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Very long baseline interferometry: accuracy limits and relativistic tests

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Abstract. We present a review on relativistic effects and best estimates of the relativistic PPN parameter γ obtained by analysis of data from the International VLBI Service for Geodesy and Astrometry (IVS). Relativistic implications are also considered in view of the upcoming new generation VLBI System: VLBI2010.

Keywords. VLBI, PPN parameter γ, VLBI2010

1. Introduction

Since the foundation of relativity by Einstein (1908) many groups have sought to verify this remarkable theory. Einstein (1911) himself was the first proposing an experimental test of the deflection of light by the Sun by observing star light very close to the Sun during a total solar eclipse. Such tests were actually carried out during almost all solar eclipses from 1919 on, e.g. by the Texas Mauritanian Eclipse Team (1976) and led to first experimental proofs of Einstein's theory within about $\pm 20\%$ uncertainty. Some years earlier, Very Long Baseline Interferometry (VLBI) came up and it was Shapiro (1967), who had the idea to utilize this new technique for the detection of light deflection. Seielstad *et al.* (1970) were among the first to realize radio interferometry for gravitational deflection in practice.

2. Determination of the PPN parameter γ by VLBI

The relativity in this context is usually described by the parameterized post-Newtonian (PPN) formalism (cf. Soffel, 1989), which defines a number of PPN parameters numerically expressing certain interactions between time, space, and e.g. mass. One of those variables, the parameter γ, describes how much space is curved by unit mass and equals unity in Einstein's theory. Expressed in the PPN formalism, the angle θ through which a radiowave is deflected is given approximately by (e.g. Shapiro *et al.*, 2004)

$$\theta \approx \frac{(1+\gamma)\,GM}{c^2 b}\,(1+\cos\phi) \tag{2.1}$$

where GM denotes the product of the Newtonian gravitational constant and the mass of the considered gravitating body, c the vacuum speed of light, b the distance of closest approach of the radiowave's path to the center of the gravitating body, and ϕ is the angle between the gravitating body and the radio source as viewed from Earth.

Besides the bending effect, interferometry is capable of measuring the temporal delay of radiowaves, also known as Shapiro delay (Fig. 1). In the case of VLBI the gravitational time delay is considered as

$$\tau_{\text{grav}} = (1+\gamma)\cdot\frac{GM}{c^3}\cdot\ln\left[\frac{|\mathbf{x_1}|+\mathbf{x_1}\cdot\mathbf{k}}{|\mathbf{x_2}|+\mathbf{x_2}\cdot\mathbf{k}}\right] \tag{2.2}$$

where $\mathbf{x_i}$ denotes the position vector of the **i**-th antenna with respect to the center of the gravitating body and $\mathbf{k}$ is the unit vector towards the radiosource as viewed from the Earth-bound baseline.

The partial derivative of the delay with respect to γ is easily comprehensible:

$$\frac{\partial\tau}{\partial\gamma} = \frac{GM}{c^3}\cdot\ln\left[\frac{|\mathbf{x_1}|+\mathbf{x_1}\cdot\mathbf{k}}{|\mathbf{x_2}|+\mathbf{x_2}\cdot\mathbf{k}}\right] \tag{2.3}$$

Up to now several groups have determined the parameter γ using the geodetic VLBI observations, which are provided by the International VLBI Service for Geodesy and Astrometry (IVS) (Tab. 1). All of those tests focus on the effects imposed by the Sun. However, there were also several efforts to observe Jupiter's deflection. Treuhaft & Lowe (1991) tried to find the deflection by Jupiter experimentally using a single long baseline DSN experiment during a near-occultation event, which was proposed by Schuh *et al.* (1988). A comparable near-occultation happened in 2002 and was investigated by several groups, e.g. by Fomalont & Kopeikin (2003).

In about mid 2002 a more stringent cut-off Sun elongation angle of about 14 deg was used for the IVS scheduling, significantly lowering the sensitivity of the VLBI observables during high solar activity, but unfortunately also for the gravitational time delay determination. Even with the new cut-off elongation angle geodetic VLBI remains competitive to γ-determinations by spacecraft ranging (Shapiro *et al.*, 1971; Reasenberg *et al.*, 1979; Bertotti *et al.*, 2003), in particular due to the large amount of involved data observing at many epochs and in most directions of the universe. Without commenting on the reported formal errors of the spacecraft ranging analyses, it can be stated, that geodetic VLBI tends to handle commited and ommited errors rather conservatively. Thus, relativity remains a point of interest to the IVS and its Observing Program Committee (OPC) is open for suggestions to carry out special Research and Development (R&D) observing sessions during relativistic scenarios.

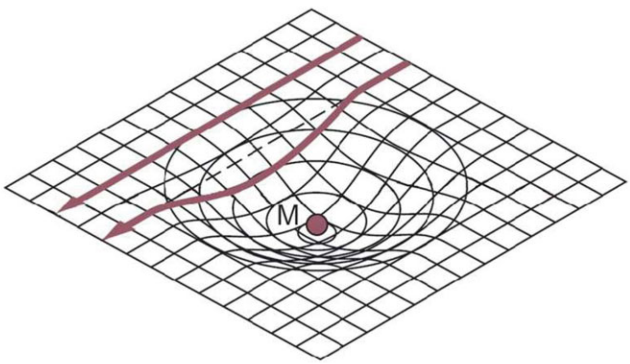

Figure 1. Gravitational time delay of radiowaves; 'Shapiro delay'.

