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Determination of the Position of Jupiter From Radio Metric Tracking of Voyager 1

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The Voyager 1 spacecraft flew by Jupiter on March 5, 1979. Spacecraft navigation was performed with radio tracking data from NASA's Deep Space Network. In the years since then, there has been a great deal of progress in the definition of celestial reference frames and in determining the orbit and orientation of the Earth. Using these improvements, the radio metric range and Doppler data acquired from the Voyager 1 spacecraft near its encounter with Jupiter have been reanalyzed to determine the plane-of-sky position of Jupiter with much greater accuracy than was possible at the time of the encounter. The position of Jupiter at the time of encounter has been determined with an accuracy of 40 nrad in right ascension and 140 nrad in declination with respect to the celestial reference frame defined by the International Earth Rotation Service. This position estimate has been done to improve the ephemeris of Jupiter prior to the upcoming encounter of the Galileo spacecraft with Jupiter.

I. Introduction

Radio metric tracking data have been used since the inception of interplanetary space exploration to determine the trajectory of the robotic probes. Several analyses have been written that describe the ability of radio metric data to determine the position of interplanetary spacecraft [1–3]. The ability to determine the plane-of-sky position of spacecraft comes from the signature imposed on the spacecraft radio signal by the rotation and orbital motion of the Earth. This signature can be analyzed to determine the right ascension and declination of the spacecraft. There is also a signature in the spacecraft radio signal due to the acceleration caused by a nearby planetary body, which can be used to determine the position of the spacecraft with respect to the planetary body. The combined signatures can be used to determine the position of the planet at the time of the spacecraft encounter.

The diurnal signature in the radio metric data gives information about the spacecraft right ascension and declination with respect to the direction of the Earth's spin axis at the time of the measurement. The direction of the Earth's spin axis and the orbit of the Earth with respect to a desired inertial celestial coordinate system must be known in order to use the radio metric data to deduce the inertial coordinates of the spacecraft.

The determination of the orbit and orientation of the Earth has been a field of intensive study. The introduction of routine very long baseline interferometry (VLBI) observations in the early 1980's has enabled the definition of a celestial reference frame, defined by the positions of extragalactic radio sources, with internal consistency of about 5 nrad (e.g., see [4]). This is about a factor of 100 better than optical star catalogs previously used to define the celestial reference frame (e.g., see [5]). The orientation of the Earth is measured by VLBI with an accuracy of about 5 nrad with respect to the extragalactic radio sources. Beginning in 1988, the International Earth Rotation Service (IERS) was formed to facilitate reporting Earth orientation in a standard way. The IERS adopted a conventional celestial reference frame defined by the positions of extragalactic radio sources. Earth orientation measurements with respect to the IERS celestial reference frame are regularly distributed [6]. Since about 1970, the orbits of the Earth, Moon, and Mars have been determined with an internal accuracy of about 5 nrad from the analysis of ranging data to the Viking landers and lunar laser ranging (LLR) [7]. The LLR data can also be used to determine the orientation of the Earth with respect to the Earth's orbit. Comparison of LLR and VLBI Earth orientation has been used to determine the orientation of the Earth's orbit with respect to the IERS celestial reference frame with an accuracy of about 15 nrad [8].

The ephemerides of the outer planets have been heavily dependent on optical astrometric measurements due to a scarcity of more accurate measurements. The limited accuracy of the ground-based optical astrometric data, and the uncertainty in orientation of the optical reference frame with respect to the radio reference frame, contributed to an apparent discrepancy in the position of Jupiter of 400 km during the Ulysses spacecraft Jupiter encounter in February 1992 [9]. This discrepancy and the upcoming encounter of the Galileo spacecraft with Jupiter in December 1995 prompted a reanalysis of radio tracking data from the Voyager 1 encounter with Jupiter to provide a radio metric position of Jupiter referred to the IERS celestial reference frame.

