ICRF3 Position and Proper Motion of Sagittarius A* from VLBA Absolute Astrometry

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Abstract Sagittarius A* (Sgr A*) is a strong compact radio source believed to be powered by a super-massive black hole at the galaxy's center. We have measured its precise coordinates as a function of time in the ICRF3 frame at K-band (24 GHz) using absolute astrometry with the VLBA. The proper motion determined allows us to estimate solar motion in and out of the galactic plane.

Keywords Sgr A*, proper motion, astrometry, VLBA

1 Introduction

The Sagittarius A* (hereafter Sgr A*) radio source is believed to be powered by a super-massive black hole at the galaxy's center [5, 4]. Precisely locating it and measuring its proper motion in the IAU's official ICRF3 [1] celestial reference frame is important in defining the galactic coordinate system, in studies of galactic structure, kinematics and dynamics, and for identification with nearby sources in the radio and IR. Extinction by gas and dust in the galactic plane prevents observing it optically. In the radio region it gets smeared out by plasma in the galactic plane, making it unobservble by VLBI at the lower frequencies, such as the traditional X/S (8.4/2.3 GHz) geodetic band. In this paper we report on the analysis of a 16-year span of VLBA observations of Sgr A* at K-band (24 GHz).

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2 Observations

Our K-band collaboration has observed Sgr A* at 45 epochs in K-band (24 GHz) absolute astrometry sessions on the VLBA, beginning in November 2017. These 24-hour sessions were made in an effort to generate, maintain, and expand the ICRF3 [1] at K-band, and each typically observed Sgr A* along with ∼225 extragalactic ICRF sources. These sessions were all made in the VLBI absolute astrometry mode, where many sources are observed all over the sky and large arcs between sources are solved for in order to locate each source in an inertial coordinate system, which in our case is the ICRF3 frame. Sgr A*, being just one of many sources targeted in each session, was observed for typically three scans totalling only 4.5 minutes, and taking up less than 0.5% of the total observing time in each session.

These sessions are only part of a much larger set of K-band VLBI sessions that were used to generate the ICRF3-K catalog [1] in 2018 and now to maintain and expand it. The larger data set contains VLBA sessions from 2002–2007 from the work of [7] and three sessions from the original processing at the Goddard Space Flight Center of the Galactic Plane Survey [8] sessions in 2006, two of which observed Sgr A*. Thus we have a 16-year span, from June 2006 through February 2022, of K-band VLBA absolute astrometry observations of Sgr A*. Due to the smearing by plasma in the galactic plane, observations of Sgr A* are somewhat limited at K-band. Sgr A* gets resolved out on the long VLBA baselines to MK-VLBA and SC-VLBA, as well as on most of the HN-VLBA and BR-VLBA baselines, thus limiting the precision of individual measurements.

3 Analysis

The Sgr A* data was taken from a recent K-band solution at USNO of the full data set of 150 K-band sessions spanning 2002–2022. In this solution, we solved for a single average position for 1,035 extragalactic ICRF sources, while the position of Sgr A* was solved for individually in each of its 47 epochs. Ionosphere corrections were computed and applied from GNSS ionosphere maps, as given in [1]. Alignment with ICRF3 was accomplished by imposing a no-net-rotation constraint on 258 ICRF3 defining sources that were well observed at K-band. This gave us a time series of the positions of Sgr A* in the ICRF3 frame. The resulting Right Ascension and Declination positions of Sgr A* are plotted in Figure 1. These positions are offset from

$$17^{\mathrm{h}}45^{\mathrm{m}}40^{\mathrm{s}},\ -29^{\circ}00'28''.$$

Solving for the RA and Dec slopes gives us the proper motion of Sgr A*. We get:

RA proper motion = -3.144 ± 0.044 mas/yr
Dec proper motion = -5.626 ± 0.080 mas/yr

And solving for the position at 2015.0 gives us the J2000 position of Sgr A* at the 2015.0 proper motion epoch in the ICRF3 frame:

$$\mathrm{RA} = 17^{\mathrm{h}}45^{\mathrm{m}}40.^{\mathrm{s}}034051 \pm 0.^{\mathrm{s}}000017$$
$$\mathrm{Dec} = -29^{\circ}00'28.''21583 \pm 0.''00045$$

For other epochs, add -0.000239665 sec/yr in RA and -0.0056255 arcsec/yr in Dec. The 2015.0 epoch is chosen for consistency with the 2015.0 galactic aberration epoch of ICRF3.

