Determining the Galactocentric Acceleration Vector from VLBI and its Impact on the Reference Frames

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Abstract The relative motion of the solar system barycentre around the Galactic centre can also be described as an acceleration (Galactocentric Acceleration, GA) of the solar system directed towards the centre of the Galaxy. So far, this effect has been omitted in the a priori modelling of the Very Long Baseline Interferometry (VLBI) observable. Therefore, it results in a systematic dipole proper motion (Secular Aberration Drift, SAD) of extragalactic radio sources building the celestial reference frame with a theoretical maximum magnitude of 5 – 6 μas/yr. In this paper, we present our estimation of the SAD vector obtained within global adjustments of the VLBI measurements (1979.7 – 2016.5) using the software VieVS. We show that the scale factor from the VLBI measurements estimated for each source individually discloses a clear systematic aligned with the direction to the Galactic centre-anticentre. Therefore, the radio sources located near the Galactic anticentre may cause a strong systematic effect, especially, in early VLBI years. For instance, radio source 0552+398 causes a difference exceeding 1 mm in the estimated intercontinental baseline length, which is clearly above the modelling requirements of the VLBI Global Observing System (VGOS). Furthermore, we introduce a new method for estimation of the SAD vector from the scale factor corrections.

1 Introduction

The acceleration of the Solar System Barycentre (SSB) directed towards the centre of the Galaxy raises through the relative motion of the SSB around the Galactic centre on a quasi circular orbit. Table 1 summarizes recent estimates of the Galactocentric Acceleration (GA) vector obtained from the geodetic Very Long Baseline Interferometry (VLBI). In general, two methods for the estimation of the GA vector were used: (1) a posteriori fitting of the radio source proper motion field (Titov et al., 2011; Titov and Lambert, 2013, 2016) and (2) estimation of the GA vector within the global adjustment of the VLBI data (Kurdubov, 2011; Xu et al., 2012; MacMillan, 2014). It can be seen that except of Kurdubov (2011) all publications yield a consistent estimates of the maximum amplitude A of the GA vector between 5.5 and 6.5 μas/yr whereas the estimated direction of the GA vector varies especially in declination between −11 and −56 deg. Theoretically, the Galactocentric acceleration vector points to the centre of the Galaxy which is supposed to be the location of the compact radio source Sagittarius A* with the estimated coordinates $\alpha_G = 267$ deg for right ascension and $\delta_G = -29$ deg for declination (Reid and Brunthaler, 2004). In this paper we present our estimates of the Galactocentric acceleration vector obtained with the software VieVS (Böhm et al., 2012) using two different methods. Section 2 contains the GA vector estimated as global parameter in the common adjustment of the VLBI sessions whereas in Section 3 we introduce a new method for the estimation of the GA vector from the globally estimated VLBI scale factor. The impact of omitting the Galactocentric acceleration in the a priori modelling on

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Table 1: Recent estimates of the GA vector from geodetic VLBI. The components of the acceleration vector are given with the amplitude A, and the equatorial coordinates of the vector direction α_G, δ_G.

	Kurdubov (2011)	Titov et al. (2011)	Xu et al. (2012)	Titov and Lambert (2013)	MacMillan (2014)	Titov and Lambert (2016)
A [µas/yr]	10.3 ± 1.1	6.4 ± 1.5	5.8 ± 0.4	6.4 ± 1.1	5.6 ± 0.4	5.9 ± 1.0
α_G [deg]	288 ± 5	263 ± 11	243 ± 4	266 ± 7	267 ± 3	273 ± 13
δ_G [deg]	0 ± 5	-20 ± 12	-11 ± 4	-26 ± 7	-11 ± 3	-56 ± 9

the estimated baseline length and the Celestial Reference Frame (CRF) is shown in Section 4.

