A Milliarcsecond-accurate Position for Sagittarius A*

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ABSTRACT

The absolute position of Sgr A*, the compact radio source at the center of the Milky Way, had been uncertain by several tens of milliarcseconds. Here we report improved astrometric measurements of the absolute position and proper motion of Sgr A*. Three epochs of phase-referencing observations were conducted with the Very Long Baseline Array for Sgr A* at 22 and 43 GHz in 2019 and 2020. Using extragalactic radio sources with submilliarcsecond-accurate positions as reference, we determined the absolute position of Sgr A* at a reference epoch 2020.0 to be at $\alpha(J2000) = 17^h 45^m 40.032863 \pm 0.000016$ and $\delta(J2000) = -29^\circ 00' 28.24260 \pm 0.00047$, with an updated proper motion $-3.152 \pm 0.011$ and $-5.586 \pm 0.006$ mas yr$^{-1}$ in the easterly and northerly directions, respectively.

Keywords: Individual Sources: Sgr A*; Black Holes; Galaxy: Center, Fundamental Parameters; Astrometry

1. INTRODUCTION

Sagittarius A* (Sgr A*) is a bright and compact radio source with overwhelming evidence for being a supermassive black hole (SMBH) at the dynamical center of the Galaxy (Ghez et al. 2008; Gillessen et al. 2009; Reid & Brunthaler 2020; Event Horizon Telescope Collaboration et al. 2022). Radio astrometry plays a critical role in the study of Sgr A*, since it is precluded from optical view by $\sim 30$ mag of visual extinction (Scoville et al. 2003) and has in the past only been detected in the infrared (IR) when flaring (Genzel et al. 2003). The absolute positions of compact radio sources are routinely obtained to an accuracy of milliarcseconds using geodetic and astrometric Very Long Baseline Interferometry (VLBI) observations at 8.4/2.3 GHz (e.g., Ma et al. 1998). However, at these frequencies Sgr A* is heavily resolved on interferometer baselines longer than several hundreds of km, owing to scatter broadening in the interstellar medium (Lo et al. 1998). Prior to 2004, the absolute position of Sgr A*, determined with the Very Large Array (VLA) and a small number of VLBI antennas at 86 GHz (Marcaide et al. 1992; Rogers et al. 1994; Yusef-Zadeh et al. 1999), was accurate from about $\pm 200$ mas to about $\pm 20$ mas. Next, improved positions for two calibrators (J1745–2820 and J1748–2907) within $\sim 0.7^\circ$ of Sgr A* were obtained from VLBI observations at 8.4/2.3 GHz. These positions, also limited by interstellar scattering, were estimated to be accurate at the $\sim 10$ mas level and were used by Reid & Brunthaler (2004, 2020) to obtain an improved position for Sgr A* (see coordinates in their Table 1 Notes).

Differential astrometry using VLBI observations involves measuring the interferometer phase on a strong “reference” source and subtracting that phase from all sources; this is known as phase referencing (Beasley & Conway 1995). This removes interferometer coherence-time limitations and allows weak sources to be imaged and relative positions measured with high accuracy (Reid & Honma 2014). An inaccurate absolute position of the source used as the interferometer phase reference in VLBI observations can cause an error in its delay/phase measurements, and these errors will be propagated to the target source (Reid & Honma 2014; Thompson et al. 2017). If the reference source position error is large enough ($\gtrsim 10$ mas), there can be significant second-order effects which lead to a relative position error and degraded image quality (Reid & Honma 2014). These errors become more serious for mm/sub-mm
Table 1. VLBA Astrometric Observations of Sgr A* in 2019 and 2020

| Epoch          | Program | Stations$^a$ | Duration (hour) | Frequency$^b$ |
|----------------|---------|--------------|----------------|--------------|
| (yyyy-mm-dd)   | Code    |              |                |              |
| 2019-06-18     | BX008A  | ALL except SC| 7              | K/Q          |
| 2019-11-01     | BX008B  | ALL          | 7              | K/Q          |
| 2020-01-26     | BX008C  | ALL except MK and SC | 7 | Q |

$^a$VLBA has 10 stations located at Saint Croix (SC), Hancock (HN), North Liberty (NL), Fort Davis (FD), Los Alamos (LA), Pie Town (PT), Kitt Peak (KP), Owens Valley (OV), Brewster (BR), Mauna Kea (MK).

$^b$The frequency band K is 22 GHz and Q is 43 GHz. Only Q band was used for Sgr A* astrometry in BX008C.

