GEOCENTRIC TERRESTRIAL REFERENCE FRAME ACCURACY: DSN SPACECRAFT TRACKING AND VLBI/LUNAR LASER RANGING

A.E. Niell
Haystack Observatory
Westford, MA 01886

ABSTRACT. From a combination of 1) the location of McDonald Observatory from Lunar Laser Ranging, 2) relative station locations obtained from Very Long Baseline Interferometry (VLBI) measurements, and 3) a short tie by traditional geodesy, the geocentric coordinates of the 64 m antennas of the NASA/JPL Deep Space Network are obtained with an orientation which is related to the planetary ephemerides and to the celestial radio reference frame. Comparison with the geocentric positions of the same antennas obtained from tracking of interplanetary spacecraft shows that the two methods agree to 20 cm in distance off the spin axis and in relative longitude. The orientation difference of a 1 meter rotation about the spin axis is consistent with the error introduced into the tracking station locations due to an error in the ephemeris of Jupiter.

1. INTRODUCTION

Four techniques are able to determine absolute or relative geocentric positions with a formal accuracy of less than twenty centimeters. Three of these - Lunar Laser Ranging (LLR), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI) - are well covered in these conferences. The fourth - radio tracking of interplanetary spacecraft by the antennas of the NASA/JPL Deep Space Network - has comparable accuracy in the geocentric equatorial components. It also provides an important tie among the planetary ephemerides, the VLBI source catalogue, and the terrestrial reference frame, and serves as an independent check of the accuracies of the other techniques.

The relative positions of the DSN antennas are well determined by VLBI observations (Sovers et al, 1984), but they must be tied to the geocenter through another technique. Lunar Laser Ranging from McDonald Observatory determines a reference point that is both geocentric and related to the planetary ephemeris, an important consideration for the overall unification of terrestrial and celestial frames. In addition the planetary ephemeris is the celestial reference system for the determination of the positions of the DSN antennas through the spacecraft tracking, and thus provides a common *a priori* orientation to be evaluated in a comparison of the two determinations of the DSN station locations. The connection between McDonald Observatory and the

A. K. Babcock and G. A. Wilkins (eds.), The Earth's Rotation and Reference Frames for Geodesy and Geodynamics, 115–120.

VLBI-determined relative positions of the DSN antennas is made by a classical geodetic survey from the observatory to the VLBI site at the George R. Agassiz Station (GRAS) 8 km away, and then by the results of VLBI measurements from the GRAS antenna to the DSN antennas.

A tie could also be made between the DSN antennas and McDonald Observatory using SLR. Although the SLR results give absolute geocentric positions in themselves, they will not be used in the present comparison since, due to their fundamentally different celestial reference frame, there is no expectation that the LLR/VLBI/DSN system, which is related to the planetary ephemeris, and the SLR system, which is determined by the arbitrary choice of a terrestrial location, will have a predetermined relative orientation at the level of their internal precision.

A brief summary of the characteristics of each technique is shown in Table I.

TABLE I

Global Terrestrial Systems with Decimeter Accuracy

System	Geocentric?	Celestial Reference	Accuracy (3-dimensions)
LLR	Yes	Planetary Ephemeris	5 - 20 cm
SLR	Yes	None	~< 10 cm
DSN S/C Tracking	Yes	Planetary Ephemeris	~20 cm (equatorial plane)
VLBI	No	Extragalactic Radio Sources	5 - 20 cm

2. The DSN Station Locations

The Jet Propulsion Laboratory operates antennas in three complexes around the world in order to be able to continuously track spacecraft as they travel to, orbit around, or transmit from other planets and their satellites. They are in California, USA; Spain; and Australia. (These locations in addition provide a reasonable distribution around the equator for the basis of a useful reference system.)

