the reference trajectory is similar to the process used in the Jupiter approach phase, described by McElrath et al.[9] The data employed for the. reference solution spanned 90 days centered about the time of closest approach to Jupiter. Range and Doppler data were acquired almost continuously throughout the data arc from stations at DSN complexes in California, Australia, and Spain. The post-fit two-way range residuals have an rms value of 2 m. The post-fit Doppler residuals have an rms of 0.3 mm/s for 60 s averaging time. ADOR measurements were made using either the California-Australia or the California-Spain baseline, with an average measurement interval of 3 days. The post-fit ADOR residuals had an rms of 29 cm. The angular positioning accuracy of the ADOR data is the differential range accuracy divided by the length of the observation baseline projected onto the plane of the sky (the plane normal to the Earth-spacecraft direction). For DSN baselines the average projected baseline length is ~8000 km so that 30 cm ADOR accuracy corresponds to an angular accuracy of ~40 nrad. For the reference solution, the range and Doppler data were weighted at 10 m and 1.0 mm/s respectively; these weights were looser than the post fit residuals to allow for systematic errors which could be absorbed by estimated parameters. The ADOR data accuracy was variable depending on the spacecraft transmitting mode so each ADOR point was weighted individually.[10] The average ADOR weight was 45 cm,

The spacecraft trajectory was integrated from initial position and velocity conditions (epoch state) using models for the dynamic forces on the spacecraft. The modeled gravitational forces on the spacecraft were due to the masses of the Sun, Jupiter, the Galilean satellites, and the oblateness of Jupiter, The relative locations of the Sun and planets were based on the JPL ephemeris labeled DE234.[8] The position of the Galilean satellites were given by Lieske.[11] The masses of the Jovian system and the oblateness Of Jupiter are given by Campbell and Synnott.[12] other forces modeled were solar radiation pressure and attitude control maneuvers, which occurred about every three days with a resulting velocity change almost entirely in the Earth-spacecraft direction.

Radio source positions were adopted from the latest realization of the IERS radio frame.[13] The initial planetary ephemeris DE234 was rotated to agree with IERS radio frame based on the rotation given in Table 1. Locations for the stations of the DSN were consistent With the IERS terrestrial reference frame.[14] The station locations were mapped from Earth-fixed locations to inertial space using models for precession, nutation, solid Earth tides, and calibrations for polar motion and length of day variations and corrections to the standard nutation model.[14] Computed values for measurements were derived from nominal values for the spacecraft epoch state, force models, and inertial Deep Space Station locations, and calibration for propagation delays due to Earth ionosphere and troposphere.[15,16] A least-squares fit to the observed minus computed measurements was made to estimate model parameters.

The estimated parameters included the spacecraft epoch state, corrections of the orbital elements of Earth and Jupiter, a constant scaling parameter for the solar radiation pressure model, and the magnitudes of the velocity impulses caused by attitude control maneuvers. Time variation in the solar radiation pressure was estimated as a Markov process with a 30 day time constant, The spacecraft spin rate, detectable in the Doppler data, was estimated as a Markov process with a 15 day time constant. Finally a range calibration bias was estimated for each tracking pass.

The estimated uncertainty for the spacecraft trajectory depended on assumed a priori uncertainties for the estimated parameters, the data arc and data weights assumed, and on a priori uncertainties for model parameters that are not estimated. The effect of uncertainties of non-estimated model parameters is included through the use of consider analysis.[17] The assumed a priori information for estimated and consider parameters is summarized in Table 2. The a priori uncertainties for spacecraft initial state were large enough to leave it essentially unconstrained, Similarly, the attitude maneuver uncertainties were large compared to their estimated uncertainties. The spacecraft solar pressure model was assumed to be correct to 20% with additional time variation at the 10% level. The initial mass uncertainty of Jupiter was given by Campbell and Synnott[12]. A covariance for the station locations was included based on knowledge of relative positions of the stations at the 2 cm level, knowledge of the geocenter at the 10 cm level, and orientation of the Earth in the ICRF91 celestial system at the 10 nrad level.[18] Uncertainties in the calibrations for the ionosphere. were taken from Royden.[19] The uncertainty in the troposphere calibration is taken from Robinson.[20] The quasar positions within the ICRF91 reference frame were assumed to have right ascension and declination uncertainties of 5 nrad. The uncertainty in the orientation of the orbit of the Earth with respect to the radio frame was set to 25 nrad.[7] The uncertainties for the remaining three orbital elements of the Earth and the uncertainties for the. orbital elements of Jupiter were taken from Standish and Williams.[8]