VLBI observations (Event Horizon Telescope Collaboration et al. 2022) and phase-referenced infrared interferometry observations (Gravity Collaboration et al. 2017) of Sgr A*, since a delay error leads to an interferometer phase error scaled by the observing frequency.

Recently the spatial resolution and sensitivity of IR and radio telescopes has significantly improved. The GRAVITY instrument on the Very Large Telescope Interferometer (VLTI) has achieved mas-scale resolution (Gravity Collaboration et al. 2017), and the Atacama Large Millimeter/Submillimeter Array (ALMA) can also perform precision astrometry of the Galactic center region around Sgr A* with high angular resolution over wide field of view (Tsuboi et al. 2022). Therefore, an accurate absolute position of Sgr A* will be valuable for the association of sources detected at different times or wavelengths.

In this paper, we report VLBA phase-referenced observations designed to improve the accuracy of the absolute position of Sgr A*. Compared to Reid & Brunthaler (2004, 2020), we used more distant (\(\sim 2^\circ\)) calibrators as position references in order to minimize the effects of scatter broadening. Using these calibrators we arrive at a mas-accurate position for Sgr A*.

2. OBSERVATIONS AND DATA REDUCTION

We conducted three epochs of phase-referenced observations of Sgr A* and four quasars at 22 (K-band) and 43 (Q-band) GHz under the National Radio Astronomy Observatory $^1$ program BX008 as listed in Table 1. Four extragalactic radio sources shown in Figure 1 and listed in Table 2 were used as background references for astrometry. The calibrators, J1744-3116 and J1752-2956, separated by \(\sim 2^\circ\) have \(\sim 1\) mas accurate absolute positions in the rfc$_{2016c}^2$ catalog and were used to improve the absolute position of Sgr A*. Note, the absolute positions of these calibrators used during the observations and in the VLBI correlator were updated later in data processing as more accurate (sub-mas accuracy) positions became available in the rfc$_{2022a}^3$ catalog (see Section 3.1). The nearby calibrators, J1745–2820 and J1748–2907, separated from Sgr A* by 0.7$^\circ$, were used to improve the proper motion of Sgr A* by combining with the data presented in Reid & Brunthaler (2020).

We observed at K and Q band alternatively in each session (except for BX008C where we only observed at Q band) and switched between Sgr A* and a calibrator source every 40/20 seconds for K/Q band. We used Sgr A* as the phase-reference, because it is stronger than the background sources and could be detected on individual baselines within a scan. Due to interstellar scattering, Sgr A* was heavily resolved on the longer baselines associated with antennas at Saint Croix (SC), Hancock (HN), and Mauna Kea (MK). The Kitt Peak (KP) antenna in program BX008C failed for unknown reasons. For each session we used 7-hour tracks. We included four \(\sim 25\)-min “geodetic blocks” at K-band scheduled before, middle and after the phase-reference observations, which allowed us to calibrate tropospheric and clock delays. Three strong “fringe finders,” J1638+5720, J1733-1304 (NRAO530) and J2236+2828, were also observed.

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$^1$ The National Radio Astronomy Observatory is operated by Associated Universities Inc., under a cooperative agreement with the National Science Foundation.

$^2$ The Radio Fundamental Catalog (RFC) with the version of rfc$_{2016c}$(http://astrogeo.org/vlbi/solutions/rfc$_{2016c}$/)

$^3$ The Radio Fundamental Catalog (RFC) with the version of rfc$_{2022a}$(http://astrogeo.org/sol/rfc/rfc$_{2022a}$/)
### Table 2. Initial Source Positions Used in the VLBA Program BX008

| Source      | R.A. (J2000) | Dec. (J2000) | \(\theta_{\text{sep}}\) | P.A. | Position Reference |
|-------------|--------------|--------------|--------------------------|------|-------------------|
|             | h m s        | \(^{\circ}\) | \(^{\prime}\) | \(^{\prime\prime}\) |      |                   |
| Sgr A*      | 17:45:40.033 | \(-29:00:28.247\) | ... | ... | Reid & Brunthaler (2004, 2020) |
| J1745-2820  | 17:45:52.496 | \(-28:20:26.294\) | 0.7 | 4 | Reid & Brunthaler (2004, 2020) |
| J1748-2907  | 17:48:45.680 | \(-29:07:39.404\) | 0.7 | 100 | Reid & Brunthaler (2004, 2020) |
| J1752-2956  | 17:52:33.108 | \(-29:56:44.916\) | 1.8 | 122 | rfc,2016c \(^b\) |
| J1744-3116  | 17:44:23.572 | \(-31:16:36.294\) | 2.3 | 187 | rfc,2016c \(^b\) |

