Applying the theory of general relativity to reducing geodetic VLBI data

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ABSTRACT

Context. We present an alternate formula for calculating gravitational time delay.

Aims. We use this formula to reduce geodetic Very Long Baseline Interferometry (VLBI) data, taking into account gravitational effects within the solar system, and to test general relativity.

Methods. The alternate formula was obtained by expanding the conventional formula in a Taylor series. We show that the gravitational delay can be split into several terms including a term due to the coordinate transformation and terms that are explicitly linked to the light deflection angle.

Results. Our formula is compared numerically with the conventional formula, and difference in arrival times within 1 ps are found at 1° from the Sun for a full range of baseline lengths.

Conclusions. We conclude that the standard reduction of geodetic VLBI data for the effects of general relativity is equivalent to displacing the reference radio sources from their original catalogue positions in accordance with the classical light deflection formula across the whole sky.

Key words. methods: analytical – astrometry – proper motions – reference systems

1. Introduction

With geodetic Very Long Baseline Interferometry (VLBI) precise group delays – the difference in arrival times of radio waves at two radio telescopes (Schuh & Behrend 2012) – can be measured, and very accurate radio source positions can be obtained (~40 microarcsec, Ma et al. 2009). There are numerous astrometric and geodetic effects that must be accounted for when reducing high-precision VLBI data. One of these effects is gravitational time delay, which is caused by the gravitational fields of massive objects along the observer’s line-of-sight (Shapiro 1964, 1967) and is responsible for the measured group delays. These massive objects also bend the path of light from distant objects, causing an apparent shift of their position in the sky, as predicted by general relativity (Einstein 1916). Within the solar system both the Sun and Jupiter are massive enough to produce these effects. The conventional equation for calculating gravitational delay is formulated in terms of the positions of the radio telescopes within the barycentric reference frame of the solar system (Kopeikin 1990; Eubanks et al. 1991; Soffel et al. 1991; Kliioner 1991), rather than the baseline length between the radio telescopes. Moreover, the total VLBI delay formula includes a coordinate term to transform from the geocentric to the barycentric reference frame.

We propose an alternate gravitational delay formula using a Taylor series expansion. In Sect. 2 we show how the conventional formula can be split into a sum of several terms. All the terms are expressed as a ratio of the baseline length to the Earth barycentric distance. One of the terms links the gravitational delay and the well-known formula for the light deflection angle at an arbitrary elongation from the Sun. Another term cancels the coordinate term explicitly presented at the equation of the total VLBI delay. It is more convenient to formulate the effect of general relativity so that it is free from this complicating coordinate term.

In Sect. 3 a numerical comparison between the new and conventional formulae is presented for the cases of the gravitational field of the Sun and Jupiter. Kaplan (1998) compared the astrometric difference in general relativity effects between the group VLBI delay and optical observations, where the observables are measured in angular quantities. It was claimed that the difference is less than 1 microarcsec using some numerical algorithms. Our analytical approach shows that the two approaches are absolutely equivalent for all elongation angles (the difference is equal to zero), except for the small area around the gravitational body, which is a special case.

In Sect. 4 we show that the formulae for the post-post-Newtonian effect can be developed using the same approach as for the standard monopole light deflection.

In Sect. 5 we discuss the application of the new formula to estimate the proper motion of an extragalactic radio source induced by the solar gravitational field.

2. Developing the conventional formula for gravitational delay

In addition to the three classical tests of general relativity (GR), a fourth test – the delay of a signal propagating in the solar gravitational field – was proposed by Shapiro (1964) and is known as the Shapiro delay. The positions of astronomical instruments
on Earth are referenced to the solar system barycentre, and the VLBI delay is equal to the terrestrial time (TT) coordinate time interval between two events of the signal arrival at the first and second radio telescopes (Petit et al. 2010). The difference between the two Shapiro delays as measured with two radio telescopes at the barycentric distances \( r_1 \) and \( r_2 \) from a body of mass \( M \) gives a gravitational delay, \( \tau_{grav} \), which must be taken into account during the standard reduction of the high-precision geodetic VLBI data (Petit et al. 2010),