Table 2: A PRIORI UNCERTAINTIES FOR MODEL PARAMETERS

Estimated Parameters	Uncertainty
Spacecraft initial position	10^5 km
Spacecraft initial velocity	100 km/sec
Solar radiation pressure scaling factor	20% constant 10% variable 30 day correlation time.
Attitude maneuver velocity impulses	10 cm/sec
Jupiter ephemeris uncertainty	
Orbit orientation (3 Euler angles)	250 nrad
Longitude with respect to periapsis	250 nrad
Semi major axis (As/a)	3 parts in 10^8
Eccentricity (Δe/e)	3 parts in 10^8
Earth ephemeris uncertainty	
Orbit orientation (3 Euler angles)	25 nrad
Longitude with respect to periapsis	10 nrad
Semi major axis (As/a)	5 parts in 10^{11}
Eccentricity (Δe/e)	3 parts in 10^{10}
Range biases	10 m
Spacecraft spin rate	0.01 rpm 15 day correlation time
Consider Parameters	
DSN station locations (27 x 27 covariance)	10 cm radial 10 cm Z-height 10 cm longitude
Ionosphere zenith delay	75 cm daytime (S-band) 15 cm nighttime (S-band)
Troposphere zenith delay	4 cm
Quasar location	5 nrad right ascension 5 nrad declination

RESULTS

For determination of the relative orientation of the orbit of the Earth with respect to the IERS radio frame, the a priori uncertainties of the angles describing the orientation were set to 1000 nrad. The estimated orientation of the Earth was found to be best determined in the direction about the ecliptic pole. The estimated rotation vector and its uncertainty, relative to the a priori value. given in Table 1, is given in Table 3, with components Ax about the direction to the equinox, A_ξ about the. ecliptic pole, and A_η about the direction orthogonal to the equinox and the ecliptic pole. For this data arc the estimate of the orientation of the Earth's orbit about the ecliptic pole is consistent with the a priori value to 1 σ. In the other two directions the frame tie estimate uncertainties from the Ulysses data arc are much larger than the a priori uncertainties.

Table 3: FRAME TIE ESTIMATE RELATIVE TO A PRIORI

Component	Estimated
A_x	70 ± 800 nrad
A_η	1003.300 nrad
A_ξ (about ecliptic pole)	48 ± 48 nrad

corrections to the. orbital elements of Jupiter were estimated with the a priori uncertainties for the Jupiter and Earth ephemerides as given in Table 2. Table 4 gives the a priori and estimated position of Jupiter at the. time of Ulysses encounter in heliocentric spherical coordinates. Fig. 1 shows the estimated position correction (and uncertainty) for Jupiter in ecliptic latitude and longitude. The Jupiter angular position uncertainty at the time. of Ulysses encounter is about 15 nrad due mainly to the accuracy of the ADOR data.

Table 4: A PRIORI AND ESTIMATED HELIOCENTRIC POSITION OF JUPITER
IN THE IERS RADIO FRAME ON FEBRUARY 8,199212:001 DB

Component	A priori	Estimated
radial (km)	807482639,6 ± 3.4	807482639.8 ± 0.4
latitude (deg)	9.5313305 ± 0,0000145	9.5313262 ± 0.0000010
longitude (deg)	160.2317911 ± 0.0000145	160,2317937 ± 0.0000008

The position uncertainty of Jupiter increases with time from Ulysses encounter since the angular velocity is not well determined by the brief encounter. Fig. 2 shows the expected position correction and uncertainty for Jupiter at the time of Galileo encounter in December 1995. The position uncertainty in ecliptic longitude has been reduced markedly by the inclusion of the Ulysses tracking data. The uncertainty in ecliptic latitude has not been significantly improved, The estimated position adjustment disagrees with the a priori position to well over one sigma in latitude. It may be that the a priori position uncertainty of Jupiter assumed was optimistic. Since the Jupiter ephemeris is highly dependent on optical transit measurements it is susceptible. to systematic errors in the star catalog. The systematic errors in the star catalogs have been assumed to be 250 nrad (0.05 arcsecond) but may be larger. There is potential to resolve this discrepancy through the use of the Hipparcos star catalog, which should have systematic errors less than 10 nrad. Alternatively, a re-analysis of other spacecraft encounters with Jupiter or VLBI measurements of the satellites of Jupiter may help to resolve the discrepancy in latitude.