**Note:** \(\theta_{\text{sep}}\) and P.A. indicate source separations and position angles (East of North) from Sgr A*.

\(^a\) The expected position of Sgr A* at the epoch 2019-06-18, which was calculated using the position \((17:45:40.04091, -29:00:28.1175)\) on 1996-03-20 and an assumed proper motion \(-3.147\) and \(-5.578\) mas yr\(^{-1}\) in the easterly and northerly directions, respectively.

\(^b\) These positions were from the Radio Fundamental Catalog (RFC) version of rfc,2016c (http://astrogeo.org/vlbi/solutions/rfc,2016c/). Both J1752–2956 and J1744–3116 had positional accuracy of approximately \(\pm 1\) mas level. Source coordinates listed in this Table were rounded to the nearest mas and adopted during the observations/correlations; these were updated later in data analysis as listed in Table 4.

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to monitor delay and electronic phase differences among the intermediate-frequency (IF) bands. We observed with four 64-MHz IF bands and recorded both right and left circularly polarized signals with Nyquist sampling and 2 bits-per-sample for a total sampling rate of 2 Gbps.

The raw data were processed with the DiFX correlator (Deller et al. 2007) in Socorro, NM, which generated 128 spectral channels for each 64-MHz IF band. Data calibration was performed with the NRAO Astronomical Image Processing System (AIPS) (Greisen 2003). Amplitude calibration was done using system noise temperatures and antenna gains logged during observations. For phase calibration, we corrected for the effects of diurnal feed rotation and errors in the Earth Orientation Parameters (EOP). Ionospheric delays were corrected for with the Global Ionosphere Map provided by the International GNSS Service (Reid & Honma 2014). After calibration, we imaged all sources and measured their position offsets relative to Sgr A* by fitting elliptical Gaussian brightness distributions.

### 3. RESULTS

Table 3 lists the measured position offsets relative to Sgr A*. Notice that the position offsets of the nearby (in angle) calibrators J1745–2820 and J1748–2907 are small. This is an historical artifact from previous observations which used inaccurate positions for the calibrators to determine the position of Sgr A*. The calibrators J1752–2956 and J1744–3116 display large position offsets of \(\approx 30\) mas relative to Sgr A*. As mentioned earlier, if the interferometer phase-reference source has a position error, this will be transferred to the other sources. Since J1752–2956 and J1744–3116 have very accurate absolute positions (\(\sim 1\) mas in Table 2) determined independently of Sgr A*, we conclude that the absolute positions of Sgr A*, J1745–2820, and J1748–2907 used by Reid & Brunthaler (2004, 2020) are in error by the reverse of the offsets seen for J1752–2956 and J1744–3116.

The problem with obtaining an accurate absolute position for Sgr A* is the extremely large scatter broadening experienced by sources within about 1° of the Galactic center. This makes previous X/S-band (8.4/2.3 GHz)VLBI astrometry, which provides absolute positions for a large number of calibrators, only marginally productive, since only very short baselines could be used to produce multi-band delays in that part of the sky. It took our study, which bootstrapped positions from calibrators outside of the large scattering region to obtain a mas-accurate position for Sgr A* and the calibrators used by Reid & Brunthaler (2004, 2020).

The position offsets or errors in the source used as the phase reference can cause errors in its delay/phase measurements, which are then propagated to the target source. For the first-order effects, the offset in the reference source position is simply transferred to the estimate of the target source position (Thompson et al. 2017). However, if the reference source position offset becomes large (\(\gtrsim 10\) mas), additional second-order effects can be important due to
Figure 1. The spatial distribution of sources from the VLBA program BX008. Sgr A* (red star) is the interferometer phase reference; two nearby sources (black dots) are from Reid & Brunthaler (2004, 2020); and two more distant calibrators (blue squares) are from the rfc2016c catalog. J1744–3116 and J1752–2956 have accurate absolute positions (∼1 mas accuracy in rfc2016c catalog, sub-mas accuracy in rfc2022a catalog) and can be used to improve the position of Sgr A*. The other two calibrators J1745–2820 and J1748–2907 are used to improve the proper motion of Sgr A* as done in Reid & Brunthaler (2020).

the fact that the target and reference sources are separated on the sky. Because they are at different positions, the interferometer phase response to a position offset at one position on the sky does not exactly mimic the response at the other position, which can lead to a small position error and to degraded image quality (Reid & Honma 2014). In order to evaluate these corrections, we re-processed the data using a corrected position of Sgr A*, shifted by (−31, +2) mas using the AIPS task “CLCOR,” and re-measured the relative positions. We then applied the same amplitude and phase calibrations described in Section 2. Figure 2 shows the second-order position errors, which were obtained by subtracting the original from the re-measured positions. These corrections were as large as −0.7 mas, and the last two columns in Table 3 have these applied.

