Observations of Radio Sources Near the Sun

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Abstract Geodetic Very Long Baseline Interferometry (VLBI) data are capable of measuring the light deflection caused by the gravitational field of the Sun and large planets with high accuracy. The parameter γ of the parametrized Post-Newtonian (PPN) formalism estimated using observations of reference radio sources near the Sun should be equal to unity in the general relativity. We have run several VLBI experiments tracking reference radio sources from 1 to 3 degrees from the Sun. The best formal accuracy of the parameter γ achieved in the single-session mode is less than 0.01 percent, or better than the formal accuracy obtained with a global solution included all available observations at arbitrary elongation from the Sun. We are planning more experiments starting from 2020 using better observing conditions near the minimum of the Solar activity cycle.

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1 Introduction

In accordance with General Relativity the radio waves slow down due to the gravitational potential of the Sun (the so-called Shapiro effect; see Shapiro, 1964, 1967), making very long baseline interferometry (VLBI) a useful tool for testing General Relativity by means of the parameterized post-Newtonian (PPN) formalism (Will, 1993). Nevertheless, the accuracy of the PPN parameter γ obtained from absolute or differential VLBI observations (Fomalont et al, 2009; Lambert and Le Poncin-Lafitte, 2009, 2011) remains worse than the current best limit of $(2.1 \pm 2.3) \times 10^{-5}$ based on Cassini radio science experiment (Bertotti et al, 2003) by an order of magnitude. The upper limits on the parameter

γ have been improved substantially in the past 30 years (Robertson and Carter, 1984; Robertson et al, 1991; Lebach et al, 1995; Fomalont and Kopeikin, 2003), but some authors (Shapiro et al, 2004; Lambert and Le Poncin-Lafitte, 2009) found degradation in the estimates of γ with elongation, and suggested that this systematic effect may limit the improvement in the VLBI-derived γ upper limits, despite the dramatic growth in the number of observations in recent decades.

The current paper focuses on radio source approaches at angular distances less than three degrees from the centre of the Sun in order to measure the light deflection effect at the highest magnitude and, thus, to avoid a possible bias caused by observations at larger elongations. We report on two special VLBI sessions, AUA020 (May 2017) and AOV022 (May 2018), on the single-session estimates of γ.

2 Data

A dedicated geodetic VLBI experiment (AUA020, 01-02 May, 2017, part of AUSTRAL program) was scheduled to probe the gravitational delay effect using a network of seven radio telescopes (Svetloe, Zelenchukskaya, Badary, HartRAO, Seshan25, Sejong, and Hobart26). Two radio sources 0229+131 and 0235+164 were observed at range of angular distances from 1.15° to 2.6° from the Sun. The position of both radio sources with respect to the Sun at the start of the experiment is shown on Fig. 1. A serious issue in such a configuration is the solar thermal noise that penetrates to the signal through the side lobes, and could cause loss of data due to striking the signal-to-noise ratio. To overcome the problem, one has to

1) select strong radio sources with larger correlated flux density in both frequency bands,

2) use large radio telescopes with narrow side lobes and better sensitivity, and

3) use the highest possible data rate recording (e.g., 1 Gbps) to gain a better signal-to-noise ratio during the same integration time.

More details about the schedule design are published in (Titov et al, 2018).

The target radio source 0229+131 is a defining source of the ICRF2 whose position is given with an accuracy close to the ICRF2 noise floor of 40 μas. The position of the second target 0235+164 is less accurate

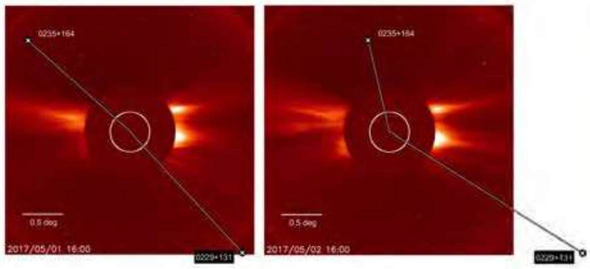

Fig. 1: Geometry of the radio sources close to the sun at the start (Left) and at the end (Right) of VLBI session AUA020 with respect to a LASCO C2 image of the solar corona. The Sun is hidden behind the occultation disc of the coronagraph, with the white inner circle representing the limb of the Sun. The field-of-view is 1.5 degrees elongation.

by a factor of five but still at the level of the ICRF2 median error and largely below the millisecond of arc. Both sources are compact and their structure indices measured at the time of the ICRF2 work were of 2.4 and 1.3, respectively, ensuring a structure delay lower than 2 ps (Fey and Charlot, 1997).