In each complex are two to four antennas that have been used for tracking various spacecraft over the past ~twenty-five years. The antennas are tied to each of the others in the same complex by geodetic or VLBI measurements so that each complex can be represented as one location. The measurements from which the locations are estimated are the ranges and Doppler shifted return signals observed in tracking the many different spacecraft over the years. These observables are first used, along with optical data, laser ranging to the Moon, and radar ranging to the planets, to determine the planetary and lunar ephemerides, assuming the best prior values for the station locations. The problem is then turned around to update the tracking station locations. In principle the station locations and ephemerides should be estimated simultaneously. The adopted procedure results in an underestimation of the uncertainties and loss of correlation information among the station locations and the ephemerides.

The precision of the observations has improved significantly with time. As a consequence each successive mission provides better data, usually on a different planet. This has the effect of weighting the station locations more heavily towards the ephemeris of the latest planet encountered. In practice this results in a rotation of the mean longitudes of the stations, but leaves the relative positions unchanged. This has been especially true when the data for the outer planet encounters, the Pioneer and Voyager encounters with Jupiter, have been added.

The planetary encounters are in the ecliptic, which restricts the maximum declination of the spacecraft-tracking data to less than +/- twenty-three degrees. The distances of the stations off the equator are thus only poorly determined, and the z-components have been obtained from other measurements. Thus, the comparison that can be made is for the equatorial components of the stations.

The formal accuracies of the distance off the spin axis and the longitude of each station are ~18 cm in both coordinates. Much larger values have generally been quoted because of the variations in longitude seen from one encounter to the next. This is now understood to be primarily the effect of improvements (and/or errors) in the ephemerides. The relative longitudes do not show these large changes.

For the comparison I have used the station locations designated LS118 which are associated with DE118 (Moyer 1983). DE118 was oriented on the dynamical equinox and used Fricke's value for the rate correction to the equinox. Thus, it should agree with the VLBI reductions in the J2000.0 system. Unfortunately, this solution includes the Voyager data and results in a larger discrepancy in the longitudes than would otherwise be determined.

3. The VLBI/LLR Connection

Very Long Baseline Interferometry provides accurate relative station locations but in a frame whose origin may be translated relative to a geocentric frame. To establish a geocentric reference for the VLBI relative locations the absolute geocentric position of one station must be determined with respect to the Earth's geocenter. The connection used is indicated in Figure 1. Near each connection is the technique used and the approximate accuracy of that measurement. For consistency each of the connections, except for the survey between McDonald and GRAS, is taken from analysis done at JPL. Thus, the same program and constants were used for all of the VLBI data analysis, and similar ephemerides were used for the VLBI and LLR analysis.

```
                                                                   (Spain)
                                                                    DSS-63
                                                                     /\
                                                                     |     VLBI
                                                                     |   (10-20 cm)
                                                      (California)   |
McDonald Obs    --->  Ft. Davis  -->  DSS-13  -->  DSS-14
    LLR          ground             VLBI          VLBI       |
 (5-20 cm)    (3-5 cm)             (3 cm)        (1 cm)      |      VLBI
                                                              |    (4-12 cm)
                                                             \ /
                                                            DSS-43
                                                          (Australia)
```

Figure 1. Illustration of the connection from McDonald Observatory to the antennas of the Deep Space Network. "LLR", "ground" and "VLBI" denote the technique; the typical uncertainties are given in parentheses. An uncertainty of 60 cm must be included in relating the VLBI and LLR orientation about the spin axis.

The location for McDonald Observatory was taken from Dickey et al.(1983). The connection from the laser reference point to GRAS intersection of axes was measured by Carter and Pettey (1981). VLBI measurements taken as part of the Crustal Dynamics Project and analysed at JPL (Allen et al, 1983) were used to connect the GRAS antenna to the antenna designated DSS-13 at the Goldstone complex in California. Special VLBI phase-delay observations were made between DSS-13 and the 64-m antenna DSS-14 at Goldstone, a distance of 22 km, to obtain the vector baseline with an accuracy of ~1 cm (Liewer,1984). These connections provided the direct tie between the geocentric point at McDonald and the 64-m antenna in California. Addition of the VLBI baselines from DSS-14 to DSS-63 in Spain and to DSS-43 in Australia (Sovers et al.,1984) complete the geocentric positions for the three widely spaced locations.