The closest approach of the Voyager 1 spacecraft to Jupiter occurred on March 5, 1979. Shortly after the closest approach to Jupiter, the spacecraft flew within 21,000 km of Io and then within 150,000 km of Ganymede and Callisto. Navigation of Voyager 1 was performed using radio range and Doppler measurements by the Deep Space Network and by using images of the satellites of Jupiter against background stars taken by the onboard camera [10,11]. The Voyager 1 navigation provided a determination of the Earth–Jupiter range at the time of encounter[1] and data for the improvement of the ephemerides of the satellites of Jupiter [12]. However, the large uncertainty of the orientation of the Earth with respect to the Earth's orbit at that time prevented a useful improvement in the plane-of-sky position of Jupiter. A reanalysis of the Voyager 1 radio tracking data, based on the previous work of the Voyager 1 navigation team and with updated models for the orbit and orientation of the Earth, has been performed to determine the right ascension and declination of Jupiter at the time of the Voyager 1 encounter.

II. Method

Two-way Voyager 1 tracking data were acquired by an antenna from the Deep Space Network transmitting a signal to the spacecraft at a frequency near 2.1 GHz (S-band) with the spacecraft receiving and coherently retransmitting the signal to Earth at 2.3 GHz or 8.4 GHz (X-band). The data employed for the reanalysis spanned 32 days, ending a few hours after the closest approach to Jupiter and before the encounter with Io. Doppler measurements were made by comparing the frequency of the received carrier with the transmitted carrier at the DSN antenna. Range measurements were made by determining the delay between the time of transmission of a range code (a set of coherent tones about the carrier) and the time of reception of the retransmitted range code. The dominant noise on the measurements was due to variations in the charged particle distribution between Earth and the spacecraft, mostly due to solar plasma. For much of the time, Voyager 1 transmitted coherent signals at both 2.3 and 8.4 GHz. For the reanalysis, only dual-band downlink data were used. Because the charged particle effects are proportional

[1] J. K. Campbell, "Earth–Jupiter Range Fixes From Voyager," JPL Interoffice Memorandum 314.8-351 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1982.

to the inverse of the square of the carrier frequency, the dual-band downlink provides a measure of the charged particle effects on the downlink signal. By interpolating the charged particle effects to the time of the uplink, it was possible to remove most of the effect on the tracking data. At the beginning of a tracking pass, there are no dual-band downlink measurements near the time of the uplink signal, so larger residuals are expected for the first 75 minutes (one round-trip light time) of each tracking pass.

The spacecraft trajectory was integrated from initial position and velocity conditions using models for the dynamic forces on the spacecraft. The modeled gravitational forces on the spacecraft were due to the masses of the Sun and planets, the Galilean satellites, and the oblateness of Jupiter. The relative locations of the Sun and planets were based on the JPL ephemeris labeled DE200 [13] but rotated so that the orbit of the Earth had the correct orientation with respect to the IERS celestial reference frame at the time of encounter [8]. The positions of the Galilean satellites were given by Lieske [12]. The masses of the Jovian system and the oblateness of Jupiter are given by Campbell and Synnott [11]. Other modeled forces were solar radiation pressure and thruster firings.

The Voyager 1 spacecraft is three-axis stabilized using unbalanced thrusters. Because of torques acting on the spacecraft (mainly due to solar pressure), the thrusters repeatedly fire to maintain a specified orientation. These thruster firings produce small velocity changes to the spacecraft trajectory. Changes in the orientation of the spacecraft caused a change in the torque on the spacecraft and a change in the pattern of the thruster firings. Information about the thruster firings was encoded in the spacecraft telemetry stream, but this information was imperfect. Instead of relying on the incomplete telemetry information, the magnitudes of the thruster firings were estimated using two models. Constant accelerations were estimated while the spacecraft was in a fixed attitude, to approximate the nearly constant thruster firings needed to maintain the attitude. Impulsive maneuvers were estimated for larger events associated with changes in the spacecraft orientation. In addition, there was one larger impulsive maneuver 12.5 days before Jupiter encounter to correct the spacecraft trajectory. Table 1 gives the acceleration and maneuver times included in the reanalysis. Some information about the history of the spacecraft orientation is no longer available, so some of the events in Table 1 were inferred from an examination of the tracking data. In principle, the only consequence of estimating too many maneuvers and accelerations is to weaken the solution.