2 Estimation of the GA vector from the global VLBI solution

Following Titov et al. (2011) the conventional equation for the group delay model (Petit and Luzum, 2010) was extended by the GA vector. Aside of that the processing followed the IERS Conventions 2010 and the technique specific VLBI analysis recommendations. Further details of the parametrisation and analysis setup for our standard global VLBI solution are given in Krásná et al. (2015). In the global solution we determined the terrestrial reference frame (position and linear velocity), celestial reference frame (position) and three components (a_x, a_y, a_z) of the GA vector. Table 2 summarizes the estimated GA vector given with its maximum amplitude A and the direction in equatorial coordinates α_G for right ascension and δ_G for declination. The first column shows the resulting GA vector from a global adjustment of nearly all available IVS sessions, i.e. ~5800 sessions from 1979.7 until 2016.5. The second column contains the GA vector determined within an adjustment of large global networks only, represented by the following specific IVS programs: the National Earth Orientation Service (NEOS-A) sessions, Rapid turnaround IVS-R1 and IVS-R4 sessions and all available two-weeks CONTinuous campaigns (CONT), i.e., ~2000 sessions from 1993 until 2016.5. Both solutions yield a value for the maximal amplitude which is consistent with the estimates published in the last few years. The direction in declination of the vector is close to its theoretical value if only the large network sessions were included in the solution which implies that this procedure is sensitive to the inclusion of weak networks.

Table 2: GA vector estimated within global VLBI solutions with software VieVS.

	1979.7 - 2016.5 ~5800 sessions	1993.0 - 2016.5 ~2000 sessions
A [µas/yr]	6.1 ± 0.2	5.4 ± 0.4
α_G [deg]	260 ± 2	273 ± 4
δ_G [deg]	-18 ± 4	-27 ± 8

3 Estimation of the GA vector from the global source-wise scale factor corrections

We developed a new method for the estimation of the GA vector. The GA vector is estimated by fitting the globally estimated scale factor F corrections. For the case of a perfect VLBI model, the measured time delay would be equal to the modelled one and the scale factor has to be equal to unity. If the additional delay produced by the acceleration of the solar system barycentre is not modelled a priori, then the scale factor manifests itself as a variable parameter, depending on the Galactocentric vector a, radio source position s and the time since a reference epoch Δt:

$$F = 1 + \frac{a \cdot s}{c} \Delta t = 1 + \Delta F. \qquad (1)$$

The mathematical background with all details is introduced in Titov and Krásná (2017). We carried out again the global adjustment of the VLBI measurements where we estimated the terrestrial and celestial reference frame in the usual way and the scale factor correction for each source individually (except the 39 special handling sources). We present here the solution where the scale factor correction was treated as a time-independent parameter. It means that we built up partial derivative of the time delay τ w.r.t. $\frac{\Delta F}{\Delta t}$ as:

$$\frac{\partial \tau}{\partial \left(\frac{\Delta F}{\Delta t} \right)} = -\frac{b \cdot s}{c} \Delta t. \qquad (2)$$

In such case the scale factor corrections are estimated independently of time, i.e. the annual variation [ppb/yr] is determined. Upper plots in Figure 1 show the estimated annual drift of the scale factor for each source individually if the a priori time delay was modelled according to the consensus model in IERS Conventions 2010. Lower plots show the annual effect on the scale factor from the difference between this standard solution and a solution where the GA vector was added a priori to the time delay as described in Titov et al. (2011) with the a priori amplitude of 5 µas/yr. The annual variation of the scale factor due to the GA effect reaches about 0.02 ppb/yr. Since the mean Δt in our data set is about 10 years the absolute effect on the scale grows up

Table 3: Estimates of the GA vector from the global $\frac{\Delta F}{\Delta t}$ corrections from a standard VLBI solution. Different cut-off limits for number of radio source observations (N) applied.

