Plan and Schedule VLBI Observations of Close Approaches of Jupiter to Compact Extragalactic Radio Sources in 2016

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Abstract Very Long Baseline Interferometry is capable of measuring the gravitational delay caused by the sun's and the planets' gravitational fields. The post-Newtonian parameter γ [1] is now estimated with an accuracy of $\sigma_\gamma = 2 \cdot 10^{-4}$ using a global set of VLBI data since 1979 [2] and $\sigma_\gamma = 2 \cdot 10^{-5}$ by the Cassini spacecraft [3]. Unfortunately, VLBI observations very close to the solar limb are not possible due to strong turbulence in the solar corona. Instead of that, close approaches of the big planets to the reference quasars could be also used for testing of the general relativity theory with VLBI. Jupiter is the most appropriate among the big planets due to its large mass and relatively fast apparent motion across the celestial sphere. Here we discuss two approaches of Jupiter to reference radio sources in 2016 and propose to observe these events using the existing VLBI facilities.

Keywords VLBI, general relativity

1 Introduction

Einstein predicted the deflection of light passing by a massive body, in particular, at the solar limb about $1''.75$. This theoretical prediction was later confirmed using optical observations of stars during a total solar eclipse. In 1964, Shapiro [4] found that the light travelling in a static gravitational field undergoes additional time delay known as "Shapiro delay". The difference between two Shapiro's delays measured by two radio telescopes makes a gravitational delay [5],[6] which may be directly linked to Einstein's light deflection [7]. The gravitational delay measured with VLBI since 1979 is used to probe general relativity and estimate the post-Newtonian parameter γ. Due to the effect of the solar corona, VLBI observations closer than 4-5° from the sun are not possible. Therefore, a large set of data collected over many years is required to provide sufficient accuracy.

In contrast, close approaches of the big planets, especially Jupiter, could be observed at a very small angular distance equal to the planet's angular radius. As a result, the general relativity effects may become significant and could be observed with a set of large radio telescopes on a short time scale (1–2 days). Three approaches of Jupiter to quasars have been observed with VLBI by now. In 1988 [8] and in 2002 [9], Jupiter passed by radio sources in observed approaches at the angular distance of more than $3'$. A large observational campaign in 2002 was arranged using the VLBA network and the 100-meter Effelsberg radio telescope. In 2008 Jupiter passed by radio source 1922-224 at the angular distance of $1'.4$. But, due to poor observing conditions and a small network (Parkes, Hobart26, Kokee, and Tsukub32), this event was observed only during four hours. (Certain of these details are included in another paper in these Proceedings).

There will be two close approaches of Jupiter to radio sources in 2016 at angular distances of less than an arcminute, including a unique event—an occultation on 9 April, 2016. Both radio sources are weak; therefore, only big antennas should be included in the provisional VLBI network. We have investigated observing conditions of these events for all suitable radio telescopes. Our results are presented in the next sections.

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2 Theoretical Background

Recently, we have developed the formulae to link the VLBI gravitational delay and Einstein's deflection angle (details are provided in another paper of these Proceedings). It is essential that the gravitational delay may be formulated in terms of the angles between vectors (Figure 1).
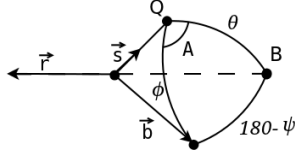
Fig. 1 Angle θ—the impact parameter, angle φ between vectors **b** and **s**, and angle ψ between vectors **b** and **r**.

The gravitational delay expressed in terms of the angles is given by

$$\tau_{GR} = \frac{2GM_J}{c^3} \frac{b \, \sin\varphi \sin\theta \cos A}{r(1 - \cos\theta)} + \text{small terms} \quad (1)$$
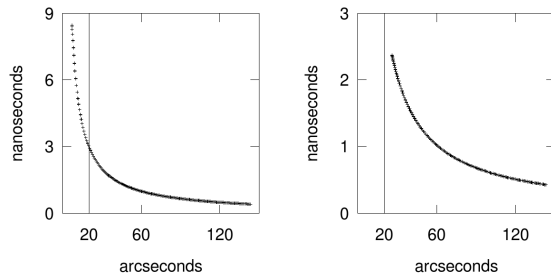
Fig. 2 Major term (Equation (1)) with respect to θ for Jupiter's approach to 1101+077 (left) and 1107+072 (right) of a baseline of length of up to 10,000 km. The vertical line separates two areas covered and uncovered by the Jupiter's disk.

The most important parameter is angle θ—the angular distance between Jupiter and the encountered quasar (Figure 2). The minimum observable distance between the radio source and Jupiter's center is equal to Jupiter's apparent radius (about $20''$). For approximation of small angles, Equation 1 could be replaced by

$$\tau_{GR} = \frac{4GM_J}{c^3} \frac{b \, \sin\varphi \cos A}{R} + \text{small terms} \quad (2)$$

where R is the physical radius of Jupiter—about 70,000 km.