Table 1. Modeled thruster firing times.

Maneuver time, 1979	Acceleration start time, 1979
February 4, 00:00	February 1, 00:00
February 5, 12:00	February 4, 08:30
February 9, 04:02	February 5, 12:00
February 17, 00:00	February 9, 04:00
February 18, 18:00	February 11, 02:00
February 19, 00:00	February 15, 00:00
February 21, 03:58	February 17, 15:00
March 1, 23:00	February 19, 05:00
March 3, 20:00	February 21, 18:00
	March 4, 00:00

Computed values for the tracking measurements were derived from nominal values for the spacecraft epoch state, force models, inertial Deep Space Station locations, and calibration for propagation delays due to Earth troposphere [14]. A least-squares fit to the observed minus computed measurement values was made to estimate model parameters. The estimated parameters included the spacecraft initial state, the position of Jupiter, the direction of Jupiter's spin axis, a range bias for each DSN antenna, and parameters to describe the thruster firings. Locations for the stations of the DSN were consistent with the IERS terrestrial reference frame [15]. The station locations were mapped from Earth-fixed locations to inertial space using models for precession, nutation, and solid Earth tides, and calibrations for polar motion and length-of-day variations and corrections to the standard nutation model in the manner defined by the IERS.

The estimated uncertainty for the spacecraft trajectory depended on assumed a priori uncertainties for the estimated parameters, the assumed data arc and data weights, and a priori uncertainties for model parameters that are not estimated. The effect of uncertainties of nonestimated model parameters is included through the use of consider analysis [16]. 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. The thruster firing uncertainty levels were based on the level of variation as recorded by the telemetry information [10] and by checking that the estimated corrections to the acceleration were significantly smaller than the a priori uncertainty. The uncertainties in the position of Jupiter and in the Jupiter spin axis direction were set large enough to not influence the solution. Because range calibrations were not recovered for the reanalysis, the DSN range bias uncertainties were set to a value corresponding to the total delay through the ground station. DSN station locations are currently known with about a 3-cm accuracy [15], but because of uncertainty in the rate of change of station locations due to plate tectonics, this was increased to a 10-cm uncertainty for the 1979 encounter data (and was large enough to include uncertainties in Earth orientation). The uncertainty in the orientation of the Earth's orbit comes from the comparison of VLBI and LLR Earth orientation [8]. The uncertainty in the troposphere calibration is taken from Robinson.[2] The uncertainties in the mass and oblateness of Jupiter's gravity field are given by Campbell and Synnott [11].

III. Results

Figures 1 and 2 show the post-fit data residuals. Some small signatures can be seen in the Doppler data in Fig. 1. These are most apparent at the beginning of tracking passes and are probably due to residual solar plasma effects. The Doppler residuals have a root-mean-square (rms) of 0.1 mm/s. Most of the data points have averaging times much longer than the standard 60 s. If the data noise is assumed to be white-frequency noise, then the Doppler data residuals correspond to an rms of 0.3 mm/s for a 60-s averaging time. The solar plasma is known to impose more noise on the Doppler data at low frequencies [17], so for the final estimate, the Doppler data were conservatively weighted at 1-mm/s uncertainty for a 60-s count time, even though the solar plasma was partially calibrated. The conservative weighting of the Doppler data prevents the small signatures in the Doppler data from excessively influencing the solution estimates and increases the formal uncertainty. The range data have an rms of 3.2 m and were weighted at 4 m in the solution.

Tables 3 and 4 give the estimated position of the barycenter of the Jupiter system at a time near the closest approach of the Voyager 1 spacecraft in Cartesian and spherical coordinates. Because Jupiter is within the solar system, the light time significantly affects the apparent position of Jupiter. To avoid complications of light-time calculation, time transformations, and other effects, Tables 3 and 4 give the instantaneous Earth–Jupiter vector in the IERS celestial reference frame. That is, the Earth–Jupiter vector is the difference between the position of Jupiter at the specified solar-system barycentric coordinate time (TDB) and the position of the Earth at the same coordinate time. For reference, the Earth–Jupiter vector is also given in the widely available ephemeris DE200.

