RADIO ASTROMETRY FROM THE MOON

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An array of three radio telescopes on the Moon, separated by 100–1000 km, could measure the positions of compact radio sources 50–100 times more accurately than can be done on Earth. These measurements would form an all-sky reference frame of extreme precision (5–10 μarcsec) and stability, with applications to the dynamics of the solar system, our galaxy, and nearby galaxies.

RADIO ASTROMETRY: EARTH-BASED LIMITATIONS

The angular resolution, θ, of a telescope of diameter d receiving electromagnetic radiation at a wavelength λ is limited by diffraction to $\theta \approx \lambda/d$. At optical wavelengths, the diffraction limit is $<1''$ for telescopes larger than about 10 cm. At radio wavelengths of 1-6 cm, where telescopes of diameter 50-100 m operate, the diffraction limit is $20''$-$10'$. This would seem to favor optical wavelengths for high angular resolution. However, the use of superheterodyne detectors at radio wavelengths allows data from widely separated telescopes to be coherently combined, thus synthesizing very large apertures. The angular resolution of this technique, radio interferometry, is limited only by the physical separation of the antennas.

The precision of radio astrometry, the measurement of angular positions on the sky, can be superior to the angular resolution. However, a number of systematic error sources limit the accuracy. The two most serious such error sources for Earth-based measurements arise from the troposphere and from deformations and irregular rotation of the Earth.

The troposphere introduces a delay of about 7 nsec to incoming wavefronts. The component of this delay due to water vapor is difficult to calibrate precisely because the distribution of water vapor is very inhomogenous, both spatially and temporally. Water vapor radiometers measure the integrated line-of-sight emission from the 22-GHz water line, an imperfect measurement of the column density of water vapor along that line of sight. Even with parameter estimation from the astrometric measurements, this limits the accuracy of the measurements. Future water vapor radiometers will improve the accuracy by an unknown amount. Based on current experience, tropospheric water vapor may well limit the accuracy of radio astrometry to 300-500 μarcsec.

The rotation of the Earth is uniform to first order, both in rate and in the direction of the rotation axis. However, there are second-order perturbations in both quantities due to a variety of effects with large stochastic (i.e., unpredictable) components. These stochastic terms arise from the evolving fluid sheath of the Earth, as well as the large fluid core. At the submilliarcsecond level of accuracy, the rotation phase will need to be measured several times per day, or perhaps even much more often, precluding the possibility of estimating it from astrometric measurements. The largest variation in the shape of the Earth is due to lunar tides, and can be modeled. However, more minor deformations due to the variable distribution of the atmosphere and of liquid and solid water greatly complicate the time variation of the vector between the two radio telescopes (the baseline vector). One or several of these rotational and tidal effects may impose a fundamental limit of 300-500 μarcsec on the accuracy of ground-based radio astrometry.

Differential Earth-based observations can determine small angular separations (i.e., between two closely spaced radio sources) to an accuracy of better than 500 μarcsec. However, the accuracy of an all-sky astrometric catalog is limited by the effects discussed above.

ADVANTAGES OF THE MOON

The Moon allows an opportunity to escape from the two largest error sources of Earth-based radio astrometry. The Moon has a negligible neutral-gas atmosphere, and because it has no fluid sheath or sizable liquid core, its rotation and deformations can be modeled to very high accuracy. This latter facet gives it a large advantage over Earth orbit as a site for high-precision astrometry.

PROPOSED LUNAR ASTROMETRIC INSTRUMENT

I propose an array of three radio telescopes on the Moon. They would be arranged very roughly in an equilateral triangle located near the lunar equator (thus allowing most of the sky to be accessible). The distance between telescopes would be in the 100-1000 km range (it is not clear what separation will give the best accuracy). Lightweight antennas of about 15-m diameter with surface tolerance in the range 0.2-0.5 mm would be used.

Microwave links or coaxial cables would connect the three antennas to a control center (this could be located near one of the antennas). Local oscillator phase would be distributed to the antennas, with intermediate frequency (IF) data transmitted back for correlation. The correlation process would reduce the data volume to a few kilobytes per hour, which would be sent to Earth for subsequent analysis.

