Few-Hundred Microarcsecond VLBI Astrometry: Applications and Reduction of Limiting Error Sources

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Abstract. A wide-field, high-accuracy VLBI astrometric technique is described along with applications: the first measurement of planetary relativistic deflection, a state-of-the-art solar deflection measurement, and possible spacecraft tracking applications.

1. Introduction

This paper presents several applications of a few hundred microarcsecond (μas) astrometric technique which has been developed and demonstrated using differential very long baseline interferometry (VLBI). A brief description of the technique along with several applications will be discussed below. This technique was developed for high-accuracy deep-space tracking (TREUHAFT, 1988), but the first application measured the apparent position shift of an extragalactic radio source due to Jovian relativistic deflection (TREUHAFT and LOWE, 1991). We have also used this technique, with modifications to treat large solar plasma effects, in a state-of-the-art solar deflection measurement (LOWE and TREUHAFT, 1994) with many orders of magnitude less data than other deflection measurements. This solar deflection experiment could be the basis of a program to improve by a factor of 5–10 the Parameterized Post Newtonian (PPN) gamma parameter (WILL, 1971). Finally, a number of future spacecraft tracking applications, described below, are also enabled by this technique.

The few-hundred μas astrometric technique presented here depends on creating a local inertial reference frame, defined by several natural extragalactic radio sources. These sources are located throughout the observing station's mutual visibility region, and represent about a 30° × 30° field in the sky. The "target" source, which can be a natural radio source or a spacecraft, is defined as the radio source whose position one wishes to measure relative to the local frame. As described below, measurements of the target's position are made at two different epochs and differenced so the position shift of the target is the final measured quantity.

To make astrometric measurements at the few hundred μas level requires aggressively eliminating dominant systematic errors. The best a priori models of the delay measurements are used, followed by a least squares estimation for parameters associated with known physical effects, such as station clock drifts, earth orientation and tropospheric delays, which effectively improve the model. By making two identical measurements, in the sidereal sense, and calculating the position shift of the target, many constant, unmodeled errors cancel. The most sensitive instrumentation, the Deep Space Network (DSN) antennas (70 m, 20°K), are also used to reduce white system noise. The two dominant error sources remaining are index-of-refraction fluctuations in the wet troposphere, and system noise. Both of these error sources can be modeled a priori; tropospheric fluctuations are modeled using Kolmogorov turbulence theory and system noise is a function of the number of data bits sampled. Thus, the measurement error covariance is calculated a priori, and not artificially inflated, as is done with most VLBI analyses. The contribution to the target shift from a variety of possible systematic effects can be estimated using sensitivity analyses. This allows one to determine how well unmodeled errors, such as station location or antenna deformation errors, cancel when forming the differential positions.

2. Planetary Relativistic Deflection

The first application of this technique was planetary (Jovian) relativistic deflection. Because this work has been published, only a quick review will be given here. The physics behind this measurement, from the General Relativity point of view, is that Jupiter's mass gives rise to a local spacetime curvature. This curvature causes electromagnetic radiation passing near the planet to experience a small angular deflection. On 21 March 1988, Jupiter passed within 200 arcseconds (≈ 10 Jovian radii) of radio source P 0201 + 113. Such an occultation occurs about twice per decade, on average. Ten measurements of the target position were made on that date over the 4 hours of mutual visibility. The average deflection, projected onto the California-Australia baseline used here, was about 300 μas. About two weeks later, on 2 April 1988, the observation sequence was repeated. On this date, Jupiter appeared about 1° from the target, and the average deflection was about 20 μas. Each of the 10 measurements had an average accuracy of 160 μas. Tropospheric fluctuations and white system noise contributed about 145 μas and 70 μas to this error, respectively. The reduced χ^2 is 0.6 for the General Relativity hypothesis and 4.1 for the no deflection hypothesis. This rejects the no deflection hypothesis with 99.999% confidence.