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[2] S. E. Robinson, "Errors in Surface Model Estimates of Zenith Wet Path Delays Near DSN Stations," JPL Interoffice Memorandum 335.4-594 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1986.

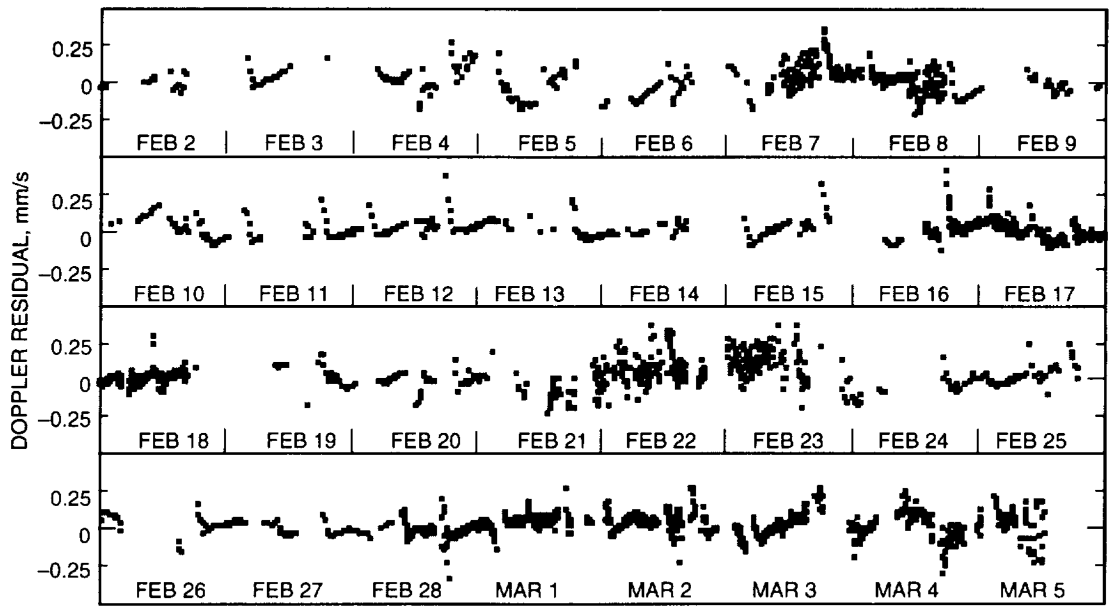

Fig. 1. Voyager 1 S-band Doppler data residuals.