Table 1. Review of γ-determination using geodetic VLBI data.

Author(s)	**Year**	γ	σ	**Data**
Counselman *et al.*	1974	0.98	± 0.06	1972 occultation of 3C279 by the Sun
Fomalont & Sramek	1975	1.0075	± 0.022	1974 occultation of 3C279 by the Sun
Fomalont & Sramek	1976	1.0035	± 0.018	1974 and 1975 occultation of 3C279 by the Sun
Robertson & Carter	1984	1.008	± 0.005	MERIT, POLARIS, IRIS
Carter, Robertson & MacKay	1985	1.000	± 0.003	POLARIS, IRIS since 1980
Robertson, Carter & Dillinger	1991	1.000	± 0.002	POLARIS, IRIS, CDP since 1980
Lebach *et al.*	1995	0.9996	± 0.0017	1987 occultation of 3C279 by the Sun
Eubanks *et al.*	1997	0.99994	± 0.00031	Geodetic VLBI sessions from 1979 to 1997
Shapiro *et al.*	2004	0.9998	± 0.0002[1]	Geodetic VLBI sessions from 1979 to 1999
Lambert & Le Poncin-Lafitte	2009	0.99984	± 0.00015[2]	Geodetic VLBI sessions from 1979 to 2008

Notes:
[1] Shapiro *et al.* (2004) estimate the standard error to 0.0004, however their reported formal error is 0.0002, which is used here to achieve a consistent comparison.
[2] Lambert & Le Poncin-Lafitte (2009) claim an estimated limit of 0.0002 to the standard error.

3. VLBI2010 and the relativistic delay model

To fulfill the requirements of space geodesy, in particular specified through GGOS, the Global Geodetic Observing System of the IAG, and to overcome the current limitations of the existing VLBI infrastructure, the IVS, in 2003, established Working Group 3 (WG3) named VLBI2010. The goal of VLBI2010 is to significantly modernize the existing VLBI system towards

- a positional acuracy of 1 mm,
- a velocity accuracy of 0.1 mm $\cdot$ yr^{-1},
- continuous monitoring of the Earth orientation parameters (EOP), and
- near real-time availibility of the results.

Working Group 3 closed its efforts presenting a Final Report to the IVS in 2005 (Niell *et al.*, 2005). The progress towards a new VLBI system, however, was taken over by the VLBI2010 Committee (V2C), which was established to continue and realize the studies recommended by WG3. To move to these targets, V2C proposed a number of strategies including VLBI antenna system considerations (Tab. 2) and extensive simulation studies were carried out (Petrachenko *et al.*, 2009).

Table 2. VLBI2010: System characteristics.

	Current VLBI	**VLBI2010**
Antenna size	5 to 100 m dish	about 12 m dish
Slew speed	about 20 to 200 deg $\cdot$ min^{-1}	$\geqslant$ 360 deg $\cdot$ min^{-1}
Sensitivity	200 to 15,000 SEFD	$\leqslant$ 2,500 SEFD
Frequency range	S/X band	about 2 to 15 GHz
Recording rate	128 or 256 Mbps	8 to 16 Gbps
Data transfer	usually ship disks, some e-transfer	e-transfer, e-VLBI ship disks when required

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The current conventional relativistic VLBI model (IERS, 2004, chapter 11) is based on the 'consensus model' (Eubanks, 1991), which united various VLBI delay models prior to 1991. Klioner (1991) presented an additional model, which considers sources at finite distances, e.g. artificial satellites or spacecrafts and baselines including space-borne or orbiting telescopes as well. At that time a precision of 1 ps was aimed for and remained sufficient until now. For the target accuracy of VLBI2010, however, it will be necessary to revisit the consensus model and to assess, whether it includes all terms down to the order of 0.3 ps.

4. Conclusion and outlook

Astrometric and geodetic VLBI is able to measure effects of general relativity, the relativistic deflection and the relativistic time delay (Shapiro delay). With its huge amount of observations in all directions of the universe, currently about 5 million delays over about 30 years, the IVS maintains universal, reliable, and robust data for applied relativity. Simulations have shown, that a network of VLBI2010 stations provides the same amount of data (5 million observations) in a few weeks. Future developments in view of VLBI2010 foresee significant improvements and demand the relativistic VLBI delay model to hold for a slightly better (0.3 ps) accuracy. Besides the Sun and the Earth, the gravitational time delays of Jupiter, Saturn, Venus, and the Moon will have to be considered in standard VLBI2010 analyses.

The main factors of uncertainty of VLBI are

- the intrinsic source structure,
- the wet neutral atmosphere contribution,
- the uneven North-South distribution of the network, and
- the solar coronal plasma for smaller Sun elongations.

With structure corrections and special VLBI sessions dedicated to general relativity the accuracy of the γ-determination could be significantly better than 10^{-4}.

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