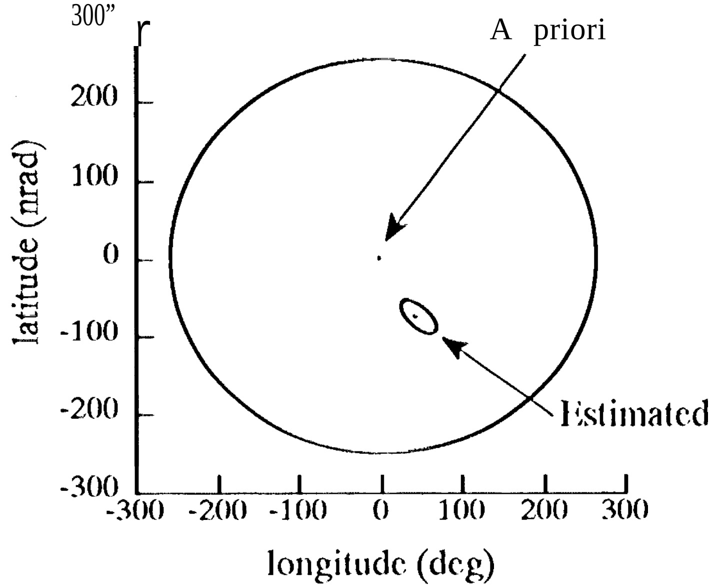

Figure 1. Heliocentric position correction **for Jupiter in February 1992.**

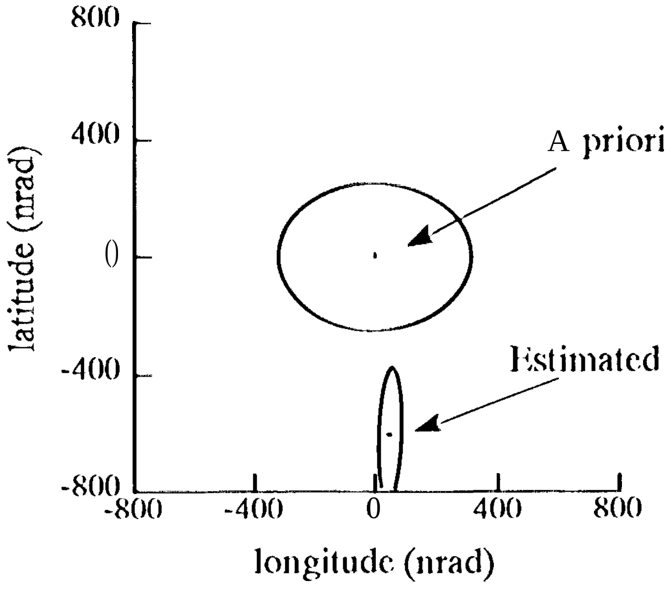

Figure 2. Heliocentric position correction for Jupiter in December 1995.

DISCUSSION

The analysis of radio metric tracking data acquired from the. Ulysses spacecraft near its encounter with Jupiter has provided estimates for the position of the Earth and Jupiter with respect to the celestial reference frame. defined by extragalactic radio sources. The orientation of the orbit of the Earth has been estimated independently from any a priori information with an accuracy of 50 nrad about the ecliptic pole and is in agreement with previous estimates. The orientation of the. Earth's orbit about the other two orthogonal directions is more poorly determined. It may be that analysis of a more extended data arc can provide better orientation information. The position of Jupiter has been estimate.d to an accuracy of 15 nrad at the time of Ulysses' encounter. This position estimate is far superior to the previous position uncertainty of 25(I nrad. The estimated position of Jupiter projected forward to December 1995 has uncertainty in ecliptic longitude reduced by a factor of four over the a priori uncertainty. "1'here is a slight discrepancy in ecliptic latitude that may be resolved by examination of other data.