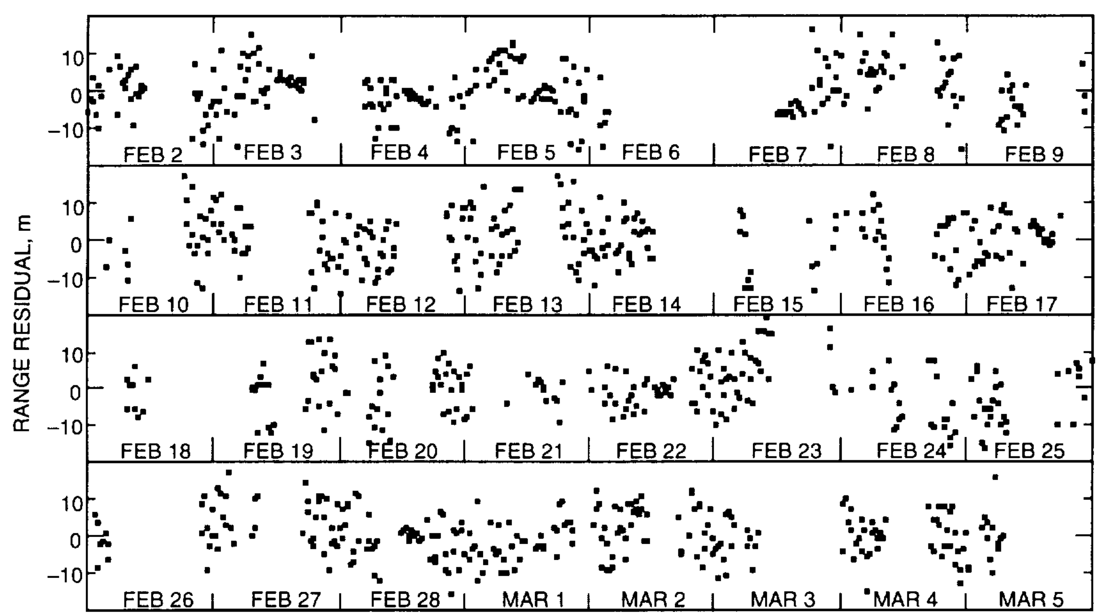

Fig. 2. Voyager 1 S-band range residuals.

The uncertainties in Table 4 correspond to 40 nrad in right ascension and 140 nrad in declination. The given uncertainties are expected to reflect the actual uncertainties as realistically as possible. The actual uncertainties are dependent on the spacecraft thruster firing history, which cannot be easily reconstructed at this late date. As a check for errors in modeling assumptions, separate fits were made using only the first 16 days of data within the arc and with only the last 16 days of data. In each case, the estimated position of Jupiter agreed with the value given in Table 3 within 1 sigma. The uncertainty in the Earth–Jupiter range is due to not having the ranging system calibrations available for the reanalysis. The

Table 2. Estimated and considered parameters and their uncertainties.

Estimated parameters	Uncertainty
Spacecraft initial position	10^5 km
Spacecraft initial velocity	100 km/s
Impulsive maneuvers (each component)	1 cm/s
Thruster accelerations (each component)	10^{-11} km/s^2
Jupiter right ascension	500 nrad
Jupiter declination	500 nrad
Earth–Jupiter range	100 km
Jupiter spin axis, right ascension	0.1 deg
Jupiter spin axis, declination	0.1 deg
DSN range biases	3 km
Consider parameters	**Uncertainty**
DSN station locations	10 cm
Earth orbit orientation with respect to IERS frame	15 nrad
Troposphere zenith delay	4 cm
Jupiter mass (GM)	100 km^3/s^2
Jupiter oblateness (J2)	0.01 percent

Table 3. Cartesian coordinates of Jupiter on March 5, 1979, 12:00:00.000 TDB.

Position	x, km	y, km	z, km
Estimated position	−339109994	536319388	241482423
Position in DE200	−339110282	536319389	241481691

Table 4. Spherical coordinates of Jupiter on March 5, 1979, 12:00:00.000 TDB.

Position	Range, km	Right ascension	Declination
Estimated position	678931392 ± 3	8 h 9 min 13.1531 s ± 0.0005 s	20° 50′ 6.487″ ± 0.028″
Position in DE200	678931276	8 h 9 min 13.1584 s	20° 50′ 6.262″

right ascension and declination estimated for Jupiter are more accurate than any other measurements except for the VLBI data taken from the Ulysses spacecraft [18]. The only other position measurement with comparable accuracy is from observations of the satellites of Jupiter with the Very Large Array, which determined the position of Jupiter with an accuracy of 125 nrad in right ascension and declination [19]. The Voyager 1 position determination will make a significant contribution to determining the ephemeris of Jupiter prior to Galileo's encounter in December 1995.

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References

[1] D. W. Curkendall and S. R. McReynolds, "A Simplified Approach for Determining the Information Content of Radio Tracking Data," *J. Spacecraft*, vol. 6, pp. 520–525, 1969.

[2] T. W. Hamilton and W. G. Melbourne, "Information Content of a Single Pass of Doppler Data From a Distant Spacecraft," *Space Programs Summary 37-39*, vol. III, Jet Propulsion Laboratory, Pasadena, California, pp. 18–23, May 31, 1966.

[3] J. O. Light, "An Investigation of the Orbit Redetermination Process Following the First Midcourse Maneuver," *Space Programs Summary 37-33*, vol. IV, Jet Propulsion Laboratory, Pasadena, California, pp. 8–16, June 30, 1965.