N	> 4	> 10	> 50	> 500	> 1 000	> 10 000	> 20 000	> 50 000
number of sources	4062	4001	3414	573	476	133	87	43
A [µas/yr]	7.1 ± 0.2	8.2 ± 0.3	5.2 ± 0.2	5.1 ± 0.3	5.0 ± 0.3	4.8 ± 0.4	5.3 ± 0.5	4.6 ± 0.7
α_G [deg]	281 ± 3	281 ± 3	281 ± 3	281 ± 4	280 ± 5	280 ± 7	281 ± 7	290 ± 13
δ_G [deg]	-51 ± 2	-55 ± 2	-35 ± 3	-34 ± 3	-32 ± 4	-28 ± 5	-34 ± 5	-24 ± 8
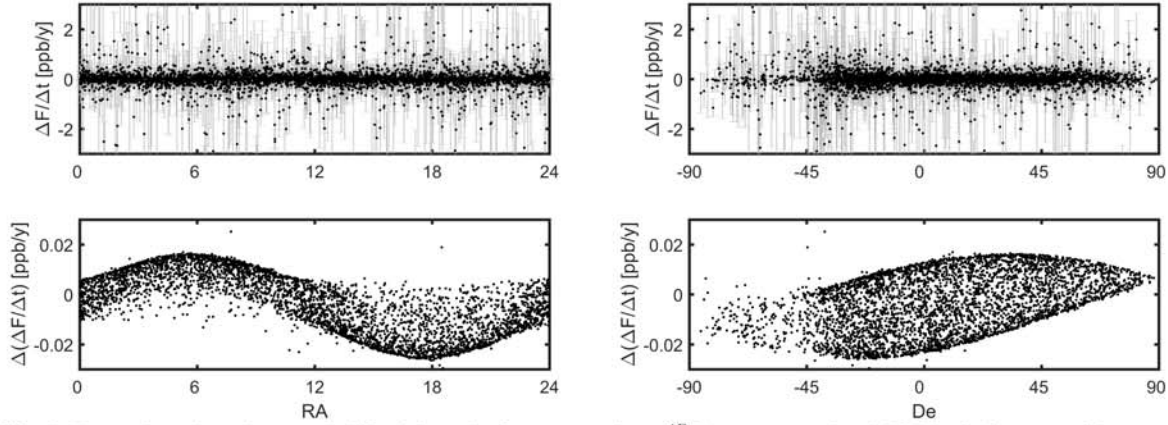
Fig. 1: Upper plots show the annual drift of the scale factor corrections $\frac{\Delta F}{\Delta t}$ from a conventional VLBI solution w.r.t. right ascension (left-hand side) and declination (right-hand side). Lower plots show the difference in $\frac{\Delta F}{\Delta t}$ from a conventional solution and a solution with GA vector modelled a priori with the amplitude 5 µas/yr.

to 0.2 ppb. The GA vector is determined by fitting the individual scale factor corrections (upper plots in Figure 1) by the following model:

$$F = a_x \cos\alpha \cos\delta + a_y \sin\alpha \cos\delta + a_z \sin\delta \quad (3)$$

using the components of the acceleration vector a_x, a_y, a_z as

$$\begin{aligned} a_x &= A \cos\alpha_G \cos\delta_G, \\ a_y &= A \sin\alpha_G \cos\delta_G, \quad (4) \\ a_z &= A \sin\delta_G. \end{aligned}$$

The resulting GA vectors from different sets of sources-wise scale corrections are summarized in Table 3. The criterion for including the scale correction to the data set was the number of observation N to the respective radio source. The first column shows the GA vector estimated from all sources with more than 4 observations, i.e., the data set consists of more than 4 000 sources. The last column shows the acceleration vector estimated from sources with more than 50 000 observations what fulfilled about 40 sources only. Estimates of the acceleration vector following a compromise between the number of observations and number of sources, i.e., (50 < N < 20 000) have a consistent maximal amplitude between 4.8 and 5.2 µas/yr and a direction in declination (from −28 to −35 deg) which is close to the theoretical value. All solutions yield a stable value for the direc-

tion in right ascension about −281 deg which should be further investigated.

