The Acceleration of the Origin of the ICRF

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Abstract From VLBI observations we have determined the Solar acceleration, based on the assumption that the proper motions of the extragalactic sources observed by VLBI are of a random pattern over the sky, with much higher accuracy than that predicted from the Galactic model (Xu et al., 2012, 2013). Our result, however, differs from that obtained by Titov et al. (2011) and Titov & Lambert (2013) using a different estimating method due to the significant vertical acceleration obtained by us. In this paper, we validate our results and investigate the vertical component. The possibilities for it are presented and discussed. In contradiction to the essence of the inertial reference frame, therefore, the origin of the ICRS, and consequently the ICRF, has an acceleration with respect to the background of the extragalactic radio sources. Finally, the impact of the acceleration on the ICRF2 is discussed.

Keywords Solar system barycenter's acceleration, vertical component, VLBI, astrometry

1 Introduction

In 1728, the English astronomer James Bradley discovered the aberration effect, which describes the apparent variation in the direction of the object as a result of the motion of the observer with respect to the coordinate system (Xu et al., 2014). Due to the aberration effect, different observers would have obtained different positions for an object. As a result, we always choose the Solar System Barycenter (SSB) as a fictitious observer to reduce and compare the positions of celestial objects obtained by all earth-based observations.

However, the SSB accelerates in the universe even though the acceleration is quite small. This leads to apparent proper motions of the observed objects. It was first predicted by Eubanks et al. (1995) in the 1990s and detected from VLBI observations in recent years. On the basis of two different methods, values for the acceleration of the SSB in the Galactic plane were determined to coincide well with each other and also with those predicted from the Galaxy model. But there is a big difference in the component perpendicular to the Galactic plane due to the significant vertical acceleration detected by us (Xu et al., 2012). From that work, this component is 3.95 $\pm$ 0.47 $mm{\cdot}s^{-1}{\cdot}yr^{-1}$, and its magnitude is about 53 percent of that of the Galactocentric acceleration.

We will discuss this component and investigate the possibilities for it in this paper and also focus on the impact of this acceleration on the ICRF. In Section 2, the validation of this acceleration will be presented, and we will investigate the vertical component in Section 3. The impact of the acceleration will be discussed in Section 4, and finally conclusions will be made in Section 5.

2 Validation

The SSB's acceleration wss determined to be (7.47 $\pm$ 0.46, 0.17 $\pm$ 0.57, 3.95 $\pm$ 0.47) $mm{\cdot}s^{-1}{\cdot}yr^{-1}$ in the Galactic coordinate system by using VLBI 24-hour

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observations and the Calc/Solve software (Xu et al., 2012). In order to check if the determination is sensitive to the a priori, we take this result as an a priori value of the acceleration and estimate its correction based on the same data analysis strategy. It turns out to be insignificant with respect to its formal error as (0.04 $\pm$ 0.46, 0.08 $\pm$ 0.57, 0.06 $\pm$ 0.47) $mm{\cdot}s^{-1}{\cdot}yr^{-1}$.

The effect of the acceleration on positions of radio sources has a dipole structure over the sky with the magnitude of 5.8 $\mu as/yr$. And, in turn, this apparent proper motion should be present in the time series of source positions. In order to make this effect visible, one of the ICRF2 defining sources, 2136+141, was selected to make a special experiment for two reasons. First of all, it lies on the great circle of the celestial sphere normal to the acceleration vector; thus it maximizes the effect of the acceleration, which has an apparent proper motion of 5.7 $\mu as/yr$ and 1.3 $\mu as/yr$ in the directions of right ascension ($\Delta\alpha \cdot cos\delta$) and of declination, respectively. Secondly, as a defining source, it has a long observational history. In this circumstance the position of 2136+141 is treated as a local parameter to get its time series. So this means that the No-Net-Rotation constraint is imposed on the remaining

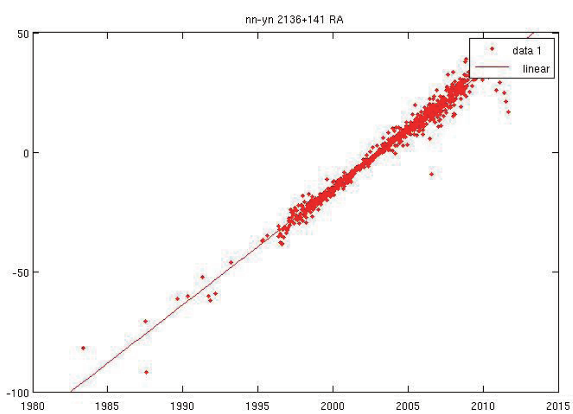

Fig. 1 The time series of right ascension of 2136+141. The linear trend is 5.7 μas per year.