\[
\tau_{grav} = \frac{(y + 1)GM}{c^3} \ln \left( \frac{|r_1| + (s \cdot r_1)}{|r_2| + (s \cdot r_2)} \right),
\]

where \( G \) is the gravitational constant, \( s \) is the unit vector in the direction of observed radio source, \( c \) is the speed of light, and \( y \) is the parameter of the parametrised post-Newtonian (PPN) formalism (Will 1993), equal to unity in GR. The classical Shapiro delay formula includes the positions of the remote body and the receiver, but the differential delay (1) only depends on the positions of the two receivers in the adopted reference system. Therefore, the formula (1) is valid for all objects regardless of their distance unless the curvature of the observed light front cannot be ignored. All extragalactic radio sources meet this condition.

We introduce the baseline vector, \( b \), as the difference between the two barycentre radius-vectors of two antennas \( b = r_2 - r_1 \). Then formula (1) may be re-written as follows (we recall that \( y = 1 \)):

\[
\tau_{grav} \approx \frac{2GM}{c^3} \ln \left( 1 + \frac{- (r_2 \cdot b)/r_2 - (b \cdot s) + \frac{b^2}{2r_2} - \frac{(r_2 \cdot b)^2}{2r_2^2}}{r_2 + (r_2 \cdot s)} \right).
\]

For typical baselines, \( |b| \ll |r_2| \), and we can use the Taylor series expansion \((1 + x)^2 \approx 1 + \frac{1}{2} - \frac{x^2}{6} \) for \( x \ll 1 \) to modify (2) as follows:

\[
\tau_{grav} \approx \frac{2GM}{c^3} \ln \left[ 1 + \frac{- (r_2 \cdot b)/r_2 - (b \cdot s) + \frac{b^2}{2r_2} - \frac{(r_2 \cdot b)^2}{2r_2^2}}{r_2 + (r_2 \cdot s)} \right].
\]

Formula (3) may be re-written using the approximation \( \ln(1 + y) \approx y - y^2/2 \) for \( y \ll 1 \) because the baseline length is much smaller than the barycentric distance to the points on Earth

\[
\tau_{grav} \approx \frac{2GM}{c^3} \left\{ \frac{- (r_2 \cdot b)/r_2 - (b \cdot s) + \frac{b^2}{2r_2} - \frac{(r_2 \cdot b)^2}{2r_2^2}}{r_2 + (r_2 \cdot s)} \right\}.
\]

One has to keep the barycentric coordinates \( r_2 \) for the second station in the formulæ below to provide consistency with the original gravitational delay model (1).

Converting the three dot products with angles \( \varphi \), \( \psi \), \( \theta \) (Fig. 1), where

\[
\begin{align*}
(b \cdot s) &= |b| \cos \varphi, \\
(b \cdot r_2) &= |b||r_2| \cos \psi, \\
(r_2 \cdot s) &= -|r_2| \cos \theta
\end{align*}
\]

\[r_2(1 - \cos \theta)] \approx \frac{b^2 \sin \theta}{r_2(1 - \cos \theta)} \approx \frac{2b^2}{r_2^2}.
\]

Angle \( \theta \) is given here with respect to the second station, that is, \( \theta = \theta_2 \) for the sake of simplicity. The difference between \( \theta_1 \) and \( \theta_2 \) is discussed in Sect. 3. Similar expressions (without terms that include \( \frac{b^2}{r_2^2} \)) have been obtained for geodetic VLBI (e.g. Finkelstein et al. 1983; Hellings 1986) and for SIM interferometry mission model delays (Turyshev 2009).

For the general case of no coplanar vectors (Fig. 1)

\[
\tau_{grav} \approx \frac{2GMb}{c^3} \cos \varphi + \frac{2GMb \sin \varphi \sin \theta \cos A}{r_2c^3} \left( 1 - \cos \theta \right) \cos \varphi + \frac{GMb^2 \sin \varphi \sin \theta \cos A}{r_2c^3} \left( 1 - \cos \theta \right).
\]