https://doi.org/10.1017/S0074180900119370 Published online by Cambridge University Press

In addition to the uncertainties shown for each leg of the connection there is an additional uncertainty in the relative orientation of the planetary ephemeris and the radio source catalog. The offset between the two celestial frames has been found by Newhall et al. (1986) to be 0."00 +/- 0."02. A non-zero value for this offset will appear as a rotation of the VLBI baselines about the McDonald position (or more correctly, about the GRAS position). One standard deviation corresponds to 60 cm, and dominates the error budget in relating the VLBI results to a geocentric reference.

4. RESULTS

No adjustment has been made between the data sets. The comparisons to be made are for the distances off the spin axis and for the longitudes of the stations. The results are summarised in Table II. (The longitude difference has been converted to approximate linear distance at the Earth's surface.) The RMS differences about the mean are disturbingly small, 14 cm in distance off the spin axis and 7 cm in relative longitude. The 1 meter rotation is due to an error of 0."2 in the longitude estimate of Jupiter in DE118 which produces a bias in the estimates of the station longitudes obtained from the tracking data. The longitude of Jupiter has been significantly improved in DE125 (Standish 1985), and the resulting station location estimates are expected to remove the 1 meter discrepancy.

TABLE II

Station location difference
VLBI/LLR minus DSN

	Difference (cm) Mean	RMS
Distance off spin axis	-6	14
Longitude	-106	7

While the scatters in the two quantities compared suggest that the two independent determinations agree at the twenty centimeter level in the equatorial components, the large uncertainty in the ephemeris-radio source catalogue dominates the comparison. This comparison can be updated using Spacecraft Tracking data with the addition of Jupiter and Saturn encounters evaluated with the improved ephemerides for these planets, more recent results of the VLBI measurements, and more recent LLR results. Moreover, by combining the accurate relative threedimensional positions of the DSN antennas from the VLBI data, the longitude orientation from the spacecraft tracking, and the z-component (height above the equator) from LLR, the ephemeris-radio source frame tie can be estimated, and a geocentric ephemeris-oriented terrestrial reference frame can be established with an accuracy of 25 cm.

Details of these calculations are given in Niell (1984). Much of the work in this paper was carried out while the author was at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Allen, S.L. et al., 1983. Crustal Dynamics Data Package.

Carter, W.E., and Pettey, J.E., 1981. "Report of survey for McDonald Observatory, Harvard Radio Astronomy Station, and Vicinity", NOAA Technical Memorandum NOS NGS 32.

Dickey, J.O., 1983. "LURE Results", IUGG Meeting, Hamburg, Germany.

Liewer, K.M. (private communication) "DSS13/DSS14 baseline with 1-cm precision"

Moyer, T.D., "Station Location Sets LS111B and LS1118", Jet Propulsion Laboratory IOM 314.5-724, 26 October 1983

Newhall, X X, Preston, R.A., and Esposito, P.B., "Relating the JPL VLBI Reference Frame and the Planetary Ephemerides," 1986, Proceedings IAU Symposium No. 109: Astrometric Techniques, Gainesville, FL (in press).

Niell, A.E., "Absolute Geocentric DSN Station Locations and Radio-Planetary Frame Tie", Jet Propulsion Laboratory IOM 335.2-159, 21 March 1984.

Sovers, O.J., et al, "Radio Interferometric Determination of Intercontinental Baselines and Earth Orientation Utilizing Deep Space Network Antennas: 1971 to 1980", Journal of Geophysical Research, Vol. 89, No. B9, p. 7597-7607, Sept 10, 1984.

Standish, E.M., "Planetary and Lunar Ephemerides, DE125/LE125", Jet Propulsion Laboratory IOM 314.6-591, 29 July 1985.