SOURCES OF ERROR AND ESTIMATED ACCURACY

This instrument would concentrate on several hundred compact radio sources, distributed more or less uniformly over the sky. It would observe the entire set of sources 3-20 times during a month (only half of them are visible at any one time).

This observing strategy reveals systematic effects in the data much better than long integrations on individual sources. A one-year observing program on 500 sources would give a total integration time of about 15 hours per source. This yields a precision from S/N limitations of

$$\Delta\theta = \frac{8\mu\text{arcsec}\ T_{50}}{D_{100}S_{100}(BW_{GHz})^{0.5}d_{15}^2\nu_{30}}$$

T_{50} is the system temperature in units of 50 K, D_{100} is the antenna separation in units of 100 km, S_{100} is the source correlated flux in units of 100 mJy, BW_{GHz} is the IF bandwidth in GHz, d_{15} is the antenna diameter in units of 15 m, and ν_{30} is the sky frequency in units of 30 GHz.

The absence of a neutral-gas atmosphere eliminates one large error source. The delay introduced by charged particles in the solar wind and the Earth's magnetosphere can be measured and removed by dual frequency observations (e.g., 40 GHz and 2 GHz). The bandwidth at the lower frequency can be much smaller than at the higher frequency.

The rotation of the Moon must be either modeled or determined via parameter estimation. Because the Moon is geologically quiet, with no atmosphere or oceans, its motions are very deterministic. Libration (nonlinear rotation) terms due to gravitational harmonics up to degree and order 4 (18 terms), with perhaps a few fifth degree terms, will be important for accuracies in the microarcsecond regime. In addition, Love numbers through degree 3 or 4 (12-18 parameters) will be required to model tidal deformations.

The proposed astrometric instrument will therefore be required to solve for 30-40 time-invariant lunar motion parameters. These parameters are of great interest in their own right, as they provide information on the physical properties of the lunar interior. In addition, there may be a small stochastic component to lunar rotation. It is at least 100 times smaller than its terrestrial equivalent, and varies on much longer timescales, allowing it to be easily determined from the data. The fundamental limitation on astrometric accuracy from lunar motions appears to be below 10 μarcsec.

Source structure effects may cause the largest errors. Compact extragalactic radio sources have nonzero sizes and time-variable structure. The relatively short baselines (<1000 km) of the proposed instrument will result in many sources being only slightly resolved. The measured positions for these sources will be that of the emission centroid. In general, the smallest apparent position shifts will occur for the most compact sources. There are many moderately weak (100 mJy) sources with estimated sizes under 50μarcsec at observing frequencies of 30-50 GHz. The variation in emission centroid will generally be <20 μarcsec. Measurements of many sources will determine a global frame to an accuracy at least a factor of 2 better, or <10 μarcsec. The desire to minimize source structure effects on the data forces the sky frequency to be at least 30 GHz, with 40-50 GHz desirable. Yet larger frequencies are disadvantageous due to higher system temperatures and degraded antenna performance.

The control of instrumental errors will be a major problem at this level. Thermal and gravitational deflections in the antennas will have to be known to better than 0.1 mm. Systematic instrumental phase errors must be smaller than 0.5° for 10 μarcsec accuracy at 40-GHz sky frequency on a 200-km baseline. Very careful design and construction will be required, but this should not be the limiting source of error.

CONCLUSIONS AND APPLICATIONS

The overall limiting astrometric accuracy of this instrument is estimated at 5-10 μarcsec, a factor of 50-100 improvement over Earth-based capability. A global reference frame with this accuracy would yield significant scientific results. The dynamics of our own galaxy could be determined to high accuracy through the study of the proper motions and parallaxes of compact galactic radio sources. The galactic rotation curve and deviations from rotational motion would be revealed in detail. Proper motions of nearby (distance less than 5 Mpc) galaxies would be measurable.

This reference frame would have other applications. The positions of planets could be determined in the frame through VLBI observations of spacecraft in orbit about those planets. This would allow very precise studies of solar system dynamics.

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