Using the small-angle approximation \((R \ll r_2)\),

\[
\cos \theta \approx 1 - \frac{R^2}{2r_2^2} \quad \text{and} \quad \sin \theta \approx \frac{R}{r_2},
\]

where \( R \) is the impact parameter and is equal to the solar radius for the case of grazing light. Therefore

\[
\frac{b \sin \theta}{r_2(1 - \cos \theta)} \approx \frac{2b}{R} \cdot \frac{\psi}{r_2(1 - \cos \theta)} \approx \frac{2b^2}{r_2^2}. \]
and with a “typical” baseline of ~6000 km the first term ~160 ns, the second term is ~1.2 ns, and the third term is ~3 ps for grazing light. As we show below, the third term is less than 1 ps for observations at θ > 1° from the Sun. This term and other small terms in (8) may be neglected because VLBI observations are not undertaken closer than 4° from the Sun. Then, the gravitational delay is given by

\[
\tau_{\text{grav}} \approx \frac{-2G M b}{r_c^3} \cos \varphi + \frac{2G M b \sin \varphi \sin \theta \cos A}{r_c^3} \left(1 - \cos \theta \right) + \frac{G M b^2}{r_c^2(1 - \cos \theta)} \left(1 - \cos \varphi \right) - \frac{G M b^2 \sin^2 \varphi \sin^2 \theta \cos^2 A}{c^3} \left(1 - \cos \theta \right)^2,
\]

(10)

or, finally,

\[
\tau_{\text{grav}} = \frac{-2G M b}{r_c^3} \cos \varphi + \frac{2G M b \sin \varphi \sin \theta \cos A}{r_c^3} \left(1 - \cos \theta \right) + \frac{G M b^2}{r_c^2(1 - \cos \theta)} \left(1 - \cos \varphi \right) - \frac{G M b^2 \sin^2 \varphi \sin^2 \theta \cos^2 A}{c^3} \left(1 - \cos \theta \right)^2.
\]

This equation is sufficient for a picosecond level of accuracy. The first term of Eq. (11) can be excluded because it cancels out a similar term from the total geocentric delay (Petit et al. 2010, Eq. (11.9)). Indeed, this formula (11.9) from the IERS Conventions includes the term

\[
\tau_{\text{coord}} = \frac{(\gamma + 1) GM (b \cdot s)}{c^2 r}.
\]

(12)

Recalling that γ = 1, the resulting effect of general relativity, τ_{GR}, in the total VLBI delay model is therefore given by the sum of the gravitational delay τ_{grav} and the coordinate term τ_{coord}

\[
\tau_{\text{GR}} = \tau_{\text{grav}} + \tau_{\text{coord}} = \tau_{\text{grav}} + \frac{2GM (b \cdot s)}{c^2 r} = \tau_{\text{grav}} + \frac{2GM b}{c^2 r} \cos \varphi.
\]

(13)

The gravitational delay (11) includes the barycentric distance of the second station r₂ in the denominator, whereas the term (12) includes the barycentric distance of the geocentre r. For the case of the Sun, the coordinate term may be as large as 400 ps (see Sect. 2.1) and should be considered carefully, but for Jupiter it does not exceed 1 ps.

The difference between two terms \(\frac{2GM b}{c^2 r} \cos \varphi\) (12) and \(\frac{2GM b}{c^2 r_2} \cos \varphi\) (11) is less than 0.1 ps, and it may be ignored for the current level of accuracy. Nonetheless, the angles θ and ϕ are to be referred to the vector r₂ for correct calculation.

In the original form the gravitational delay is expressed in the BCRS system, whereas the baseline length in (12) is given in the GCRS system. This means that theoretically, one has to convert the baseline length b and r₂ into Eq. (11) from BCRS to GCRS before comparing the coordinate terms from two different parts. However, in practice, the corresponding correction in time delay does not exceed 1 ps for grazing light and a baseline of 6000 km.
To investigate the accuracy of the alternative formula (14), one has to sum the original gravitational delay formula (1) and the term (12)
\[
\tau_{GR_2} = \frac{2GM}{c^3} \ln \frac{|r_1| + (s \cdot r_1)}{|r_2| + (s \cdot r_2)} + \frac{2GMb}{rc^3} \cos \varphi.
\]
(17)

Figure 3 shows the difference between the delays \(\tau_{GR_2}\) (14) and \(\tau_{GR_2}\) (17) for the Sun and a baseline of 10 000 km: the difference between the two formulae only exceeds 1 ps at \(\theta = 0.5^\circ\). Thus, the difference between the two formulae is negligible for the light propagation in the solar system as measured by geodetic VLBI at the current level of precision.