3 Analysis and Results

For purpose of cross-checking the results and testing their robustness, we processed the VLBI session AUA020 within two independent teams with two independent geodetic VLBI analysis software packages. The duplication of the analyses with two software packages also allows to use some specific options that are available on only one of them. The first analysis package is OCCAM (Titov et al., 2004) that implements the least-squares collocation method (Titov, 2000) for calibrating the wet troposphere fluctuations, and to account for the mutual correlations between observables. The second one is Calc/Solve (Ma et al., 1986), developed and maintained by the geodetic VLBI group at NASA GSFC, that uses classical least-squares. More details about the data analysis design are discussed in (Titov et al, 2018)

Table 1 shows the results of the AUA020 experiment data analysis. Uncertainties on γ lie between 0.9×10^{-4} and 4×10^{-4}. Our estimates appear therefore as precise as that obtained from global solutions using thousands of VLBI experiments (Lambert and Le Poncin-Lafitte, 2009, 2011). The formal error is about two times lower when γ is fitted to the observations of the radio source that is two times closer to the centre of the Sun (0235+164) than to that of its counterpart (0229+131). Using all scans returns a result similar to using only scans relevant to 0229+131 and 0235+164, confirm that only sources a low elongation can efficiently constrain the PPN parameter. Solutions from both software packages are consistent within the standard errors. The difference of postfit rms between OCCAM and Calc/Solve might find its origin in the different modeling of the nuisance parameters (stochastic versus CPWL function). No large systematics are detected except a 2.7σ deviation in the Calc/Solve solution when only 0229+131 is used and whose origin is unclear: as both solutions started from the same a priori, the issue could rather be in the estimation method or in the handling of troposphere/clock parameters.

It appears that during session AUA020, data in three channels at Sejong station were lost due to technical reasons. Therefore, we reprocessed the previous analyses after downweighting (but not suppressing) Sejong data. (We could test this option with OCCAM only since Calc/Solve does not handle downweighting.) The postfit rms of the solution is significantly lowered. The formal error on γ is marginally lowered down to 9×10^{-5}.

For purpose of comparison of the AUA020 session with other standard geodetic VLBI sessions, we estimated γ with Calc/Solve using the parameterization described above for each of sessions of the full geodetic VLBI data base made available by the International VLBI Service for geodesy and astrometry (IVS) since 1979 (at the exclusion of intensive sessions). The median postfit rms is 27 ps that is close to the postfit rms of the AUA020 session. The distribution of the obtained values of $\gamma-1$ is shown in Fig. 2 along with distributions of errors and normalized estimates. The distribution of errors in log-scale is slightly asymmetric, exhibiting a 'tail' on its right side that might traduce results from sessions not designed for precise astrometry. Nevertheless, assuming a Gaussian shape, the log-scaled distribution peaks at 10^{-2} with a σ of ~ 0.5. This makes the error estimate from AUA020, that is two orders of magnitude less, somewhat 'outstanding'. The bottom-right panel of Fig. 2 shows that the major part of the sessions does not bring severe systematics, the estimates of γ being unity within the error bars; session AUA020 is part of the session group that presents the lowest systematics.

Table 1: Estimates of $\gamma-1$ for the session AUA020, in unit of 10^{-4}, along with the session χ^2 and the postfit rms delay r in ps.

		$\gamma-1$ 10^{-4}	σ_γ 10^{-4}	χ^2	r
OCCAM	All stations				
	All scans	0.56	1.15	0.34	28
	0235+164	1.34	1.58	0.34	28
	0229+131	−1.54	3.41	0.34	28
	Both	0.53	1.14	0.34	28
	With Sejong downweighted				
	All scans	0.91	0.94	0.27	21
	0235+164	1.64	1.29	0.27	21
	0229+131	0.32	2.83	0.27	21
	Both	0.89	0.94	0.27	21
Calc/Solve	All sources	−0.22	1.10	0.84	26
	0235+164	1.85	1.48	0.84	26
	0229+131	−6.84	2.53	0.84	26
	Both	−0.26	1.09	0.84	26

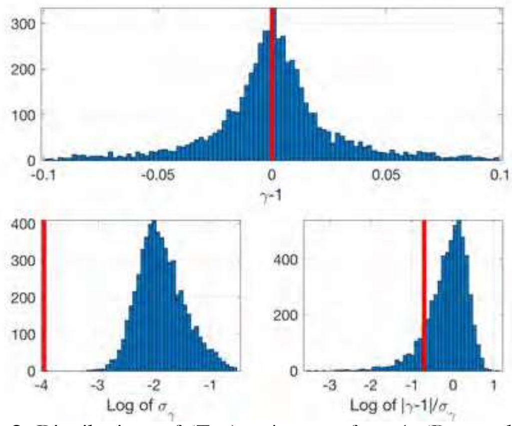

Fig. 2: Distributions of (Top) estimates of $\gamma-1$, (Bottom-left) their formal errors, and (Bottom-right) normalized estimates of $\gamma-1$ for all of the geodetic VLBI sessions. The vertical, red bar stands for the results of the AUA020 session.