4 Impact of the GA on the reference frames

Figure 2 and Figure 4 show the effect of the omitted Galactocentric acceleration in the VLBI analysis on the estimated celestial reference frame and the baseline length of selected baselines, respectively. Plotted is the difference between a conventional solution minus a solution with the GA vector modelled a priori with the amplitude of 5 µas/yr. The amplitude of the difference in CRF reaches 50 µas. The effect of the uncertainty of the GA amplitude on the CRF is modelled in Figure 3 which shows the difference in the CRF between a solution with $A = 6.5$ µas/yr minus a solution with $A = 5.0$ µas/yr. In the baseline length there is a systematic shift resulting from selected sessions in the early VLBI years. The reason is the scheduling style and the limited number of observed sources which allows the sources close to the Galactic centre or anticentre where the correction is at largest to have an hight impact on the solution. To prove that assumption we computed another solution where we applied the GA modelling for all sources with the exception of radio source 0552+398
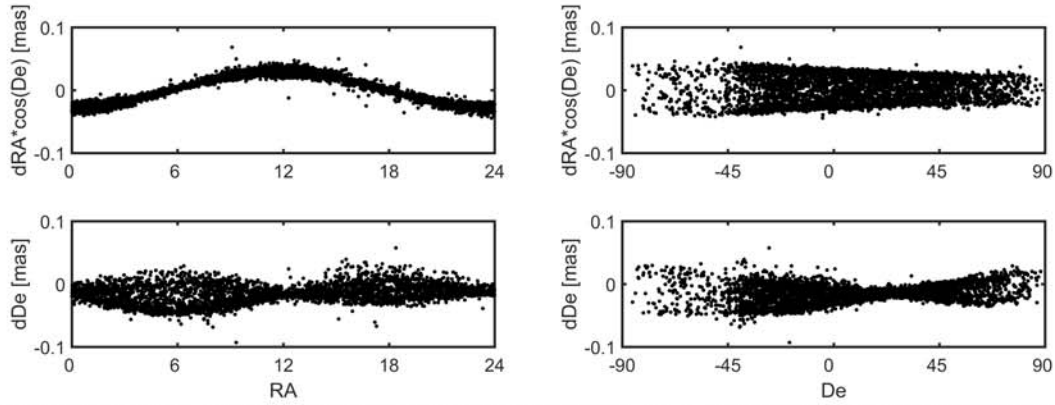
Fig. 2: Difference in source coordinates (CRF) due to the omitted GA effect. Standard solution (without GA) minus the solution with GA applied apriori ($A = 5.0$ μas/yr).

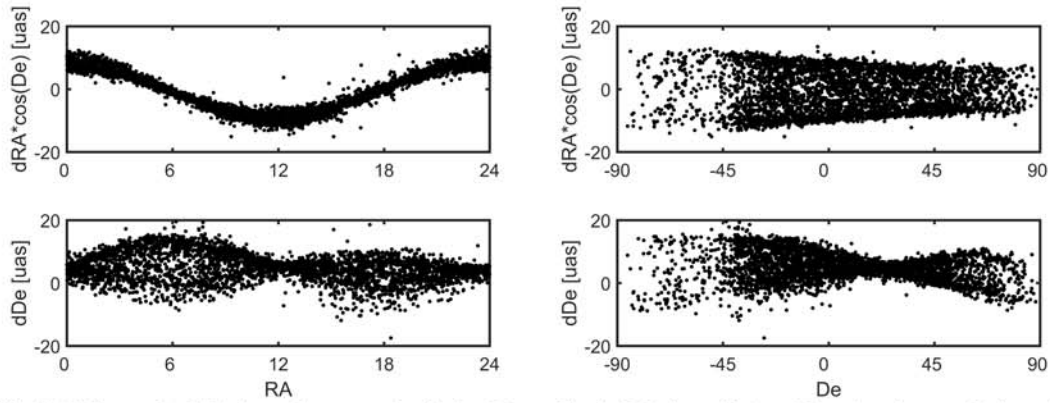**Fig. 3**: Difference in CRF due to the uncertainty in the GA amplitude. Solution with $A = 6.5$ μas/yr minus a solution with $A = 5.0$ μas/yr.