3.1. The Absolute Position of Sgr A*

In active galactic nuclei (AGN) jets, the core of the radio emission can shift as a function of observing frequency owing to differences in the opacity (Blandford & Königl 1979; Hada et al. 2011); this is known as the “core-shift” effect. The differences in position offsets measured at K and Q band at the same epoch generally are ≲0.2 mas and are consistent within their joint uncertainties (see Table 3). This is consistent with the lack of a frequency-dependent core-shift between K and Q band for Sgr A* (which would lead to an apparent core-shift in the calibrators) reported by Bower et al. (2015) at a comparable level. Therefore, we average the K and Q band results when estimating absolute positions.

In order to estimate the absolute position of Sgr A*, we do the following: First, we corrected the data for improved positions for J1744–3116 and J1752–2956, compared to those used during the correlation of the VLBA data, using the latest RFC version rfc2022a (see Table 4). Second, we correct the individual position offsets to a reference epoch 2020.0, assuming Sgr A* has an easterly motion $-3.156 \pm 0.006$ mas yr$^{-1}$ and a northerly motion $-5.585 \pm 0.010$ mas yr$^{-1}$ (Reid & Brunthaler 2020); we also correct for Sgr A*’s parallax of 0.123 mas assuming a distance of 8.15 kpc.
Position of Sgr A*

Table 3. Residual Position Offsets Relative to Sgr A* in Program BX008

| Source     | Epoch  | Frequency | East Offset A$^a$ | North Offset A$^a$ | East Offset B$^b$ | North Offset B$^b$ |
|------------|--------|-----------|-------------------|-------------------|-------------------|-------------------|
|            |        | Band      | (mas)             | (mas)             | (mas)             | (mas)             |
| J1745–2820 | 2019.461 | Q         | −0.11 ± 0.06      | 0.34 ± 0.13       | −0.11 ± 0.05      | 0.42 ± 0.12       |
|            |        | K         | −0.13 ± 0.07      | 0.25 ± 0.14       | −0.07 ± 0.06      | 0.34 ± 0.12       |
|            | 2019.835 | Q         | 1.34 ± 0.03       | 2.58 ± 0.06       | 1.36 ± 0.03       | 2.56 ± 0.06       |
|            |        | K         | 1.26 ± 0.05       | 2.44 ± 0.08       | 1.26 ± 0.05       | 2.43 ± 0.08       |
|            | 2020.070 | Q         | 1.86 ± 0.06       | 4.10 ± 0.12       | 1.86 ± 0.06       | 4.21 ± 0.14       |
| J1748–2907 | 2019.461 | Q         | 1.45 ± 0.05       | −1.52 ± 0.12      | 1.43 ± 0.04       | −1.22 ± 0.11      |
|            |        | K         | 1.58 ± 0.05       | −1.75 ± 0.09      | 1.58 ± 0.04       | −1.44 ± 0.09      |
|            | 2019.835 | Q         | 2.85 ± 0.04       | 0.35 ± 0.10       | 2.78 ± 0.02       | 0.76 ± 0.07       |
|            |        | K         | 2.98 ± 0.08       | 1.41 ± 0.21       | 3.03 ± 0.06       | 1.75 ± 0.20       |
| J1752–2956 | 2019.835 | K         | 31.36 ± 0.10      | −5.32 ± 0.26      | 31.29 ± 0.03      | −6.43 ± 0.11      |
| J1744–3116 | 2019.461 | K         | 30.19 ± 0.10      | −5.73 ± 0.25      | 30.18 ± 0.09      | −5.79 ± 0.23      |
|            | 2019.835 | Q         | 31.48 ± 0.07      | −2.48 ± 0.17      | 31.47 ± 0.06      | −2.49 ± 0.18      |
|            |        | K         | 31.36 ± 0.09      | −2.27 ± 0.20      | 31.39 ± 0.08      | −2.30 ± 0.19      |

$^a$Case A: Position offsets relative to Sgr A* in the correlated interferometer visibilities. The coordinates used in correlation are in Table 2. The formal position uncertainties reflect thermal (random) noise in the phase-referenced interferometric images but do not include systematic uncertainties.