3. Solar Deflection

This technique has been recently used to make a solar deflection measurement. This measurement was motivated by the fact that, except for solar plasma effects, a solar deflection measurement similar to the Jovian experiment should result in about a 0.1% measurement; equal to the best measurement to date (Reasenberg *et al.*, 1979; Robertson *et al.*, 1991). It was also motivated by the fact that no significant improvement in solar deflection measurements has been made since the late 1970s. On 4 October 1992, 9 measurements of the position of 3C 279 were made relative to a local reference frame defined by 10 other reference sources. On this date, 3C 279 was 3.0° from the sun's center. Six days later, on 10 October 1992, observations using the identical sidereal schedule were made. On this date, 3C 279 was 2.9° from the sun's center, but on the other side of the sun, relative to the 4 October session. The data were correlated at the JPL/CIT Block II correlator using a non-standard operating mode where cross-correlator phasors are calculated at 0.025 second intervals. These short integration times are required to freeze solar plasma fluctuations in order to avoid incoherence. The post-correlation analysis was very similar to that used in the Jovian deflection experiment. The final result, expressed in terms of the PPN gamma parameter which specifies the amount of space-time curvature per unit mass, is:

$$\gamma - 1 = (-0.24 \pm 2.37) \times 10^{-3}.$$

This number is consistent with General Relativity, and the measurement error is very close to that expected from a covariance study performed before the data were taken. This result is also consistent with the Viking lander timing result (not a solar deflection measurement),

$$\gamma - 1 = (0. \pm 2.) \times 10^{-3}$$

and Robertson *et al.* result which measured solar deflection,

$$\gamma - 1 = (0.2 \pm 2.) \times 10^{-3}.$$

Robertson *et al.* result also used VLBI, but required over 340,000 observations taken over 10 years, while the result presented here is based on 94 observations from two 6-hour data-taking sessions. The high sensitivity and low system temperatures of the Deep Space Network were critical to this success.

Because the result presented here is based on a relatively small data set, repeating this measurement several times to obtain a more accurate gamma determination is a viable possibility. Future plans include studying the possibility of using tropospheric calibrations to significantly reduce the dominant systematic error far from the sun. This could result in highly accurate observations further from the sun (5–10 degrees, where plasma effects are much smaller) being the optimal configuration for measuring γ in terms of sun-earth-source angle. Combining several of these more accurate experiments should result in about an order-of-magnitude improvement in gamma's determination.

4. Spacecraft Tracking Applications

This few-hundred μas technique also opens up many potential deepspace tracking applications for missions to the outer planets (for reference, a 160 μas angular error corresponds to a 580 meter transverse position error at Jupiter). Current operational spacecraft tracking has angular errors on the order of 10 mas; a factor of 50 improvement could be possible if this technique were used. One problem in tracking spacecraft to the outer planets is that the spacecraft position is known in the radio reference frame while the planet's position is known in the planetary ephemeris frame. This technique could be used to better determine the angular offsets between the two frames by observing a spacecraft in orbit or on the surface of a planet. Similarly, a number of position measurements of a spacecraft as it approaches a planet could be used to determine the planet's position in the radio frame through the signature of gravity acting on the spacecraft. Some missions plan to release probes as they approach a planet. Position measurements of the spacecraft before and after the probe release can be used with momentum conservation to reconstruct the probe's trajectory. Such a measurement was planned for Galileo's probe release as it approaches Jupiter in December 1995, but this requires the on-board high-gain antenna which failed to deploy. The Cassini mission, which is to study Saturn and its rings and satellites, also plans a probe release; this one into Titan's atmosphere. Cassini could also use this technique to better measure the ring radii, which is a limiting error source in some ring dynamics models. Finally, missions could greatly reduce on-board fuel (and thus weight) if they could enter orbit by using a planet's atmospheric drag to slow it down, rather than by firing thrusters. Aerocapture, as this is called, would require high-accuracy navigation to guide the spacecraft into a narrow window in the upper atmosphere.

5. Summary

In summary, a radio metric technique with 160 μas accuracy over wide angles has been developed and demonstrated. This technique was used to make the first measurement of planetary relativistic deflection. The dominant error sources were modeled, so no arbitrary error inflation was necessary. A slight modification of this technique has been used to make a solar deflection measurement, comparable to the best measurement but with several orders-of-magnitude less data. This technique has also enabled several spacecraft tracking applications. Work is also underway to reduce tropospheric fluctuation effects, the dominant systematic error, by building an improved water vapor calibration system. This system would probably consist of an advanced water vapor radiometer (WVR), along with other ancillary data from radiosondes, microwave temperature profilers (MTPs), GPS observables, etc., to help convert the WVR brightness temperatures to path delays. Proof of concept experiments have been performed and are currently being analyzed.

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