Relating the Planetary Ephemerides and the Radio Reference Frame

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The positions of Venus, Mars, and Jupiter have been obtained in the VLBI radio reference frame by measuring the position of a satellite (natural or artificial) of each planet relative to an extragalactic source in the radio catalogue. From the results for Mars and Venus we conclude that the offset in right ascension of the radio frame from the dynamical equinox defined in DE200 is 0″.00 ±0″.04. The observations for Jupiter imply a correction to its position from DE200 of -0″.18 ±0″.04 in right ascension and -0″.06 ±0″.05 in declination on 1983 April 29. The right ascension of Jupiter relative to the inner planets has been measured independently using Doppler tracking data near Jupiter encounter from Pioneers 10 and 11 and from Voyagers 1 and 2 by tying the tracking station positions, through previous spacecraft missions, to the DE200 ephemerides of the inner planets. This technique yielded a correction to Jupiter's right ascension of -0″.22 ±0″.05, in good agreement with the results from the direct radio measurements.

I. Introduction

There are two practical celestial reference systems, one based on stars through optical observations, the other on extragalactic objects through radio observations. For optical observations the current fundamental catalog FK4 (Ref. 1) contains positions of approximately 1500 stars which were obtained by optical meridian transit measurements and are on the B1950.0 system. This catalog will be superseded by FK5 which will contain some 4500 stars having positions on the J2000 system. The reference frame for radio sources is based on Very Long Baseline Interferometry (VLBI) observations and is on the J2000 system.

For use as a fundamental reference frame the system formed by the radio observations has two advantages: i) since the extragalactic objects are at such great distances, any velocity that they might have transverse to the line of sight is negligible, and they thus provide an effectively inertial frame of reference; and ii) the accuracy of the positions is 10 to 100 times better than for the optical system.

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A second *inertial* frame exists in the form of the ephemerides of the inner planets (Mercury through Mars) and the Moon. These ephemerides have been derived from accurate measurements of the planetary and lunar distances by radar or laser ranging to their surfaces and by ranging to spacecraft, especially the Viking Lander. (They provide an inertial system because the ranging measurements are sensitive to the motion relative to an inertial frame and not just to the motion relative to background objects.) The orbit of the earth is included in this ephemeris; thus a natural product is the calculation of the dynamical equinox, which defines the origin of right ascension. Although the accuracy of positions calculated from the ephemeris is better than for the optical system, the planetary system is not as useful because of the small number of objects visible and because the objects themselves are large in angular extent.

Since the two inertial frames are independent, it is important to establish their relative orientation. In declination the two should agree because each determines absolute values. However, in right ascension radio interferometry determines only relative values, and the origin must be found by reference to the planetary ephemeris.

An important reason for determining the relationship between these two frames arises from navigation of deep space probes (Ref. 2). Although the target of the navigation is a planet whose position is known in the planetary frame (for Mercury through Mars) or the stellar frame (for the outer planets), the spacecraft can be more precisely navigated by the measurement of differential displacements from radio sources. Thus, the problem is to determine the positions of the planets in the frame of the extragalactic radio sources.

In this report we summarize our current understanding of the relationship between the radio reference frame and the ephemerides of the planets out to Jupiter. Observations will be described which a) relate the origin of right ascension of the radio frame to the dynamical equinox; b) give the position of Jupiter in the radio frame; and c) improve the ephemeris of Jupiter relative to the inner planets.

II. Reference Frame Accuracies

A. Optical Star Catalogues

The optical reference system consists of the stars of the FK4 fundamental catalogue (Ref. 1) plus a greater number of stars whose positions have been measured relative to the primary stars, the AGK3RN. The uncertainties in position of these objects include not only the original position error but also the contribution from uncertainties in proper motion extrapolated to the epoch of interest. The combination of these errors is at least 0″.1. In addition there are systematic variations about the sky of up to 0″.2. Upon completion of the FK5 the uncertainties will be reduced, though not significantly below 0″.1. (See Ref. 3 for a more complete summary.)

