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LUNAR RADIO ASTROMETRY

Roger Linfield
NASA Jet Propulsion Laboratory
Pasadena, California 91109

Abstract

The accuracy of Earth-based radio astrometry is limited in a fundamental way by the variable delay of the troposphere and by the centimeter-scale motions of a dynamic Earth. Going to Earth orbit solves the variable-delay problems, but problems with evolution of the baseline vector remain. The Moon can provide a stable platform where the potential accuracy of radio astrometry is one to two orders of magnitude better than from the Earth.

Background

Radio astrometry can be broadly separated into two types.

1. Connected-element interferometry – With this type of radio astrometry, the local oscillator (LO) signal is distributed and the relative phase at the two ends of a baseline is measured. The angular measurement precision is

$$\Delta\theta \sim \frac{\lambda}{D\, SNR}$$

where λ is the wavelength of observation, D is the baseline, and SNR is the signal-to-noise ratio; $SNR \propto (BW_{tot})^{0.5}$, where BW_{tot} is the total correlated bandwidth.

2. VLBI – In this type of radio astrometry, independent LO's are used and the relative arrival time at the two ends of a baseline is measured by bandwidth synthesis (BWS). The angular measurement precision is

$$\Delta\theta \sim \frac{c}{D\, BW_{span}\, SNR}$$

where c is the speed of light and BW_{span} is the spanned bandwidth, which is generally larger than BW_{tot}. As in the other case, $SNR \propto (BW_{tot})^{0.5}$.

Current Accuracy and Limitations

Currently, on Earth, very-long-baseline interferometry (VLBI) yields higher accuracy astrometry than does connected-element interferometry. The accuracy, as determined by comparing independent VLBI catalogs, is approximately 3 marcsec and is limited primarily by two effects. The first is the delay introduced by the troposphere: typically 7 nsec and highly variable. Much of this variation is due to water vapor and is difficult to calibrate. Water vapor radiometers enable an estimate of the delay by measurement of the brightness temperature of atmospheric water vapor emission at 22 GHz. The accuracy of this method is limited by uncertainty in the (variable) vertical distribution of water vapor in the troposphere; this effect may fundamentally limit the accuracy of Earth-based astrometry at about the 1-marcsec level.

The second major error source involves the evolution of the baseline vector between the two telescopes. This evolution is primarily the result of the (nearly) constant rotation of the Earth, but numerous secondary effects (e.g., polar motion, short-term variations in rotation rate, solid Earth tides, variable atmospheric and ocean loading on the continents) are important for accuracies below about 50 marcsec. Because of the active dynamics of the Earth, it is difficult to calibrate these effects to high precision. Their short time scales (<1 day) and stochastic nature may also introduce an ultimate limitation of ~ 1 marcsec to Earth-based astrometric accuracy.

Lunar Radio Astrometry

Use of the Moon as a platform for astrometry offers a chance to completely escape the effects of the troposphere and to greatly reduce the effects of baseline evolution. Consider an instrument of three identical antennas on the Moon arranged in an equilateral triangle. Antenna separations (baselines) would lie somewhere in the 100- to 2000-km range. The lunar environment would allow use of very lightweight (possibly remotely deployed) antennas with diameters of 10 to 15 m. Whether the instrument would give higher accuracy in a connected-element (distributed LO) mode or VLBI (separate LO's) mode is not certain. Over short distances, the LO signal could probably be distributed very accurately by cable or microwave link between relay towers; over longer distances, it might have to travel by satellite, and the path length uncertainty would be a problem. Both operating modes will be considered. For either mode, the received data would be amplified, mixed to a lower frequency, and transmitted to a single site (probably at a human colony) for real-time correlation of $\sim$500-MHz bandwidth. Correlated data plus calibration and bookkeeping information could be transmitted to Earth for analysis. Either a low-bandwidth link or the regular delivery of data on tape would suffice. Power for the antennas could be supplied by solar cells with storage batteries for the lunar night; by this means, the instrument could operate continuously.

Error Analysis of Proposed Instrument

Propagation effects are a major error source on Earth. The Moon has no troposphere, but there will be some delay introduced by charged particles in the lunar ionosphere, in the solar wind, and (occasionally) in the Earth's magnetotail. This effect, already small, can probably be reduced to insignificance by observing at high frequencies (20 to 30 GHz), since the delay varies as the square of the observing wavelength. If necessary, the effect of charged particles can be completely removed with dual-frequency observations, as is often done on Earth with simultaneous 2.2-GHz and 8.4-GHz measurements.