While the two minor terms, \(t_2\) and \(t_3\), contribute less than \(t_1\), they cannot be ignored completely. The contribution of these terms grows rapidly with baseline length (\(\tau \sim b^2\)) and is 72 ps at \(\theta = 1^\circ\) for \(b = 10\,000\) km (Fig. 4).

Herewith, we consider two observational VLBI sessions to separately investigate the effect of \(t_1\) separately during a standard 24 h session for the Sun and Jupiter. The VLBI experiment R&D1208 was carried out on 2–3 October, 2012 to track several reference radio sources in close vicinity to the Sun. While the Sun travelled along the ecliptic during the 24 h session, quasar 1243–072 was tracked in the range of angular distances from \(3.7^\circ\) to \(4.3^\circ\). The four curves in the left-hand of plot of Fig. 5 reflect the variation in \(t_1\) for four selected VLBI baselines of differing length: Kokee – Tsukub32 (KT; 5755 km), HartRAO – Wettzell (HtW; 7832 km), Onsala60 – Wettzell (OW; 920 km), and HartRAO – Onsala60 (HIO; 8525 km) with respect to the angle \(\theta\) of the approach of the Sun to the radio source 1243-072. This varies steadily due to the relatively slow apparent motion of the Sun.

The largest solar system planet Jupiter approached the radio source 1922-224 on 18–19 November, 2008. This event was observed during the 24 h experiment OHI60. Four stations – Hobart26, Kokee, Tsukub32, and Parkes participated in tracking the radio source over only 12 h because of observing constraints. The angle \(\theta\) between the radio source and Jupiter changed from \(1.4^\prime\) to about \(5^\prime\) within 12 h. The right plot of Fig. 5 shows the variations in \(t_1\) as a function of \(\theta\) during this event. This term reaches its maximum of about 400 ps for the longest available baseline (Hobart26 – Tsukub32 (HT) of \(b = 8088\) km) and becomes negligible after a short period of time. For the shorter baselines (Parkes – Tsukub32 (PT; 7233 km) and Hobart26 – Parkes (HP; 1089 km)), this term is lower in magnitude.

The coordinate term calculated for both events (Fig. 6) is significant for the Sun (reaching 300 ps) but is negligible for Jupiter (less than 0.1 ps). In accordance with Eq. (17), the coordinate term does not depend on the impact parameter and, therefore, it does not grow at small angles, as seen in Fig. 2. All variations in Fig. 6 are caused by the variations in angle \(\varphi\) and baseline length.

Figure 7 illustrates the residuals between Eqs. (14) and (17) for these two events. The difference does not exceed 1 ps for
3. Small-angle approximation

The monopole effect of the general relativity results in a circular motion of the deflected object (Sazhin et al. 2001; Kopeikin & Makarov 2007). Therefore, the radio sources draw a regular pattern on the sky due to the light deflection. Here we consider the impact of the minor terms in Eq. (14) on the formula for the deflection angles in Fig. 8. for all baselines are the same.

Thus, once in single-telescope mode, only the main angle (19) is presented; in the two-telescope mode, the secondary deflection angle (20) represents the difference between angles \( \alpha_s \) and \( \alpha_{s'} \), if \( \alpha_s = \frac{4GM}{c^2R_2} \) and \( R_1 = r_2 \cos \theta_2 \). Even though the parallactic shift of the Sun \( \theta_1 - \theta_2 \) is about 8'' for \( b = 6000 \) km, this difference between \( \alpha_s \) and \( \alpha_{s'} \) is not negligible in the small-angle approximation. The formula shows that the secondary deflection angle depends on the baseline length, but it reduces to Einstein’s classical expression (19) for a zero-length baseline (i.e. \( b = 0 \)).

Table 1 shows the meaning of the angle \( \alpha_s \) for the Sun and Table 2 for Jupiter with different combinations of the parameters \( \theta_2 \) and \( R_2 \). This effect rapidly grows as \( b \) is decreasing and may be detected with a long-baseline radio-interferometer at a very close approach of the Sun (<5”) or large planets (<1”) to a distant radio source.