B. Planetary Ephemerides

The relative positions of the *inner* planets (Mercury, Venus, and Mars) in a geocentric coordinate system have uncertainties of only a few hundredths arc second in the latest ephemerides DE118 (B1950.0) or DE200 (which is DE118 rotated to the equator and equinox of J2000) (Ref. 4). They are derived from distance measurements obtained by radar ranging to the surfaces of the planets and by ranging to spacecraft both during flybys and while orbiting the planets. The origin of right ascension for the ephemerides is the dynamical equinox, for which the uncertainty is given as $\sim$0″.01.

The positions of the *outer* planets have been calculated from optical meridian transit observations, and their accuracies are limited both by the observational errors and by the systematic errors of the stellar reference system. As a result the uncertainties relative to the inner planets increase from $\sim$0″.2 for Jupiter to $\sim$1″ for Pluto (Ref. 5).

C. VLBI Radio Reference Frame

The positions of $\sim$130 extragalactic radio sources as determined by VLBI have accuracies of better than 0″.005 in absolute declination and in relative right ascension of epoch J2000 (Refs. 6-8). These sources span the declination range -45 degrees to +84 degrees.

Since the VLBI observations are only weakly sensitive to the ecliptic, through orbital aberration, the origin of right ascension is poorly determined. In order to fix the origin for the radio frame the right ascension of one source, the quasar 3C273B, has been assigned the value obtained by Hazard *et al.* (Ref. 9). Their position was derived as an average of: i) optical measurements relative to stars, whose positions were on the FK4 system, and ii) occultations of the radio emission of 3C273B by the Moon. The two methods agreed, yielding an uncertainty in their average of 0.01 seconds of right ascension (= 0″.15 = 750 nanoradians). The accuracy of measurements of the optical position of 3C273B relative to reference stars suffers the same approximately 0″.1 limitation as measurements of the outer planet positions, due to the systematic errors which vary with right ascension and declination. The lunar occultations have a lower limit on their uncertainty of 0″.1 set by the lack of knowledge of the shape of the limb of the Moon. Thus, neither of these techniques offers the possibility of significant improvement in relating the origins of the two reference frames.

III. Observations

The value of radio interferometry, and of Very Long Baseline Interferometry in particular, is the capability of measuring the positions of compact sources of radio emission with great precision. However, the planets are large in angular size when compared to the compact components of the extragalactic radio sources and to the measurement accuracy which is possible. Thus, for interferometers with small fringe spacings, the planets would be resolved, while for larger fringe spacings the positional accuracy is degraded.

Alternatively, the position of a smaller object bound to the planet, such as a satellite or space probe, may be measured in the radio frame. The problem then consists of two parts: obtaining the position of the satellite or probe relative to the radio sources, and obtaining its trajectory or orbit about the planet.

This technique has been applied in two ways: i) an orbiter of each of Mars and Venus has been used for VLBI connection of these two planets to the Radio Reference Frame (see Section IV); ii) for Jupiter the Very Large Array (VLA) has been used to observe the Galilean satellites relative to extragalactic radio sources (see Section V). The VLA is appropriate because it provides both the sensitivity which is necessary to detect the thermal emission of the satellites and the spatial resolution which is matched to the angular sizes of the satellites. (The VLA is described by Napier *et al.* [Ref. 10].)

IV. Frame-Tie by Inner-Planet Orbiters (XXN, RAP, PBE)

The positions of the Viking Mars Orbiter and the Pioneer Venus Orbiter (PVO) relative to extragalactic radio sources were measured in several experiments from 1980 to 1983 using differential VLBI phase measurements. Data from eight passes of the Viking spacecraft and three of PVO were successfully analyzed (see Ref. 11 for more details).

The results are shown in Fig. 1 in which the apparent positions of the radio sources in the planet frame are given. The average right ascension offset is 0''.00 ±0''.04 (0 ±200 nrad) and the average declination offset is 0''.01 ±0''.05 (40 ±250 nrad). The uncertainty is obtained from the rms scatter of the eleven data points.