294 ICRF2 defining sources. Two solutions were made based on this solution strategy. In one, the observations used to determine the acceleration included the observations of 2136+141, and in the other, the observations did not include those of 2136+141. When we speak of not including one observation, in practice, it means that for that observation the derivation of the group delay with respect to the acceleration is set to be zero instead of to the calculation from the model. Consequently, two time series were obtained, and the differences between them are shown in Figures 1 and 2. As we can see, this difference clearly reveals the apparent proper motion caused by the acceleration. It demonstrates that the code used for the estimation is correct, and the VLBI observation and the Calc/Solve software are exactly sensitive to the level of μas. This experiment shows us that if there is a systematic effect on the position of a radio source at the level of μas, it can be extracted from VLBI observations.

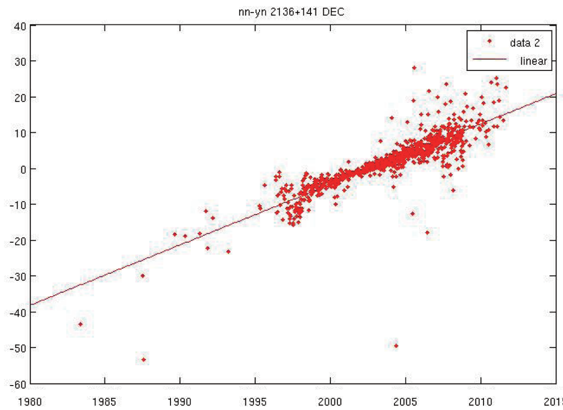

Fig. 2 The time series of declination of 2136+141. The linear trend is 1.3 μas per year.

3 Investigation of the Vertical Component

From the results we have obtained, the vertical acceleration is half of the domain component, the Galactocentric acceleration. As we know, the acceleration in the Galactic plane can exactely be validated by the current Galactic model. Contrary to that, there is not enough knowledge to directly identify the vertical acceleration, and there are not enough other observations to make a clear comparison.

Nevertheless, the oscillation of the Solar system over the Galactic plane is evident according to the researches in astronomy, even though the exact period and vertical distance of this oscillation has not been obtained yet. In the past 30 years, this oscillation has been pervasively used to explain phenomena with ultra-long periods on the Earth, such as the terrestrial mass extinction, cometary impacts, climate change, the inversion of the Earth magnetic field and so on (see, e.g., Rampino & Stothers 1984, Bahcall & Bahcall 1985, Shuter & Klatt 1986, Stothers 1998, Binney & Tremaine 2008, and Bailer-Jones 2009). The gravity potential can be established from the mass distribution model of the Galaxy, and as a result of other assumptions, such as the location and the vertical velocity of the Solar System, the period of this motion was expected to lie in the range of 52 $\sim$ 87 Myr. However, we should not expect that it can be used to validate the vertical component we obtained because of the large uncertainty of these studies.

The pulsar timing is another observation that may provide information about the motion of the SSB within the Galaxy, because the time of arrival (TOAs) of pulses is affected by the relative motion of the pulsar and the SSB. The effect in TOAs caused by the rotations of the SSB and pulsars round the Galactic center can be taken into account directly from the Galactic model. Therefore, if an ensemble of pulsars selected nevertheless manifests a common motion from the TOA observations, this collective motion can be assumed as, or at least used to constrain, the motion of the SSB apart from the rotation around the Galactic center. Harrison (1977) first suggested that the Sun has an undetected companion star as an explanation of the decrease in the period of a small group of pulsars. Later this was discussed in more detail by Cowling (1983) and Thornburg (1985). However, these studies could only constrain the SSB's remaining acceleration to $\sim 32\ mm{\cdot}s^{-1}{\cdot}yr^{-1}$, which is much higher than that of the vertical acceleration determined from VLBI data, 3.95 $mm{\cdot}s^{-1}{\cdot}yr^{-1}$ when expressed in the same unit. Recently, Zakamska & Tremaine (2005) used the timing data of millisecond pulsars, pulsars in binary, and pulsating white dwarfs to constrain the limit of the acceleration. The results showed that the SSB's remaining acceleration was on the upper limit of 4.73 $mm{\cdot}s^{-1}{\cdot}yr^{-1}$, comparable with the vertical component but without information for the direction. Thus, this method would be insufficient to check our result effectively.