$^b$Case B: same as Case A, but correcting for second-order effects (see Section 3) of the position offset ([−31, +2] mas) we find for Sgr A*.

(Gravity Collaboration et al. 2019; Reid et al. 2019). Third, we correct for second-order effects of correlating the data with the “old” Sgr A* position, which is in error by about 30 mas (i.e., “Case B” in Table 3). Fourth, we average the position offsets at the reference epoch 2020.0, and infer a shift for Sgr A* of (−32.26 ± 0.24, 4.28 ± 0.53) mas relative to J1752–2956 and (−31.29 ± 0.37, 4.83 ± 1.02) mas relative to J1744–3116. Finally, we average (variance weighting) these position offsets and reverse their signs to arrive at our best position of Sgr A*. Similarly, relative to the best positions of Sgr A*, we average the position offsets of the other two calibrators at the reference epoch 2020.0, and infer a shift for J1745–2820 of (−30.28 ± 0.22, 7.93 ± 0.53) mas and for J1748–2907 of (−28.84 ± 0.23, 6.00 ± 0.49) mas. Our best positions for Sgr A* and the four calibrators are given in Table 4.

Recently, using geodetic and astrometric VLBA observations at 24 GHz, Gordon et al. (2022) reported an absolute position of Sgr A* at a reference epoch 2015.0 to be at α(J2000) = 17h45m40s03451 ± 0′′000019 and δ(J2000) = −29°00′28″21583 ± 0′′00045, and a proper motion −3.144 ± 0.044 and −5.626 ± 0.080 mas yr$^{-1}$ in the easterly and northerly directions, respectively. Transforming the reference epoch from 2015.0 to 2020.0, results in its position of α(J2000) = 17h45m40s032853±0′′00025 and δ(J2000) = −29°00′28″24396±0′′00060, which is consistent with our results within a 1-σ error in α and a 2-σ error in δ, respectively.

3.2. The Updated Proper Motion of Sgr A*

Our Q band data for J1745–2820 and J1748–2907 can also be used to update the proper motion of Sgr A* of Reid & Brunthaler (2020) by extending the time spanned to 25 years (1995–2020). The prior measurements are equivalent to “Case A” in Table 3, and in order to be internally consistent, we list the positions of the two quasars relative to

4 The quoted uncertainties include the following added in quadrature: i) thermal noise of (±0.03, ±0.11) mas for J1752–2956 and (±0.08, ±0.20) mas for J1744–3116; ii) the propagated error from proper motion and parallax (±0.01, ±0.01) mas of Sgr A*; iii) the uncertainties in the absolute positions of (±0.20, ±0.40) mas for J1752–2956 and (±0.36, ±0.70) mas for J1744–3116, and iv) estimated uncertainties from phase-referencing (±0.12, ±0.33) mas for J1752–2956 and (±0.06, ±0.71) mas for J1744–3116 based on Pradel et al. (2006).

5 The quoted uncertainties include the following added in quadrature: i) thermal noise of (±0.05, ±0.10) mas for J1745–2820 and (±0.04, ±0.12) mas for J1748–2907; ii) the uncertainties in the absolute positions of (±0.21, ±0.47) mas for the updated Sgr A*, and iii) estimated uncertainties from phase-referencing (±0.03, ±0.23) mas for J1745–2820 and (±0.08, ±0.06) mas for J1748–2907 based on Pradel et al. (2006).

6 https://drive.google.com/file/d/1350Itc6wVb14HzrcoRzn-Ew-L-x_VwL3/view
Figure 2. The position error due to the second-order effects of the position offset ([−31, +2] mas) of Sgr A*. The error bars are joint thermal uncertainties from phase-referenced images with and without the position offset correction. The horizontal axis is the separation angles in eastern direction between each calibrator and Sgr A*. Data from different epochs and different bands are offset slightly horizontally for clarity.

