REFERENCE FRAME STUDIES AT JPL/CALTECH

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Introduction, Interconnections and Unification

In recent years, a revolution in astronomical position measurements has been taking place with the advent of modern space techniques. These new techniques, which supplement the traditional astrometric measurements, include laser ranging to the moon and artificial satellites, very-long-baseline interferometry (VLBI) of galactic and extra-galactic radio sources and spacecraft, radio tracking of satellites, and radar-ranging and spacecraft tracking during planetary encounters. Impressive accuracies have been achieved and further improvements are forthcoming. Each technique can be expected to establish its own reference frame which is derived from observations of a particular class of objects. The celestial and terrestrial coordinate systems are related through adopted constants and definitions. Contemporary astronomy has led to the development of three principal celestial coordinate systems: the optical frame (FK4/FK5) based on positions of galactic stars; the planetary/lunar ephemeris frame based on the major celestial bodies of the solar system; and the radio frame constructed from observations of extragalactic radio sources (quasars). Each frame is rotated with respect to others; furthermore, the optical frame offset is time variable. It is important that all frames be interconnected and unified. The optical frame is being connected to the radio frame by VLBI observations of radio emitting stars. The radio frame is being tied to the ephemeris frame in several ways - one is via differential VLBI measurements between quasars and planet-orbiting spacecraft.

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Another is the determination of a pulsar's position in the ephemeris frame (via timing measurements) and the radio frame [via radio interferometry (Backer et al., 1985)]. The zero point of celestial right ascension can be set at the dynamical equinox (the intersection of the mean equator and ecliptic) as was done for the JPL ephemeris DE200/LE200. Currently, the moon and the four inner planets have uncertainties with respect to the dynamical equinox of 0.01", with smaller differential uncertainties. The zero point of terrestrial longitudes is fixed, if the dynamical equinox is adopted. The terrestrial coordinate systems can be tied to the celestial reference systems through ground stations. For a detailed account on reference frames and their unifications, see Williams et al. (1984).

Tie Between VLBI and Optical Frames Via Radio Stars

The Hipparcos optical coordinate system will be tied to the non-rotating extragalactic JPL VLBI radio reference frame (Fanselow et al., 1984 and Niell et al., 1984) by measuring the differential positions of optically bright radio stars and angularly nearby quasars with the VLBI technique (for a more detailed account, see Lestrade et al., 1985). The analysis of these differential VLBI observations of eight radio stars has resulted in measurement accuracies as fine as 2 milliarseconds (mas). These radio emitting stars have been positioned in the JPL-VLBI (J2000) reference frame following the IAU 1976 recommendations. Optical positions of these have been measured with the automatic meridian circle in Bordeaux by Requieme and Rapaport, at the epoch of the VLBI observations (Lestrade et al., 1985). Results indicate that the JPL VLBI reference frame and the J2000 stellar system are aligned after transformation from 1950.0 to J2000 at the level of the precision of the optical measurements.

Tie between VLBI and Ephemeris Frames via Differential VLBI

A series of VLBI observations of planet orbiting spacecraft and angularly nearby quasars using the technique of differential VLBI has provided an estimate of the relative orientation of the JPL VLBI reference frame and the ephemeris frame (Standish, 1982). (For a detailed account of these analyses, see Newhall et al. (1984). Between 1980 and 1983, eleven successful spacecraft-quasar differential VLBI observations were completed: eight used the Viking-Mars orbiter and three used the Pioneer-Venus orbiter. In addition, Doppler tracking data for a complete spacecraft revolution about the planet were recorded and analyzed, allowing a precise determination of the spacecraft orbit. For each experiment the coordinates of the quasar were determined in the ephemeris frame of the JPL ephemeris DE 200/LE200. The *a priori* quasar radio-frame coordinates were subtracted from the observed values in the planetary frame to obtain the offset between the two frames. We find the two frames to be coincident in both right ascension and declination to less than about 20 milliarcsecond (mas). The scatter in the results is probably limited by uncertainties in the spacecraft orbits.

VLA Measurements of Jupiter, Saturn and Uranus Systems

Jupiter and Saturn have large natural satellites which emit sufficient radio flux for position measurement, while Uranus is angularly small enough that its position can be accurately measured with radio-interferometry. The motivation of the VLA measurements was two-fold: the tie between the outer planet ephemeris and the radio frame, and the improvement of the ephemerides themselves. For a detailed account, see Muhleman et al. (1986). These observations determined the positions of the three systems with respect to the JPL radio source catalogue (Fanselow, et al., 1984, Niell, et al., 1984) via differential measurements with angularly nearby extragalactic radio sources. The analysis was originally done with respect to JPL Ephemeris DE200/LE200. Subsequent to the original analysis, offsets were determined with respect to the more recent JPL ephemeris DE125, which serves as the final Uranus Delivery Ephemeris for Voyager and the Launch Ephemeris for Galileo (Standish, 1985). These VLA measurements were not included in the fits of either DE200 or DE125 analyses and therefore can be used as valuable independent checks of the ephemerides. The DE200 results for the three planets are very similar and suggest that the ephemeris reference frame for the outer planets is in error by roughly -0.2 arc sec in right ascension. The agreement with DE125 is significantly better. For example, the residuals of the VLA Uranus observations with respect to DE125 are -0.06" ± 0.03" in right ascension and 0.00" ± 0.04" in declination. DE125 represents a major improvement to the ephemerides of the four Jovian planets, which may be attributed to two major sources: a change in the data reduction procedure for the optical transit observations and the addition of new and more accurate data types (e.g., Voyager spacecraft tracking).

Prospects for the Future

The future is promising with on-going and planned efforts in several areas. For optical astrometry, Hipparcos will measure a network of stars over the entire sky with accuracies of ~ 2 mas (Kovalevsky, 1980), while the Space Telescope will measure small fields with a similar differential accuracy. However, the Space Telescope can observe much fainter objects (Jefferys, 1980) and could well observe the optical counterparts of extragalactic radio sources, all but one of which are too faint for Hipparcos. A joint program would produce an accurate stellar network from Hipparcos to be linked to the radio frame by the Space Telescope. The occultations of stars by planets may provide a link between the optical and ephemeris frames. Observations of such occultation stars by Hipparcos would allow a second ephemeris-radio tie when the radio-optical connection is available. For the millisecond pulsar observations, improved reference ties will certainly come from refined modeling, longer data arcs and from the possible discoveries of more of these objects.

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