The angle \( \alpha_{s'} \) can change comparatively fast when Jupiter passing by a radio source. An example of the fast variations of \( \alpha_{s'} \) is shown in Fig. 8 for the approach of Jupiter and the radio source 1922-224 discussed in Sect. 2.1. The corresponding time delays as shown in the right plot of Fig. 5 are different, but the light deflection angles in Fig. 8, for all baselines are the same.

4. Post-post-Newtonian effect

As shown by (Klioner 1991), the main term of the post-post-Newtonian effect is given by

\[
\tau_{\text{PPN}} = \frac{4GM}{c^2} \left[ \frac{4}{|r_1| + (r_1 \cdot s)} - \frac{4}{|r_2| + (r_2 \cdot s)} \right].
\]
Using the mathematical transformation of Eqs. (2) and (5),

$$
\tau_{\text{PPN}} = \frac{4G^2M^2}{c^2} \left[ \frac{4}{r_2(1 - \cos \theta)} - \frac{4}{r_2(1 + \cos \theta)} \right].
$$

(23)

If the baseline length is negligible with respect to the barycentric distance \(b \ll r_2\), one could recall \(x = \frac{2 \cos \varphi + b \cos \psi}{r_2(1 + \cos \theta)}\) and apply the approximation \(\frac{1}{r_2} = (1 + x)\) using Eq. (7) to solve the spherical triangle (Fig. 1) and to develop (23) as follows:

$$
\tau_{\text{PPN}} = \frac{4G^2M^2b}{c^2} \frac{\cos \varphi}{r_2^2(1 - \cos \theta)^3} - \frac{4G^2M^2b}{c^5} \frac{\sin \varphi \sin \theta \cos A + \cos \varphi}{r_2^2(1 - \cos \theta)^3} - \frac{4G^2M^2b}{c^5} \frac{\sin \varphi \sin \theta \cos A}{r_2^2(1 - \cos \theta)^3}.
$$

(24)

In the small-angle approximation \((R \ll r_2)\) (24) is given by

$$
\tau_{\text{PPN}} = \frac{4G^2M^2b \cos \varphi}{c^3 R^2} - \frac{16G^2M^2b \sin \varphi \sin \theta \cos A}{c^5 R^3}.
$$

(25)

For the grazing light the first term in Eq. (25) is about 1 ps, whereas the second one can reach 300 ps at a “standard” baseline of 6000 km (Klioner 1991).

When the first term in Eq. (24) is negligible, we can introduce a new variable

$$
\alpha_{\text{PPN}} = \frac{4G^2M^2}{c^4} \frac{\sin \theta}{r_2^2(1 - \cos \theta)^2}
$$

(26)

and re-write the second term of Eq. (24) as follows:

$$
\tau_{\text{PPN}} = - \frac{b}{c} \sin \varphi \cos A.
$$

(27)

It is obvious that the variable \(\alpha_{\text{PPN}}\) plays the role of the post-post-Newtonian deflection angle at arbitrary \(\theta\), and converting between the deflection angle and the corresponding part of gravitational delay uses the same factor \(\frac{b}{c} \sin \varphi \cos A\) for the post-Newtonian effect as in Eqs. (15) and (16). It enables us to present the sum of the two delays \(\tau_{\text{GR}}\) and \(\tau_{\text{PPN}}\) (27) in the form of two angles, Eqs. (19) and (26), multiplied by \(\frac{b}{c} \sin \varphi \cos A\), that is,

$$
\tau_{\text{GR}} + \tau_{\text{PPN}} = (\alpha_{\text{GR}} + \alpha_{\text{PPN}}) \frac{b}{c} \sin \varphi \cos A.
$$

(28)

Finally, we recall that the second term of Eq. (24) corresponds to formula (11.14) from the IERS Conventions (Petit et al. 2010).

5. Proper motion of extragalactic radio sources induced by the Sun

The solar gravitational field will result in a proper motion of extragalactic radio sources if the effects of general relativity are not accounted for in VLBI data reduction. The rapid change of the observed positions during a typical 24 h VLBI session may be detected for observations within 10° from the Sun.