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REFERENCES

1. J. S. Border et al., "Determining Spacecraft Angular Position with Delta VLBI: The Voyager Demonstration", paper AIAA-82-1471 presented at the AIAA/AAS Astrodynamics Conference, San Diego, California, August 9-11, 1982.
2. P. K. Seidelmann, "1980 IAU Theory of Nutation: The Final Report of the IAU Working Group on Nutation", Celestial Mechanics Vol. 27, pp. 79-106, 1982.
3. E. F. Arias, M. Feissel, and J.-F. Lestrade, 1988; "An Extragalactic Celestial Reference Frame Consistent with the 13111 Terrestrial System", BIH Annual Report for 1987, 1)-113.
4. C. Hazard et al., 1971; "Accurate. Radio and optics] Positions of 3C273b", Natural Physical Science, 233, pp. 89-91.
5. E. M. Standish Jr. and J. G. Williams; 1990. "Dynamical Reference Frames in the Planetary and Earth-Moon Systems", in *Inertial Coordinate Systems on the Sky,* J. 11. Lieske and V. K. Abalakin eds., Kluwer Academic, Dordrecht, pp. 173-181.
6. E. M. Standish Jr., 1982; Orientation of the JPL Ephemerides DE200/LE200 to the Dynamical Equinox of J2000, Astron. Astrophys, Vo. 114, pp. 297-302.
7. M. H. Finger and W. M. Folkner, "A Determination of the. Radio-Planetary Frame Tie from Comparison of Earth Orientation Parameters", TDA Progress Report 42-109, Vol. January-March 1992, pp.]-2.1, May 15, 1992.

8. E. M. Standish, "The J] 'l. Planetary and Lunar Ephemerides DE234/LE234", JPL IOM 314.6-1348, October 8, 1991 (internal document).

9. T. McElrath, B. Tucker, P. Menon, E. Higa, and K. Criddle, "Ulysses Navigation at Jupiter Encounter", paper AIAA 92-4524 presented at the AIAA/AAS Astrodynamics Conference, Hilton head, South Carolina, August 10-12, 1992.

10. A. J. Mannucci, "Very Long Baseline Interferometry Tracking Support For Ulysses Navigation", 'IDA Progress Reports (in preparation),

11. J. H. Lieske, "Improved Ephemerides of the Galilean Satellites", Astron. Astrophys. vol. 82, pp. 340-348, 1980.

12. J. K. Campbell and S. P. Synnott, "Gravity Field of the Jovian System from Pioneer and Voyager 'l'racking Data", Astron. J. Vol. 90, pp. 364-372, 1985.

13. International Earth Rotation Service, Annual Report for 1991, Observatoire de Paris, Paris, Prance, July 1992.

14. J. A. Steppe, O. J. Sovers, and S. H. Oliveau, "Smoothed Standard-Coordinate Earth Rotation from Deep Space Network VLBI", in *IERS Technical* Note 11: *Earth Orientation, Reference Frames and Atmospheric Excitation Functions Submitted for the 1991 IERS Annual Report, P.* Charlot ed., Observatoire de Paris, Paris, France, June 1992.

15. C. C. Chao, "The Troposphere Glib ibration Model for Mariner Mars 1971", JPL "1'ethnic.al Report 32-1587, pp. 61-76, Jet Propulsion Laboratory, March, 1974.

16. H. N. Royden, D. W. Green, and G. R. Walson, "Use of Faraday-Rotation Data from Beacon Satellites to Determine Ionospheric Corrections for Interplanetary Spacecraft Navigation", Proc. Satellite Beacon Symposium, Warsaw, Poland, May 1980.

17. G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation,* Academic Press, 1977.

18. W, M. Folkner, "DE234 Station Locations and Covariance for Mars Observer", JPL IOM 335.1-013, May 26, 1992 (internal document).

19. H. N. Royden, "Ionospheric Error Model in the. Orbit Determination Program", JPL IOM 335.5-87-52, March 30, 1987 (internal document).

20. S. E. Robinson, "Errors in Surface Mode] Estimates of Zenith Wet Path Delays Near DSN Stations", J]']. IOM 335.4 -S94, September 3, 1986 (internal document).