Another experiment (AOV022) was undertaken on 01-02 May, 2018 with ten radio telescopes (Svetloe, Zelenchukskaya, Badary, Hobart26, Seshan25, Kunming, Ishioka, Yarragadee, Katherine, Warkworth). The same radio sources (0229+131 and 0235+164) were scheduled with the same strategy. The statistics of the result was found to be 2-3 times worse than from AUA020, presumably, due to severe source structure delay effect. Fig. 3 shows the post-fit residuals of for radio source 0229+131 for two baselines, Ishioka-Seshan25 and Badary-Zelenchk. The variations of the residuals are consistent to the variations induced by

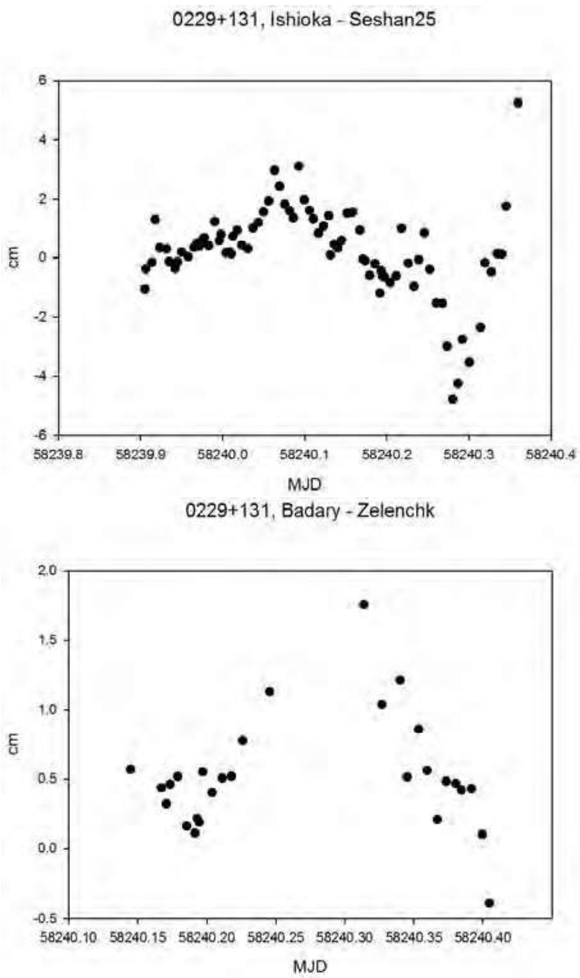

Fig. 3: Post-fit residuals of 0229+131 with baselines Ishioka-Seshan25 and Badary-Zelenchk.

the source structure (Titov and Lopez, 2018) therefore, we believe, that more detailed analysis is required to obtain a better statistic for this experiment.

4 Conclusions and outlook

In this paper we discuss our results on testing of general relativity with geodetic VLBI using the close approach of the Sun to the reference radio sources. It was a general misconception in the past that the effect of the plasma of the solar corona completely disturbs the interferometric responce for light rays passing within several degrees from the Sun. We proved that these perturbations are at an acceptable level unless the signals pass active streamers in the solar corona. Therefore, the standard dual frequency calibration facilitates the stochastic noise induced by charged particles the solar corona by the same way as for the ionosphere around the Earth.

While the systematic effects based on radial or dipole models of the corona appear to be negligible, individual group delay observations are affected by random scatter caused by small-scale coronal structure and temporal variations thereof. Since these perturbations do not systematically affect the observations, we assume that they cancel out over the period of observations (17 hours with observations angularly close to the Sun). Since the ray paths to the radio sources 0235+164 and 0229+131 within small solar elongation happened to be in quiet regions (cf. Fig. 1), the scatter was small enough that precise group delays could be successfully determined at such small elongations.

The major source of stochastic noise in VLBI measurements resides in the unknown wet troposphere delay. The difference between VLBI estimates of the wet troposphere delay and independent radiometer data appears to stay within 3 mm, or 10 ps (Titov and Stanford, 2013) suggesting that the impact of the wet troposphere delay on the astrometric light deflection angle estimation near the Sun is negligible.

Overall, a total improvement of the uncertainty on γ by a factor of ten is expected, enabling to challenge the current limit imposed by the Cassini radio science experiment of Bertotti et al (2003), although the Gaia astrometry on Solar system objects is expected to deliver an accuracy of 10^{-6} (Mignard and Klioner, 2009).

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