The small terms depending on the baseline length are negligible for larger impact parameters but should be implemented for very small angles between two objects.

Once the separation between Jupiter and the quasar approaches this limit, the gravitational delay and deflection angle grow rapidly.

3 Events of 2016

There will be two close approaches in 2016 between Jupiter and reference radio sources (1107+072 on 26 March, 2016 and 1101+077 on 9 April, 2016) (Table 1). The minimum angular distances are $26''$ and $8''$ for the first and second event, respectively. Jupiter's angu-
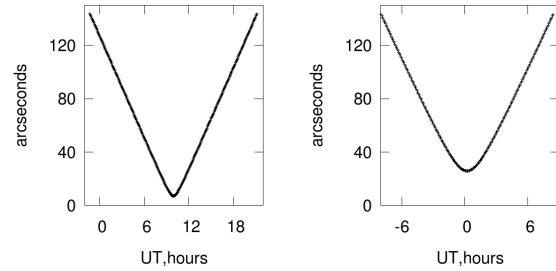

**Fig. 3** Impact parameter (θ) with respect to UT for 1101+077 (left) and 1107+072 (right).

lar size is about $20''$. Therefore, a unique event, occultation of the radio source 1101+077 by Jupiter, will be observed. The radio source will not be seen for about four hours during this occultation. Variations of θ with respect to UT are shown in Figure 3, while Figures 4 and 5 show the light deflection angle with respect to θ for the major and minor terms. For 1101+077, the effect of light deflection achieves its maximum value, approximately 16 mas on Jupiter's limb. The small terms grow faster ($\frac{b^2}{R^2}$), and the deflection angle measured at a very close angular separation will be dependent on the baseline length. It will reach about 3 mas for longer baselines (10^4 km). Therefore, the baseline-dependent effect could be measured by the existing geodetic VLBI facilities.
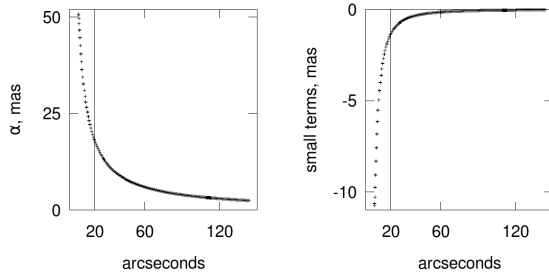
Fig. 4 Deflection angle calculated from Equation (1) (left) and from small terms (right) for 1101+077 and baseline length of 10,000 km. The vertical line separates two areas covered and uncovered by Jupiter's disk.
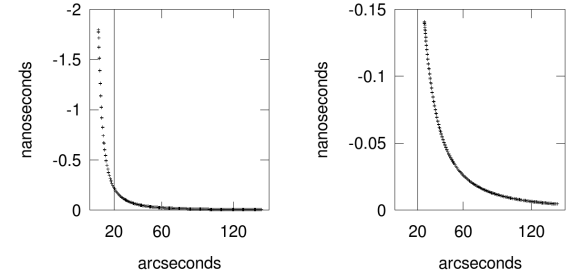
Fig. 6 Small terms (Equation (1)) with respect to θ for 1101+077 (left) and 1107+072 (right) and a baseline length of 10,000 km. The vertical line separates two areas covered and uncovered by Jupiter's disk.
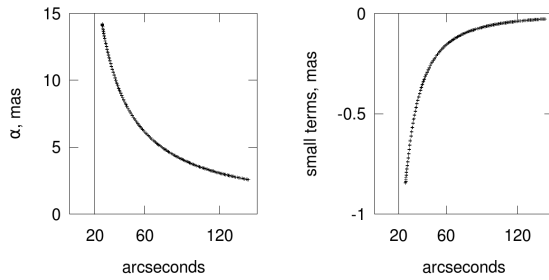
Fig. 5 Deflection angle calculated from Equation (1) (left) and from small terms (right) for 1107+072 and baseline length of 10,000 km. The vertical line separates two areas covered and uncovered by Jupiter's disk.
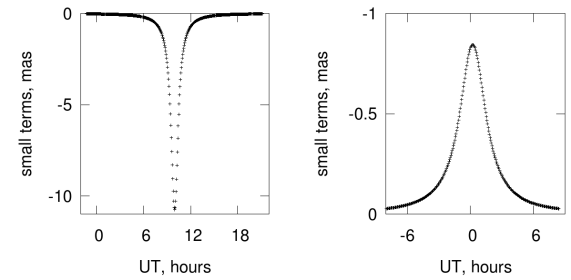
Fig. 7 Deflection angle converted from small terms (Equation (1)) with respect to UT for 1101+077 (left) and 1107+072 (right) and a baseline length of 10,000 km.