It is clear that the scatter of the data points is larger than would be expected from the individual experiment results. The reason for this is not understood. Among the primary sources of error are the planetary ephemerides, the positions of the radio sources for the Viking measurements, and the determination, from Doppler tracking data taken on the same orbit, of the orientation on the sky of the line of nodes of the spacecraft orbit. Estimates of these errors are included in the uncertainties assigned to each measurement. A possible source of error, not included as it was thought to be small, is the degree to which the phase connection between the individual differential VLBI observations has been successful. The correction for charged particle dispersion is only partially complete in that, although the downlink was observed at both S- and X-band, the uplink was S-band only.

Thus, although it seems fortuitous, given an *a priori* uncertainty of 0''.15 (750 nrad), the radio source and planet frames seem to agree to better than 0''.04 (200 nrad) in right ascension. In declination the results for both Mars and Venus are consistent within the *a priori* uncertainty of 0''.02 (100 nrad) (Ref. 5).

V. The Position of Jupiter in the Radio Frame (AEN, DOM, GLB, DJR)

The position of Jupiter in the radio frame has been inferred by measuring the position of its satellite Ganymede relative to two extragalactic radio sources, whose positions are accurately known by VLBI, using the VLA in the C configuration at 2-cm wavelength. The positions of Europa and Callisto were also measured, but Callisto has a larger ephemeris uncertainty than Ganymede, and the results for Europa were adversely affected by the proximity of Jupiter at the time of the observations.

The positions of the satellites were obtained by adding their positions from Lieske's Galilean satellite ephemeris E-2 (Ref. 12) to the DE200 ephemeris for Jupiter. The down-track (right ascension) uncertainties for Europa and Ganymede are about 110 km and for Callisto about 200 km, corresponding to 0''.03 and 0''.06, respectively, at the 4.5 AU distance of Jupiter at the time of observation. The cross-track (declination) uncertainties are, respectively, 80, 60, and 200 km (0''.03, 0''.02, and 0''.06) (J.H. Lieske, private communication).

The VLA observations were made at both 6-cm and 2-cm wavelength as part of a combined program to measure both the physical and the astrometric properties of the Galilean satellites. However, only the 2-cm results were used for astrometric results because the larger primary beam at 6-cm wavelength does not sufficiently attenuate the radio emission from Jupiter.

Two radio sources were used as position calibrators. They were chosen to be approximately equally spaced on either side of the Jupiter system in order to reduce systematic errors due to elevation angle effects (e.g. tropospheric refraction) or to incorrect modeling of the Earth's orientation. The epoch J2000 positions of the two sources, NRA0530 and P1519-273, were taken from the JPL/DSN radio source catalogue designated 1983-4 (see e.g., Ref. 6) and have an absolute accuracy of ~0".005 in declination and in relative right ascension. As discussed in the previous section the origin of right ascension is consistent with that of the inner-planet ephemeris to 0".04.

The observables at the VLA are the amplitude and phase of the two independent circular polarizations for all interferometer pairs formed by the twenty-five operating antennas. The phases and amplitudes are calibrated by assuming that the positions and flux densities of the calibrator sources are known and then interpolating corrections for the amplitudes and phases at the time of the satellite observations. The positions of the satellites are then found by doing a least-squares fit to the amplitudes and phases (obtained during the six hours of observation each day) for the position and brightness temperature of a uniform disk the size of the satellite.

The observed displacements of the satellites from their expected positions are shown in Fig. 2. For all satellites there are two positions indicated for each day, representing the measurements in both senses of circular polarization. As can be seen the observed positions of Ganymede for the two polarizations for the two days agree within the uncertainties. The two measurements of Europa at one polarization, but on separate days, also agree with the Ganymede data. However, because of the possible corruption by Jupiter the Europa data are not used. Nor is the position of Callisto used, because of the larger uncertainty in its ephemeris and because of the disagreement of the results on the two days. This offset from Ganymede will be used to obtain an improvement to the Callisto ephemeris.