Our absolute astrometry measurement agrees well with the phase referencing (relative astrometry) measurement by [10] of -3.156 mas/yr $\pm$ 0.006 mas/yr and -5.585 mas/yr $\pm$ 0.010 mas/yr. Their relative astrometry measurement is able to achieve smaller uncertainties because of the very small angles between Sgr A* and the phase referencing calibrator sources, and because their observations were made at Q-band (43 GHz), where Sgr A* is smeared out only $\sim$1/3 as much as at K-band, and because they observed Sgr A* and two nearby phase referencing sources for much longer periods ($\sim$eight hours in each of 23 epochs spanning 18 years) than our observations ($\sim$4.5 minutes in each of 47 sessions). However, their relative astrometry measurements are not able to accurately locate Sgr A* in the ICRF3 frame since there are no nearby ICRF3 sources. Also, phase referencing can be subject to systematic errors from calibrator position variations due to source structure or other effects, though these are expected to be small at Q-band.

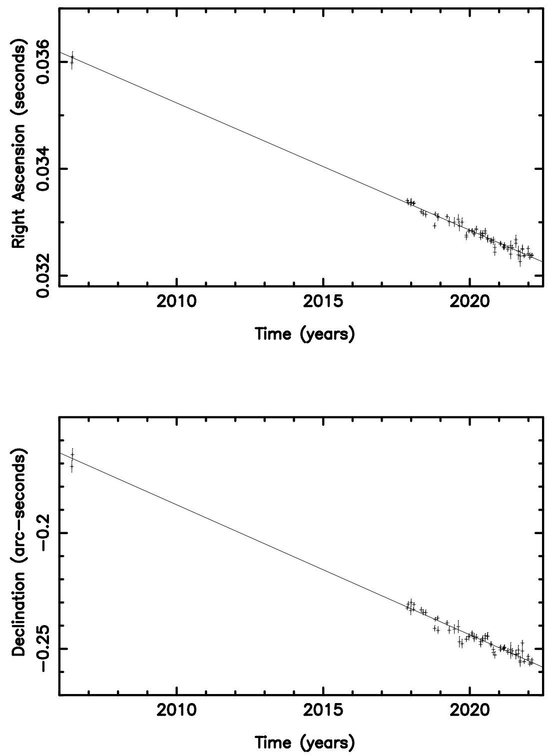

Fig. 1: Positions of Sgr A* from 2006–2022, offset from $17^{\mathrm{h}}45^{\mathrm{m}}40^{s}$, $-29^{\circ}00'28''$.

Combining the RA and Dec proper motions gives a total proper motion vector of 6.44 ± 0.09 mas/yr at a position angle of $209.2^{\circ} \pm 0.7^{\circ}$. This differs from the 211.4° position angle of the galactic plane by some $2.2^{\circ} \pm 0.7^{\circ}$, indicating out-of-the-plane proper motion of $\sim 0.25 \pm 0.08$ mas/year. If we assume a circular orbit for the Sun about the galactic center and a recent value for the distance to the galactic center of 8.15 kpc [3, 6, 9], our proper motion measurement yields a velocity of 249 ± 4 km/sec for the Sun within the galactic plane. And if attributed to solar motion, the $\sim 2.2^{\circ}$ deviation from the galactic plane indicates out-of-the-plane solar motion of 9.7 ± 3.1 km/sec towards the north galactic pole. This is in fairly good agreement with the recent value of 7.26 ± 0.36 obtained by [2].

4 Conclusions

Using absolute astrometry at K-band on the VLBA, we have found the proper motion of Sgr A* to be -3.144 ± 0.044 mas/yr in Right Ascension and -5.626 ± 0.080 mas/yr in Declination. And its position in the ICRF3 frame as a function of time is:

$$17^{\mathrm{h}}45^{\mathrm{m}}40.^{\mathrm{s}}034051 - 0.^{\mathrm{s}}000239665 * (year - 2015.0)$$
$$-29^{\circ}00'28.''21583 - 0.''0056255 * (year - 2015.0)$$

The position uncertainty is at approximately the 0.5 mas level due to limitations imposed by the interstellar medium. K-band sessions are continuing on the VLBA approximately monthly and, although Sgr A* is not observed every time, these results can be expected to slowly but steadily improve.

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