Baseline knowledge is the other limiting error source on Earth. As revealed by lunar laser ranging, the situation on the Moon is quite different. The nonlinear terms in the lunar rotation rate are as large as for the Earth, but they are much more predictable. The Moon has no fluid sheath around it and is much quieter dynamically than is the Earth. At the level of 0.1 marcsec, there are about 30 constant terms in the lunar potential and elasticity (e.g., Love numbers for solid-body tides) which would need to be measured to adequately describe the baseline evolution. These quantities would be solved for as part of a global fit to the delay or phase measurements made with the interferometer. The stochastic component of the Moon's motion is about 100 times smaller than that of the Earth, and it varies much more slowly (time scales of 1 month and longer). Therefore, it can easily be solved for from the data. Lunar motions should have no effect on accuracy at the 0.1-marcsec level if appropriate care is taken.

Source structure will cause systematic errors in astrometric measurements. This effect is most serious for bandwidth-synthesis measurements of a source which is significantly resolved, and can be many milliarcseconds in size. The baselines of the proposed lunar interferometer are sufficiently short that there will be many nearly unresolved sources (especially at 20 to 30 GHz); the interferometer could concentrate exclusively on such objects. In that case, the measured astrometric position will be the emission centroid at that frequency.

High observing frequencies (20 GHz or higher) are thus desirable, as source sizes shrink with increasing frequency for most sources, and the centroid should be closer to the massive "central engine" powering the source than at lower frequencies. At 30 GHz, many sources will be 0.1 to 1.0 marcsec in extent. Time variation of the emission centroid is of concern, particularly for super-luminal sources of moderate size such as 3C 345 and 3C 273. The VLBI maps made on Earth will be of help in this instance and should be useful in calibrating this time variation to 0.1 marcsec or better. Many sources will have structure much less variable than that of 3C 345, and this calibration will not be necessary.

Signal to noise will be more of a limitation than for Earth-based astrometry. When compared to antennas and receivers used on Earth, the lunar antennas will be smaller, and, because of the expense of refrigeration, the receivers may be of lesser quality. Furthermore, the baselines are shorter, and the required accuracy is higher. A 1-year observing program on 500 sources will allow 100 10-minute scans per source. The sensitivity limitations on angular accuracy are as follows.

1. For BWS (VLBI),

$$\Delta\theta = \frac{0.06 \text{ marcsec } T_{50}}{D_{1000} S_{0.2} (BW_{500})^{0.5} d_{15}^{2} BW_{span}}$$

2. For radiofrequency (RF) phase measurement (connected-element interferometry),

$$\Delta\theta = \frac{0.006 \text{ marcsec } T_{50}}{D_{100} S_{0.2} (BW_{500})^{0.5} d_{15}^{2} \nu_{30}}$$

Here, T_{50} is the system temperature in units of 50 K, D is the antenna separation (in units of 1000 km for VLBI, 100 km for connected-element interferometry), $S_{0.2}$ is the correlated flux in units of 0.2 Jy, BW_{500} is the correlated bandwidth in units of 500 MHz, d_{15} is the antenna diameter in units of 15 m, BW_{span} is the spanned bandwidth in units of 1 GHz, and ν_{30} is the observing frequency in units of 30 GHz.

Instrumental effects will be a major problem. For VLBI observations, the quality of the local oscillators will probably be the critical issue. Hydrogen masers have errors of ~40 psec in 10^4 sec, but 0.1 marcsec corresponds to a delay precision of 1.5 psec over a 1000-km baseline. A new generation of frequency standards would be required.

For connected-element observations, the clock quality is not critical. However, as 0.1 marcsec corresponds to a delay of only 0.15 psec (0.05 mm light travel time) over a 100-km baseline, extreme care would be needed in the distribution of the local oscillator signal and in the calibration of any instrumental phase and delay effects. This constraint would probably pose the greatest technical difficulty to performance of astrometry with an accuracy of 0.1 marcsec or better. Three possible ways to improve the accuracy are

1. Increase baseline length to decrease the sensitivity to the effect.

2. Use round-trip transmission to cancel out length variations in the LO signal transmission path.

3. Distribute the LO signal from a satellite in Earth geosynchronous orbit. Any errors in knowledge of the satellite orbit would be reduced by the ratio of baseline length to Earth-Moon separation.

Applications of Sub-0.1-Milliarcsecond Astrometry

An improvement in astrometric accuracy by more than an order of magnitude would have significant astronomical implications. A search for quasar proper motions would be of interest. The absolute motions of components in superluminal sources could be measured. On a galactic scale, it would be possible to measure the Sun's motion about the galactic center (5 marcsec/yr, allowing a 2% measurement in just 1 year). By observing a number of water masers (not possible with BWS) and radio stars, definitive studies of galactic dynamics become possible.

Spacecraft navigation would be helped by such high-precision astrometry. Missions to the outer solar system and beyond would benefit especially. An error of 0.1 marcsec corresponds to 2 km at Neptune's orbit and 15 000 km (0.0001 AU) at 1 pc.