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Recent VLBA/VERA/IVS tests of general relativity

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Abstract. We report on recent VLBA/VERA/IVS observational tests of General Relativity. First, we will summarize the results from the 2005 VLBA experiment that determined gamma with an accuracy of 0.0003 by measuring the deflection of four compact radio sources by the solar gravitational field. We discuss the limits of precision that can be obtained with VLBA experiments in the future. We describe recent experiments using the three global arrays to measure the aberration of gravity when Jupiter and Saturn passed within a few arcmin of bright radio sources. These reductions are still in progress, but the anticipated positional accuracy of the VLBA experiment may be about 0.01 mas.

Keywords. gravitation—quasars: individual (3C279)—relativity techniques: interferometric

1. The VLBA 2005 Solar-Bending Experiment

The history of the experiments to measured the deflection of light by the solar gravitational field is well-known. The 1919 optical experiment during a solar eclipse in Brazil established the viability of GR, and Shapiro (1964) suggested that radio techniques would provide much better accuracy. The precision of radio experiments over the last 40 years $\gamma < 0.001$ was achieved (e.g. Lebach *et al.* 1995, Shapiro *et al.* 2004).

Since the inception of operation in 1990, the positional accuracy that the Very Long Baseline Array (VLBA) can achieve has increased markedly, and it is now capable of measuring the angular separation between compact radio sources that are a few degrees apart in the sky with an accuracy of about 0.01 mas. These advances were made from increased stability and sensitivity of the array, more accurate determination of astrometric and geodetic parameters from the International VLBI Service (IVS), and the use of phase delay referencing even with antenna baselines greater than 5000 km. We, thus, observed on eight days in October 2005 in order to determined the change in relative

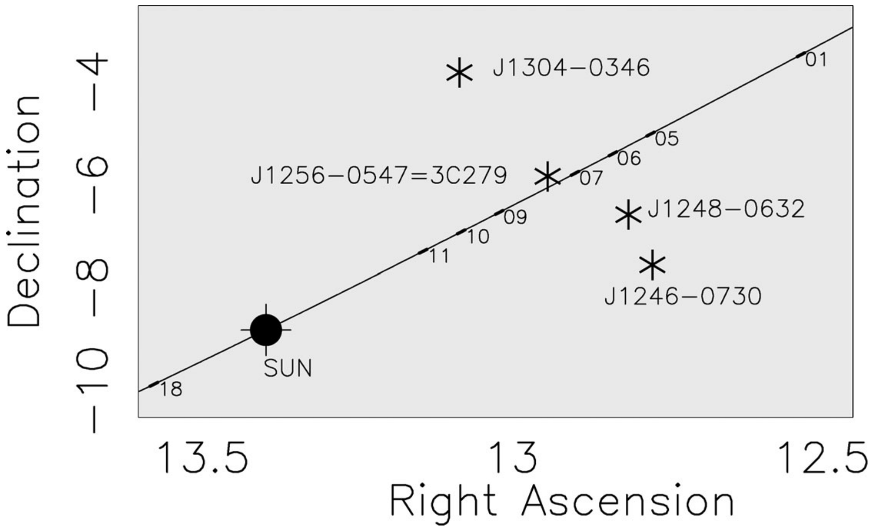

Figure 1. The Source Configuration for the Solar Deflection Experiment of 2005: The solar trajectory between October 1 and 18 is shown by the diagonal line, with the eight observing days superimposed. The location of the four radio sources are indicated.

position among four sources as the sun moved through the area in order to measure γ with high precision. The observing days and sources are shown in Fig. 1.

In order to minimize the effects of the solar corona, we used the highest routinely used VLBA frequency of 43 GHz. In order to lessen the effects of the changing tropospheric refraction above each telescope, we alternated source observations every 40 seconds. The choice of sources was a compromise among three criteria: sufficiently strong and compact to be detectable by the VLBA in about 20 sec; sufficiently close in the sky to avoid large tropospheric phase changes; but not closer than about two degrees in order to have a significant differential solar gravitational bending. We also observed at 23 GHz and 15 GHz (switching frequencies every 40 min) in order to estimate and remove the long-term coronal refraction.

The description of the experimental parameters, the reduction methods, and the analysis technique to estimate γ and its uncertainty are given in Fomalont *et al.* (2009). The results are $\gamma = 0.9998 \pm 0.0003$ (standard error). This is the most accurate radio interferometric result to date, although it is less accurate than the 2002 Doppler-tracking Cassini experiment (Bertotti *et al.* 2003) if one postulates that the translational gravito-magnetic field affects propagation of radio waves exactly as predicted in general relativity. This postulate was not parameterized in NASA ODP code and could not be directly tested in the Cassini experiment (Kopeikin *et al.* 2004, Bertotti *et al.* 2008, Kopeikin *et al.* 2009).