The partial derivative \(\frac{d\tau_{\text{GR}}}{d\theta}\) is given by

$$
\frac{d\tau_{\text{GR}}}{d\theta} = - \frac{2GMb \sin \varphi \cos A}{c^3 r(1 - \cos \theta)}.
$$

(29)

For an arbitrary angle \(\theta\), the proper motion \(\mu = \frac{d\alpha}{d\theta}\) (where \(\alpha\) is from (15)) may be presented by re-arranging Eq. (29) as follows:

$$
\mu = - \frac{d\alpha}{d\theta} = \frac{b \sin \varphi \cos A}{c \sin \varphi \cos A} \frac{d\tau_{\text{GR}}}{d\theta} = - \frac{2GM}{c^3 r} \frac{d\theta}{(1 - \cos \theta) d\theta}.
$$

(30)

Figure 9 illustrates Eq. (30) for a range of angles \(\theta\) from 0° to 10°. It is obvious that all distant radio sources across the sky will display a circular motion if general relativity is not accounted for in VLBI data reduction. The magnitude of the effect is proportional to \(\frac{\sin \theta}{1 - \cos \theta}\). In particular, a source near the ecliptic poles \(\theta = 90°\) will draw a circle of 4 mas in size. The daily displacement between the consecutive days will be equal to \(\frac{2GM}{c^3 r} \frac{d\theta}{(1 - \cos \theta) d\theta}\). For the Sun, \(\frac{d\theta}{d\theta}\) = 0.0174, and the daily displacement is \(\approx 0.07\) mas. For all other sources, the daily displacement will be proportional to the factor \(\frac{1}{1 - \cos \theta}\) in Eq. (30).

In the small-angle approximation, Eq. (30) may be written as follows:

$$
\mu = - \frac{4GMr d\theta}{c^3 R^2} = \frac{\alpha}{R} d\theta.
$$

(31)

For background radio sources that are co-planar with the plane of the body, the apparent motion, \(\mu\), rapidly grows from 0.5 \(\mu\)s/year at \(\theta = 10°\), to 1.6 \(\mu\)s/year at \(\theta = 5°\), and 40 \(\mu\)s/year at \(\theta = 1°\). Therefore, a systematic pattern of proper motion in a particular area of the sky may serve as an indicator of a hidden mass in this direction.

6. Conclusion

The effects of general relativity are explicitly contained in both components of the total VLBI delay model – the gravitational delay and the coordinate term with a factor of \(1 - \frac{2GM}{c^2 R}\). While the former component uses the individual barycentre positions of the radio telescopes to calculate the effect, the latter component is

\[\text{A&A 574, A128 (2015)}\]
expressed in terms of the baseline between the radio telescopes. Coupling between both parts has not been investigated until now.

The Shapiro effect as measured by radars and the deflection of light measured with traditional astronomical instruments are considered two independent tests of general relativity. We showed that the total group delay model joins the two tests within one observational technique – geodetic VLBI. The gravitational delay that traditionally originated from the Shapiro effect is linked to the light deflection angle. Therefore, the two approaches, VLBI delay and angular, are absolutely equivalent.

For almost all realistic situations this angle does not depend on the baseline length, thus, a standard geodetic VLBI interferometer acts as a traditional astronomical instrument. In addition, the coordinate term explicitly presented in the conventional total delay model ceases to exist because it is compensated by the same effect in the gravitational delay with opposite sign. Thus, the proposed alternative version of the general relativity contribution to the total VLBI group delay model is free of the coordinate effects. Therefore, the two approaches, time delay and angular, are absolutely equivalent.

The final equation of the general relativity contribution expressed in angular terms also comprises two smaller terms that are significant at very small angular separation between the deflecting body and distant radio source. These terms may be considered as an increment in the light deflection angle due to the additional time delay for the propagation of the light from station 1 to station 2. This effect becomes significant at $\frac{b}{R} > 0.1$.

It is unlikely that the effect will be detected with ground-based interferometers, but it may be detected with space-baseline interferometers, for example, RadioAstron with $b$ up to 300,000 km (Kardashev et al. 2013).

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Fig. 9. Daily proper motion calculated from Eq. (30) near the Sun.

A128, page 7 of 7