Table 1 Information about quasars.

quasar	date	θ''	Flux X(S), mJy	α, mas	other, ps
1107+072	26.03	26	~ 10 (20)	14.5	140
1101+077	09.04	20(8)	~ 38 (68)	16(46)	200(1600)

Basic information about these events in Table 1 also includes data flux densities of the radio sources in S- and X-bands. Unfortunately, both radio sources are weak; therefore, large radio telescopes are required for planning the experiments in order to keep the integration time at a reasonable level (less than five minutes).

Figure 6 shows additional contributions of the minor terms to the total delay with respect to the angle θ during the both events. The same additional contribution expressed in seconds of arc with respect to UT during both events is shown in Figure 7 (for a 10,000 km baseline).

It is important to note that the time delay for each baseline should be converted to the light deflection an-

gle using the angle A between directions to the baseline vector and the vector to the barycentric position of the deflecting body (as shown in Figure 1). Angle A is individual in every baseline; therefore, multiplication by the factor $\cos A$ in Equation (2) is necessary to calculate the path of the observed source position correctly for each time epoch. Then the meaning of the deflection angle for every epoch will be common for all baselines regardless of their lengths (Figure 8).
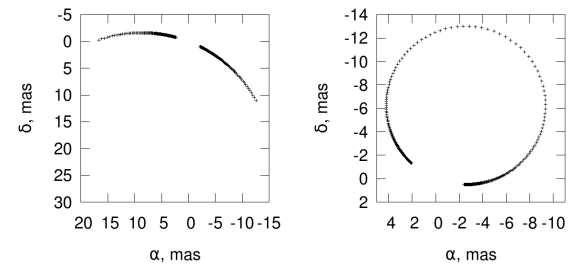
Fig. 8 Einstein's light deflection angle for 1101+077 (left) and 1107+072 (right).

4 Observational Goals

We are planning to arrange two dedicated geodetic VLBI sessions in 2016 to observe the unique astronomical events. The primary goal of this project is to test the previously proposed formulae, especially to indicate the tiny effect of minor terms at the closest angular distance between the radio source and the limb of Jupiter using a combination of baselines with different lengths, including lengths as much as 9,000 km and longer. It would be interesting to probe the predictions at the small impact parameter approach, first of all, whether the deflection angle is actually proportional to the baseline length due to effect of the minor terms in Equation (2).

Technically, we are aiming to obtain the deflection angle and the radio source positions at each observational epoch. For accurate estimation of the deflected position, one has to 1) collect as many single scans during the event as possible and 2) use as many VLBI antennas for each individual scan as possible. But, due to rather low fluxes of both radio sources, a compromise between the scan length and the number of observations must be the subject of careful consideration.

5 Technical Setup

The length scan for a single baseline is calculated as follows

$$\text{scanlen} = \left(\frac{\text{k} \times \text{SNR}}{\text{F}} \right)^2 \times \frac{\text{SEFD}_1 \times \text{SEFD}_2}{\text{Rate}} \quad (3)$$

where k is the efficiency coefficient for S- or X-band, SNR is the adopted signal-to-noise ratio, F is the flux density of a radio source in S- or X-band, Rate represents the antenna recording rate parameters, and SEFD (System Equivalent Flux Density) represents the antenna technical parameters. Table 2 shows SEFD values for several radio telescopes suitable for observing weak radio sources.

Table 2 List of stations SEFD_X.

Svetloe	250	Zelenchuk	255
Badary	300	VLBA network	500
Parkes	200	Tsukub32	320
Kunming	600	Sheshan25	700

We have calculated observing schedules of both events in different modes to provide as many observations as possible keeping the parameters below. All simulations were done with the VieVS software [10].

- SNR (S) = 20, SNR (X) = 15
- SEFD (1, 2) = 200/700
- number of channels = 14
- bandwidth = 4/16 MHz and bandwidth = 128/512 MHz
- rate $\approx$ 16/64 Mbps and rate $\approx$ 512 Mbps / 2 Gbps

Expected scan lengths at different bandwidths and other parameters kept fixed are presented in Table 3.

Table 3 Table of rates.

bandwidth	scan length 1107+072, 26.03.16 flux = 10 mJy in X band	scan length 1101+077, 09.04.16 flux = 38 mJy in X band
16 MHz		8/24 min
32 MHz		4/12 min
128 MHz	20 min	50 sec/2 min
512 MHz	4 min	40 sec/56 sec

6 Conclusions

Two close appoaches of Jupiter to weak reference radio sources will happen in 2016. These events are favorable to test some predictions of general relativity, in particular, fast changes of the light deflection angle and small baseline-dependent effects. Two 24-hour specially scheduled sessions should be organized within IVS to observe the rare astronomical events.

Acknowledgements

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