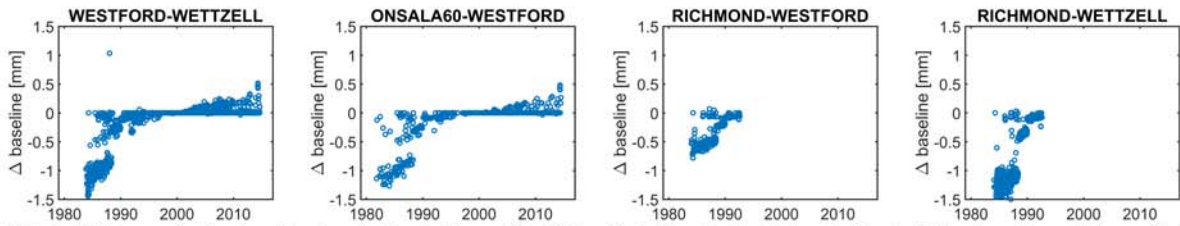**Fig. 4**: Difference in the baseline length due to the omitted GA effect. Standard solution (without GA) minus the solution with GA applied apriori ($A = 5.0$ μas/yr).
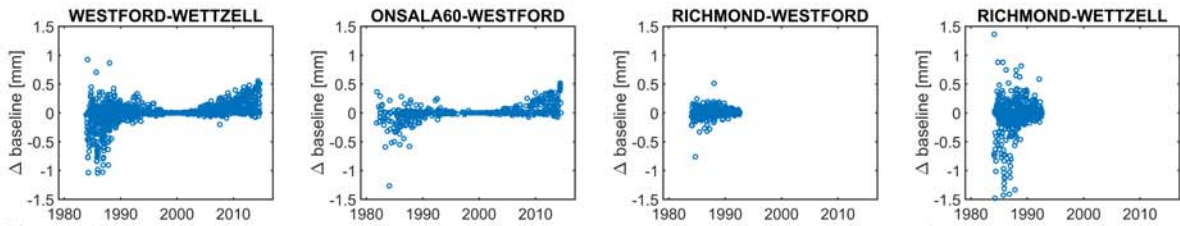

Fig. 5: Difference in the baseline length between a conventional solution minus a solution where the GA effect was modelled a priori for all sources with an exception for source 0552+398.

which is a frequently observed source near the Galactic anticentre. The difference between this solution and the conventional solution for the selected baselines plotted in Figure 5 shows that the large systematically shifted differences in the early VLBI years vanished.

5 Conclusions

We introduce a new method for estimation of the Galactocentric acceleration vector from geodetic VLBI measurements based on fitting the scale factor corrections estimated for each source individually within a global solution. From fitting the individual scale factor corrections of sources with more than 50 observations during $1979.7 - 2016.5$ we got the GA vector with the amplitude of 5.2 ± 0.2 μas/yr, and the direction $\alpha_G = 281 \pm 3$ deg and $\delta_G = -35 \pm 3$ deg. The GA vector was also estimated directly within a global adjustment of the VLBI data. GA vector determined from selected large network IVS sessions after 1993 ($A = 5.4 \pm 0.4$ μas/yr, $\alpha_G = 273 \pm 4$ deg, $\delta_G = -27 \pm 8$ deg) is closer to its theoretical value than the estimate from the entire VLBI history. Neglecting the Galactocentric acceleration in the a priori VLBI observation model causes errors in the estimated baseline length which can exceed 1 mm especially in the early VLBI years, and systematic errors in the determined celestial reference frame (up to 50 μas). Results presented in this paper are computed with the VieVS software and verified with the OCCAM software package.

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