As we have discussed before, it is very likely that this vertical component arises from the oscillation motion of the Sun over the Galactic plane. If this is the real case, this means that the dynamical plane near the Sun is tilted with respect to the current Galactic plane in an unusually large angle, and the mass model for the Galaxy may need to be investigated. Because the Sun is probably located in the north of the Galactic plane (see, e.g., Humphreys & Larsen 1995; Perryman 2009, Chap. 9), the vertical acceleration should point to the south pole of the Galaxy, which is the inverse direction of our result. Moreover, the Sun is considered to be near the plane, and the vertical component is supposed to be one order of magnitude smaller than the Galactocentric component (Kopeikin & Makarov 2006).

On top of that, there are two other possibilities. One is that the Galaxy accelerates toward its north pole in the universe. But currently no one knows. The second one is that the proper motions of the ICRF2 sources, especially of the 295 defining sources, have a systematic pattern. It is obvious that if they also have a dipole structure toward north pole, then the acceleration determined would include this effect. In this case, even though it cannot be interpreted as the SSB's acceleration, it should be taken into account as well for the celestial reference frame.

4 The Impact of the Acceleration

The SSB's acceleration changes the apparent positions of radio sources over time by approximately 5.8 $\mu as/yr$ based on our results, which breaks the rules of the establishment of the current ICRF. Table 1 shows the magnitude of this effect from different studies. The first two results were predicted from the Galaxy model, whereas the last two ones were determined from VLBI observations. If this effect is not taken into account, the position discrepancy for the 295 defining sources will exceed 100 μas for the approximately 30-year history of VLBI observations. The aberration

Table 1 The magnitude of the apparent proper motion caused by the SSB's acceleration. Unit: $\mu as \cdot yr^{-1}$

Reference	Magnitude
Kovalevsky 2003	4.0
Malkin 2011	5.0
Xu et al. 2012	5.8
Titov et al. 2011, 2013	6.4

effect, which has a dipole pattern, in essence would not lead to any global rotation, but the distribution for the 295 defining sources is obviously not uniform on the sky. This global rotation is identified to exist in the

ICRF2. The main term is the rotation around the z-axis of the ICRF2 with a magnitude of 25 μas per century (Xu et al., 2013).

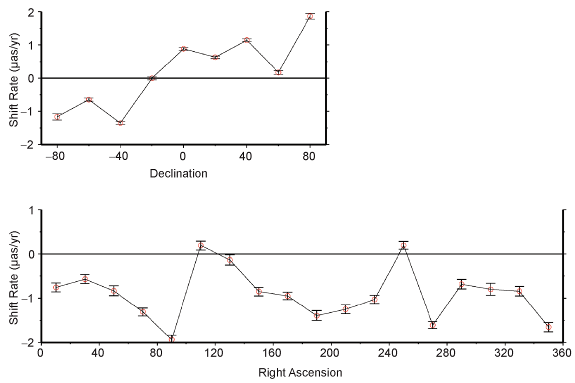

Fig. 3 The impact of the SSB's acceleration.

Figure 3 shows the impact of the SSB's acceleration on the equator plane and the zero right ascension. As we can see, the equator is moving toward the south pole with the speed of one μas per year on average.

5 Conclusions

Currently, it seems impossible to clearly explain and validate the vertical acceleration. The practical way is to keep monitoring it with more VLBI data in the future or to detect it from Gaia observations that are expected to be available in 2020. However, it was for the first time obtained directly from observations with high accuracy. As a real signal extracted from VLBI observations, it would be meaningful for the research of the Galaxy.

Although there are still some differences between the SSB's accelerations from various studies, it is apparent that it cannot be ignored. We propose a pilot program in the International VLBI Service for Astrometry and Geodesy community (IVS; Schuh & Behrend, 2012) to validate it and make it useful for VLBI data analysis.

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