The errors which contribute to the uncertainty in these measurements are a) error due to receiver noise, atmosphere, and confusion by background sources; b) satellite ephemeris uncertainties; c) variations in physical temperature across the satellite disk; d) differential refraction for the satellite positions relative to the calibrator positions; e) bias in the positions due to the proximity of Jupiter, which is 2500 times as strong as the satellites. These errors are summarized as follows:

a) Measurement errors for two days:	0".015
b) Ephemeris uncertainty relative to Jupiter:	0".03 in RA 0".04 in DEC
c), d), and e)	0".02
RSS Total:	0".04 in RA 0".05 in DEC

Thus the correction to the position of the Jupiter system barycenter calculated from the DE200 ephemeris for 1983 April 29 (JD 2445453.5) as determined by the observations of Ganymede relative to the radio reference frame is

$$\Delta RA \cos DEC = -0''.18 \pm 0''.04$$
$$\Delta DEC = -0''.06 \pm 0''.05$$

VI. Jupiter Relative to the Inner Planets (JKC, EMS)

Encounters of spacecraft with the inner planets provide a relationship between those planetary ephemerides which are best known and the terrestrial coordinate system of the stations of the Deep Space Network (T.D. Moyer, private communication, 1980). Subsequent observations of spacecraft encounters with other planets, which are also sensitive to the station locations, may then be used to locate the outer planets in the frame of the inner planets. The Doppler tracking of the Mariner spacecraft to Venus, Mercury and Mars, and especially the ranging data to the Viking Orbiters, have provided relative station locations with accuracies in the equatorial plane of less than a meter, corresponding to an angular resolution of ~0".03.

Data from the encounters with Jupiter of Pioneers 10 and 11 and Voyagers 1 and 2 (Ref 14) were included in a joint solution with all of the planetary ephemeris data, yielding a correction to the position of Jupiter relative to the inner planets as it was given in DE 118. The result is

$$\Delta RA \cos DEC = -0''.22$$
$$\Delta DEC = -0''.06$$

with uncertainties of ~0".05.

Thus, the spacecraft data confirm the offset of Jupiter relative to the inner planets as determined by measurements relative to sources of the radio reference frame. The agreement of the two methods also provides support for the conclusion that the currently adopted value for the position of 3C273 is correct to within the measured uncertainty.

VII. Improvements

It may be possible to obtain a better tie between the radio frame and the planetary ephemerides for the inner planets by using the VLBI determination of the relative locations of the stations of the Deep Space Network and the encounter Doppler data for the inner planets (A.E. Niell, private communication, 1984). The potential accuracy is < 0″.02 but may be limited by uncertainties in the ephemerides.

Continued observations of Jupiter via the Galilean satellites with the VLA should verify the results reported here and reduce the uncertainty. Observations have also been made of Titan to improve the position of Saturn in the radio frame, but the analysis is not complete (Muhleman, private communication). Uranus and Neptune are sufficiently small in angular size to permit direct observation with the VLA with a possible position uncertainty of ~0″.05 to 0″.1.

Johnston *et al.* (Ref. 13) have reported the first measurements of the positions of minor planets with the VLA. However, even the largest asteroids are much weaker than the Galilean satellites, and the reported positional accuracy was only about 0″.1. In the FK4 system they found the right ascension of 1 Ceres to be off by -0″.3 and that of 2 Pallas by 0″.7. The *a priori* uncertainty in the optical positions was thought to be ~0″.3. Their observing program now also includes Hygeia and Vesta. All four objects are observed twice per year. With improved ephemerides for these objects they hope to establish the right ascension origin for the VLA astrometric catalogue consistent with the planetary ephemerides.

VIII. Summary

By using planetary satellites and deep space probes as sources of radio emission, it has been possible to measure the positions of the planets Venus, Mars, and Jupiter in the celestial reference frame defined by VLBI observations. While the absolute declinations and relative right ascensions of the extragalactic radio sources are accurate to better than 0″.005, the origin of right ascension has an uncertainty of ~0″.15. The tie to Venus and Mars by VLBI observations of the orbiters of those planets reduces the uncertainty of the origin, relative to the dynamical equinox, to less than 0″.04 in the J2000 system. The results imply that *no* change is needed to the currently assumed right ascension value for 3C273B, the compact component of 3C273, which is used to define the origin (RA(J2000)=12:29:06.6997).