[4] J. L. Fanselow, O. J. Sovers, J. B. Thomas, G. H. Purcell, Jr., E. J. Cohen, D. H. Rogstad, L. J. Skjerve, and D. J. Spitzmesser, "Radio Interferometric Determination of Source Positions Utilizing Deep Space Network Antennas—1971 to 1980," *Astron. J.*, vol. 89, pp. 987–998, 1984.

[5] C. Ma, D. B. Shaffer, C. de Vegt, K. J. Johnston, and J. L. Russell, "A Radio Optical Reference Frame, I. Precise Radio Source Positions Determined by Mark III VLBI: Observations From 1979 to 1988 and a Tie to the FK5," *Astron. J.*, vol. 99, pp. 1284–1298, 1990.

[6] International Earth Rotation Service, *Annual Report for 1988*, Observatoire de Paris, Paris, France, 1989.

[7] E. M. Standish, Jr. and J. G. Williams, "Dynamical Reference Frames in the Planetary and Earth–Moon Systems," *Inertial Coordinate Systems on the Sky*, edited by J. H. Lieske and V. K. Abalakin, Dordrecht, Netherlands: Kluwer Academic, pp. 173–181, 1990.

[8] W. M. Folkner, P. Charlot, M. H. Finger, J. G. Williams, O. J. Sovers, XX Newhall, and E. M. Standish, "Determination of the Extragalactic-Planetary Frame Tie From Joint Analysis of Radio Interferometric and Lunar Laser Ranging Measurements," *Astron. Astrophys.*, vol. 287, pp. 279–289, 1993.

[9] T. McElrath, B. Tucker, P. Menon, E. Higa, and K. Criddle, "Ulysses Navigation at Jupiter Encounter," AIAA Paper 92-4524, presented at the AIAA/AAS Astrodynamics Conference, Hilton Head, South Carolina, 1992.

[10] J. K. Campbell, S. P. Synnott, J. E. Riedel, S. Mandell, L. A. Morabito, and G. C. Rinker, "Voyager 1 and Voyager 2 Jupiter Encounter Orbit Determination," AIAA Paper 80-0241, presented at the AIAA 18th Aerospace Sciences Meeting, Pasadena, California, 1980.

[11] J. K. Campbell and S. P. Synnott, "Gravity Field of the Jovian System from Pioneer and Voyager Tracking Data," *Astron. J.*, vol. 90, pp. 364–372, 1985.

[12] J. H. Lieske, "Improved Ephemerides of the Galilean Satellites," *Astron. Astrophys.*, vol. 82, pp. 340–348, 1980.

[13] E. M. Standish, Jr., "Orientation of the JPL Ephemerides DE200/LE200 to the Dynamical Equinox of J2000," *Astron. Astrophys*, vol. 114, pp. 297–302, 1982.

[14] C. C. Chao, *The Troposphere Calibration Model for Mariner Mars 1971*, JPL Technical Report 32-1587, Jet Propulsion Laboratory, Pasadena, California, pp. 61–76, 1974.

[15] C. Boucher, Z. Altamimi, and L. Duhem, *Results and Analysis of the ITRF93*, IERS Technical Note 18, Observatoire de Paris, France, 1994.

[16] G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*, New York: Academic Press, 1977.

[17] J. W. Armstrong, R. Woo, and F. B. Estabrook, "Interplanetary Phase Scintillation and the Search for Very Low Frequency Gravitational Radiation," *Astrophys. J.*, vol. 230, pp. 570–574, 1979.

[18] W. M. Folkner and T. P. McElrath, "Determination of Radio-Frame Position for Earth and Jupiter From Ulysses Encounter Tracking," AAS Paper 93-167, AAS/AIAA Spaceflight Mechanics Meeting, Pasadena, California, 1993.

[19] D. O. Muhleman, G. L. Berge, D. J. Rudy, A. E. Niell, R. P. Linfield, and E. M. Standish, "Precise Position Measurements of Jupiter, Saturn, and Uranus Systems With the Very Large Array," *Celestial Mechanics*, vol. 37, pp. 329–337, 1985.