The accuracy of future VLBA experiments can be increased by a factor of four with several improvements: observing on all days when the sources were between 4° to 7° from the sun; choosing available sources in April to August when the sun is at its most northern declinations; increasing the relative observing time at 43 GHz since the coronal refraction correction was small; and scheduling an experiment as often as possible since about ten groups of sources near the ecliptic are available for a high precision experiment.

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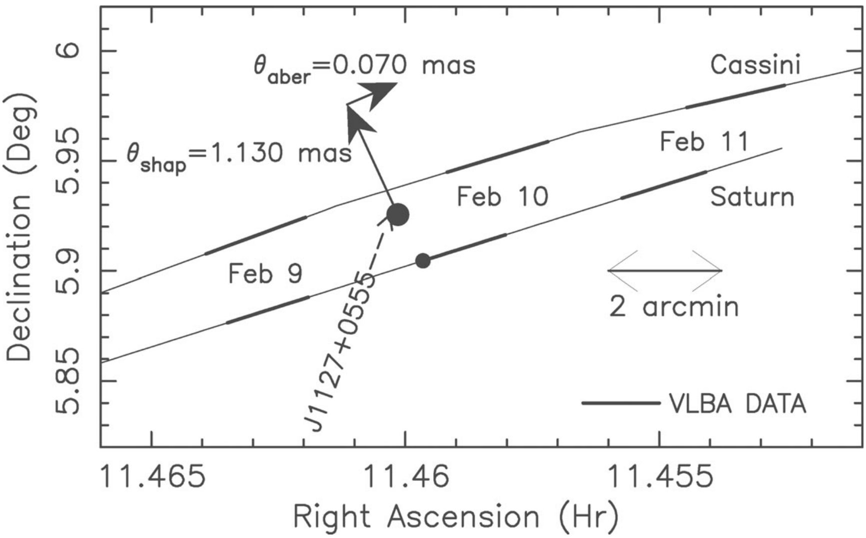

Figure 2. The Source Configuration for the February 2009 Aberration Experiment: The sky motion of Saturn and the Cassini spacecraft are shown by the lines from the lower left to upper right. The VLBA observing periods are shown by the bold part of the lines. At the closest approach of Saturn to J1127 + 0555, the predicted source deflection is 1.13 mas and the aberrational deflection is 0.070 mas.

2. The Planetary Gravitational Aberration Experiments

On September 8, 2002, Jupiter passed within 4′ of the quasar J0842+1835. Because of the motion of Jupiter, the gravitational bending of the quasar position was not precisely radial from the planet. For this experiment, the GR prediction of the non-radial deflection is 0.05 mas in the direction of Jupiter's motion in the sky at closest Jupiter/quasar encounter. (The radial deflection component at this time was 1.1 mas.) This aberrational-type deflection varies as $(v_J/c)\,d^{-2}$, where d is the angular separation in the sky between Jupiter and the quasar, and v_J is the *heliocentric* velocity of Jupiter (Kopeikin 2001). This aberrational deflection was measured with the VLBA with an accuracy of 20% (Fomalont & Kopeikin 2003). It demonstrated the gravito-magnetic effect caused by translational mass-current of a moving body, and also initiated many discussions about the experimental interpretation in the framework of the general theory of relativity.

Two planetary near encounters with bright radio sources have recently occurred. On November 19, 2008, Jupiter passed within 1.4′ of J1925 − 2219, and on February 10, 2009, Saturn pass within 1.3′ of J1127 + 0555. The arrays that observed these encounters were: International VLBI Service (IVS) array for both dates, the Japanese VLBI Exploration of Radio Astronomy (VERA) array for the November encounter (Honma *et al.* 2003), and the VLBA for the February encounter. The IVS observing programs are coordinated with the international community and use a variety of telescopes for semi-weekly to bi-monthly observations to monitor the earth orientation (see http://www.iers.org). For the November 19 experiment, the observing array included Parkes, Hobart26, Kokee, and Tsukub32. The nominal IVS 24-hour schedule (session OHIG60) was modified so that additional 8-hour observations of J1925 − 2219 and a nearby source J2000 − 1748 were included in order to determine the change of their relative position during the experiment. For the February 10 experiment (session RD0902), the observing array consisted of Parkes, Hobart26, Medicina, Matera, Badary, LA-VLBA, and KP-VLBA. The calibrator