The position of Jupiter in the radio reference frame has been measured with an accuracy of 0″.04 by observing the position of Ganymede with the Very Large Array. The observed position requires corrections of -0″.18 ±0″.04 in right ascension and -0″.06 ±0″.04 in declination to the position for Jupiter calculated for 1983 April 29 from DE200.

An improvement to the ephemeris of Jupiter relative to the inner planets has been independently obtained from spacecraft encounter Doppler data, and the corrections of -0″.22 in right ascension and -0″.06 in declination, with uncertainties of ~0″.05, agree well with those derived from the direct radio observations of Jupiter and the inner planets with respect to extragalactic radio sources.

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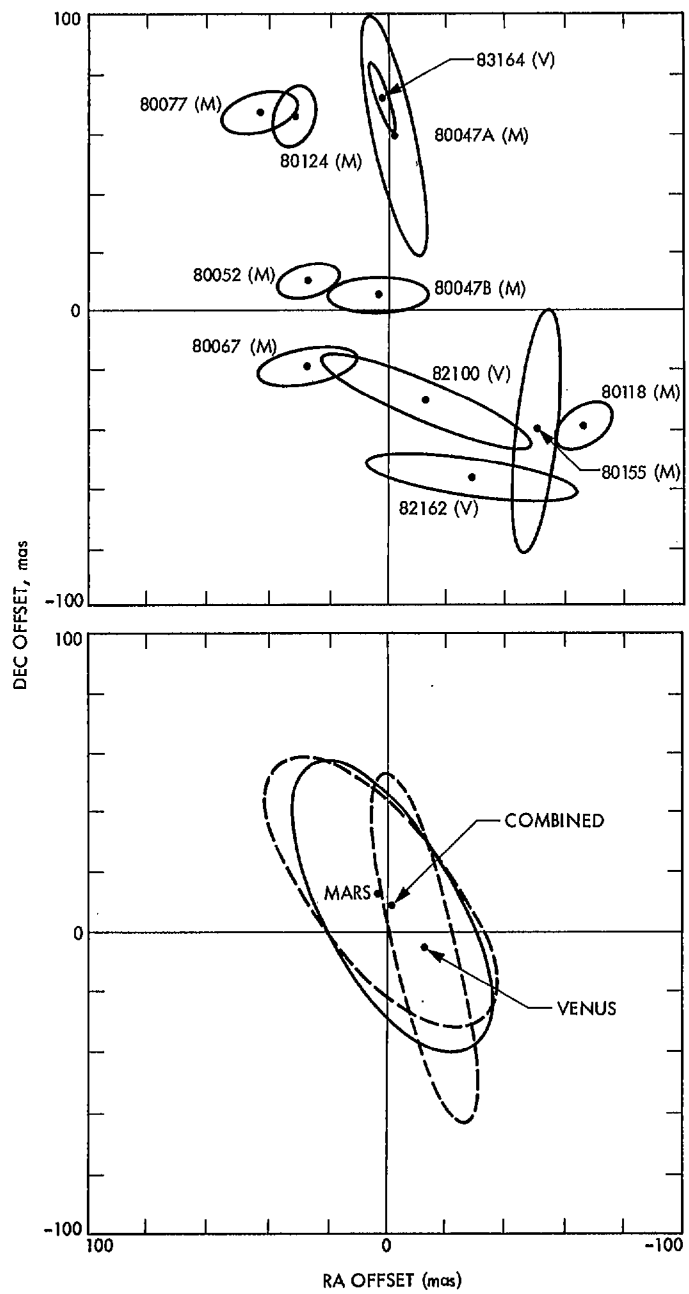

Fig. 1. Δ VLBI measurement of inner planet positions with respect to radio reference frame: (a) Offsets of radio source positions from those expected assuming planet positions from ephemeris DE200 and radio source positions from catalogue JPL 1983-4. (V): Pioneer Venus Orbiter. (M): Viking Mars Orbiter; (b) RMS scatter ellipses for each planet and for the combined data (solid ellipse).