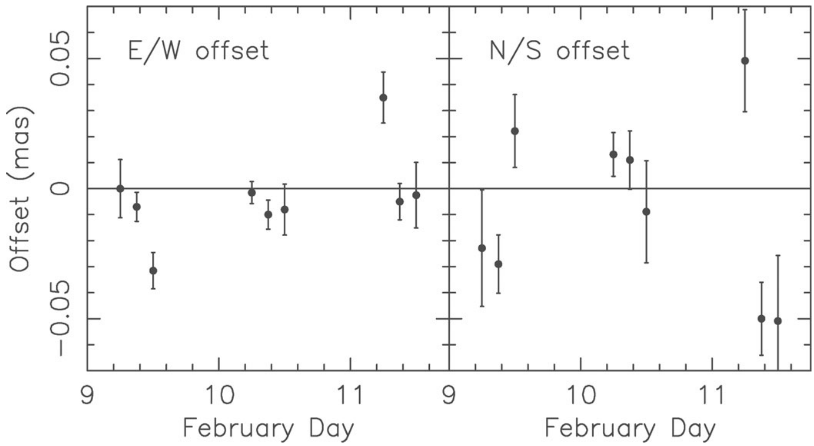

Figure 3. The Residual Differential Separation Between Cassini and J1127+0555: The separation between the two sources, after removal of the best-fit offset, velocity and acceleration from the measured offsets. The predicted gravitational bending of both Cassini and J1127 + 0555 has been removed, so the difference should be zero if the GR prediction is correct. The left plot is the east-west difference, the right plot is the north-south difference. The position difference estimates were obtained for the three 2.5-hour intervals on each day, and the error are the one-sigma errors expected from signal-to-noise considerations alone.

source for J1127 + 0555 was J1112 + 0724. The analysis of these two experiments are progressing.

The VERA observations were made on November 17, 19 (day of close encounter) and 22, each day for seven hours. This array has a dual-beam system so that two sources within 2.2° can be observed simultaneously—J1923−2104 and J1925−2219 are separated by 1.4°—and the expectation is that their relative positions can be determined to an accuracy of about 0.05 mas every two hours. The analysis is also in progress.

The reductions for the February VLBA experiment are nearly completed. The source configuration during the experiment is shown in Fig. 2. An interesting aspect of this experiment is that J1127+0555 was measured with respect to Cassini. (The emission from Saturn is too extended to be detected by the VLBA.) which was within 5′ of the source between February 9 to 11. With such a close encounter, the effects of the tropospheric refraction are small so the relative position of Cassini and the source could be measured with high accuracy, with the limit imposed by the signal-to-noise of the experiment of 0.004 mas. Both objects were sufficiently close to be observed simultaneously, rather than by switching between sources, further decreasing the tropospheric effects. However, the measurement of the deflection of the source requires that the orbit of Cassini is precisely known.

Because the VLBA experiment was correlated in early March using an approximate orbit of Cassini, the assumed position of Cassini used in the reductions produced a position difference with that of J1127+0555 that slowly drifted during the 3-day experiment. Cassini's orbital parameters cannot be predicted more than one month in advance because of interactions with the Saturnian moons and also by the occasional Cassini thrusts to optimize the orbit. We expect to have a much more accurate orbit for Cassini from the JPL Cassini navigation group by mid-2009.

Nevertheless, it is possible to surmise the positional sensitivity of the VLBA experiment. A good assumption is that the orbital model error of Cassini used in the VLBA reductions can be approximated by constant offset, velocity and acceleration over the observing period. If we further remove the radial and aberration deflection prediction by GR, then the resultant relative position of Cassini with respect to J1127 + 0555 should be zero. This position difference with the above adjustments is shown in Fig. 3. The departure of the residuals from zero has an error of about 0.01 mas E/W, and 0.02 mas N/S (this resolution is twice as poor). Since the aberrational deflection is 0.07 mas at closest encounter on February 10, this experiment may be a more accurate measure of the aberration deflection than that of the 2002 Jupiter experiment (Fomalont & Kopeikin 2003).

For the actual position comparison, we will use the observations on February 9 and 11 to determine the residual offset and velocity of Cassini with respect to J1127 + 0555. The acceleration residial of the Cassini orbit, however, must be known to less than 2.6×10^{-6} m^{-2}, corresponding to angular change of 0.02 mas over 48 hours, in order to interpolate the spacecraft quasar offset accurately on February 10 when the gravitational deflection is large.

3. Conclusion

Using the VLBA at 43 GHz with phase referencing observation, we have measured γ with an rms precision of 0.0003. With improved experimental strategies and observations of many source clusters near the ecliptic, the precision can be increased by at least a factor of four.

Recent experiments with the VLBA, the IVS array and VERA of radio sources with near encounters with Jupiter and Saturn will provide more accurate measurements of the gravito-magnetic effect by measuring the aberrational deflection of the sources. Results are not yet available, although the VLBA precision may be about 0.01 mas and, thus, produce a more accurate result than the 2002 VLBA experiment (Fomalont & Kopeikin 2003).

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