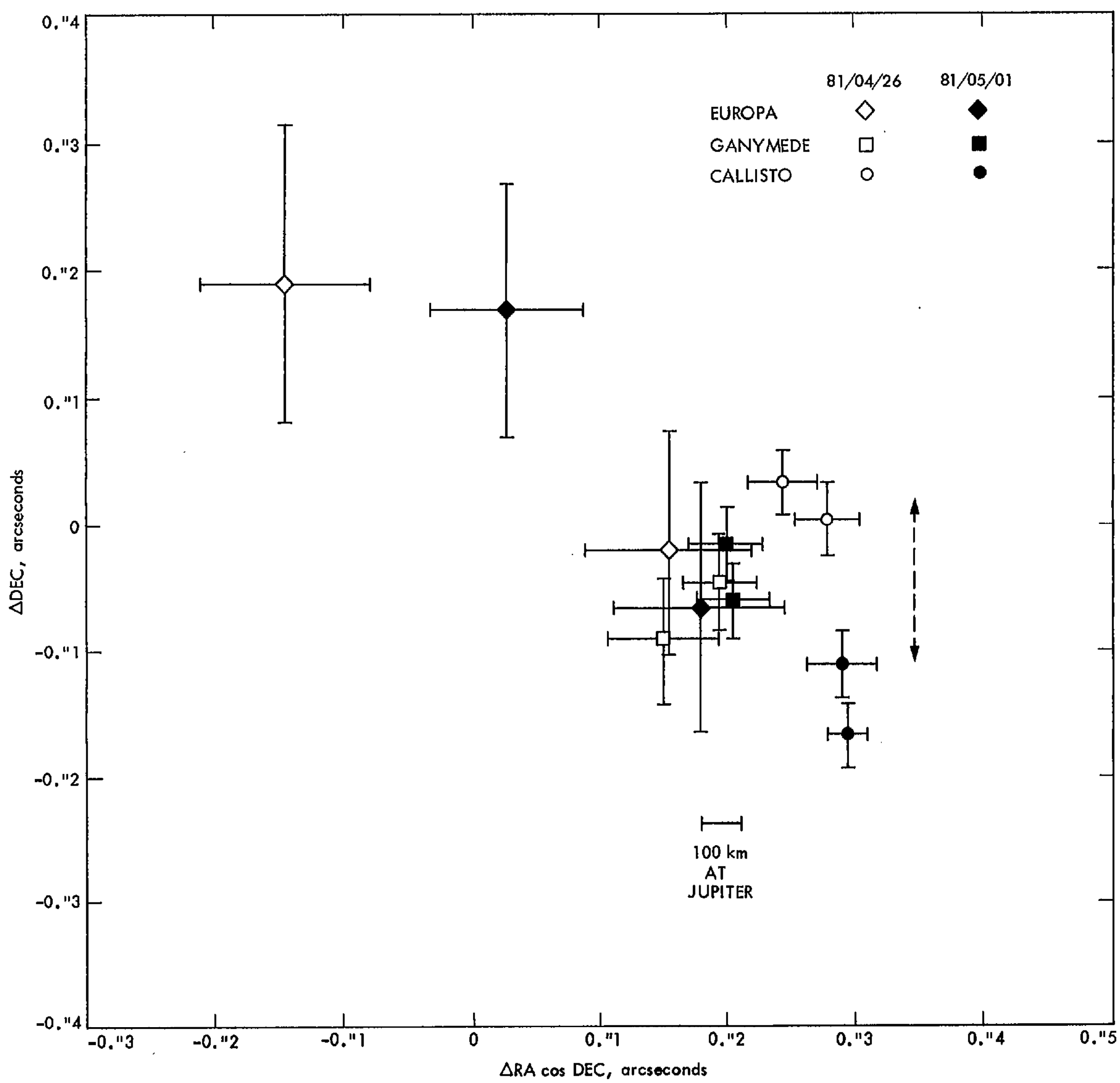

Fig. 2. Positions of the Galilean satellites in the Radio Reference Frame as determined by measurements with the VLA. The same symbol appears twice for each object on each day, since the two polarizations were treated separately. The dashed arrow indicates the declination uncertainty of Callisto relative to Ganymede.