Table 4. The Updated Sources Positions

| Source         | R.A. (J2000)          | Dec. (J2000)          | Epoch   | Reference |
|----------------|-----------------------|-----------------------|---------|-----------|
|                | h m s (± s)           | ° ′ ″ (± ″)           |         |           |
| J1752–2956     | 17:52:33.108059 (±0.000013) | −29:56:44.91541 (±0.000040) | 2000.0  | rfc_2022a |
| J1744–3116     | 17:44:23.578245 (±0.000024) | −31:16:36.29107 (±0.000070) | 2000.0  | rfc_2022a |
| Sgr A*         | 17:45:40.032863 (±0.000016) | −29:00:28.24260 (±0.000047) | 2020.0  | This Paper |
| J1745–2820     | 17:45:52.494492 (±0.000017) | −28:20:26.28607 (±0.000053) | 2020.0  | This Paper |
| J1748–2907     | 17:48:45.683802 (±0.000018) | −29:07:39.39800 (±0.000049) | 2020.0  | This Paper |

The updated positions of J1752–2956 and J1744–3116 are from the Radio Fundamental Catalog (RFC) version rfc_2022a (http://astrogeo.org/sol/rfc/rfc_2022a/), which had better accuracy than the positions in Table 2 from version of rfc_2016c.

The position uncertainties include estimates of systematic effects, dominated by small residual errors in modeling atmospheric delays.

Before fitting for motions, we made a small correction for the parallax effect (<= 0.123 mas), assuming a distance to the Galactic center of 8.15 kpc (Gravity Collaboration et al. 2019; Reid et al. 2019), to all the measurements. Then fitting apparent motions of Sgr A* relative to J1745–2820 and J1748–2907 using variance-weighted least-squares we find the motions listed in Table 6. The northerly motions measured against the two quasars are statistically consistent. However, in the easterly direction the motions formally differ by 0.021 ± 0.0064 mas yr⁻¹, suggesting that there might be a small systematic difference between them. One possibility is one or both quasars are not stationary point sources, owing to jet emissions within our resolution element. In order to allow for systematics, we add one-half the difference Sgr A* in Table 5. Note that these do not use our updated positions for Sgr A* and J1745–2820 and J1748–2907.


**Table 5.** Residual Position Offsets Relative to Sgr A* for updating the proper motion of Reid & Brunthaler (2020)

| Source       | Date of Observation | Band | East Offset (mas) | North Offset (mas) |
|--------------|---------------------|------|-------------------|-------------------|
| J1745–2820  | 2019.461            | Q    | 73.35 ± 0.1       | 129.34 ± 0.2      |
|              | 2019.835            | Q    | 74.80 ± 0.1       | 131.58 ± 0.2      |
|              | 2020.070            | Q    | 75.32 ± 0.1       | 133.10 ± 0.2      |
| J1748–2907  | 2019.461            | Q    | 74.91 ± 0.2       | 127.48 ± 0.6      |
|              | 2019.835            | Q    | 76.31 ± 0.2       | 129.35 ± 0.6      |
|              | 2020.070            | Q    | 76.44 ± 0.2       | 130.41 ± 0.6      |

Note—The coordinate offsets are relative to the following J2000 positions used by Reid & Brunthaler (2020): Sgr A* (17 45 40.0409, −29 00 28.118), J1745–283 (17 45 52.4968, −28 20 26.294), and J1748–291 (17 48 45.6860, −29 07 39.404).

**Table 6.** The Updated Apparent Relative Motions

| Source – Reference | Easterly Motion (mas y\(^{-1}\)) | Northerly Motion (mas y\(^{-1}\)) |
|--------------------|----------------------------------|----------------------------------|
| Sgr A* – J1745–2820 (1995–2020) | −3.141 ± 0.005 | −5.585 ± 0.007 |
| Sgr A* – J1748–2907 (1995–2020) | −3.162 ± 0.004 | −5.588 ± 0.012 |
| Sgr A* – Combined (1995–2020) | −3.152 ± 0.011 | −5.586 ± 0.006 |

Note—Motions values are from weighted least-squares fits to the data in Table 1 of Reid & Brunthaler (2020) and Table 5, with uncertainties scaled to give a reduced chi-squared of unity. The scale factors for the uncertainties are 0.92 for “Sgr A* – J1745–2820” and 0.75 for “Sgr A* – J1748–2907”. “Combined” motions are variance-weighted averages of the individual results with formal uncertainties (see text for a discussion of systematic uncertainty).

in the motion measurements relative to the two quasars in quadrature with the formal uncertainties. This yields a combined motion estimate for Sgr A* of −3.152 ± 0.011 mas yr\(^{-1}\) in the easterly direction and −5.586 ± 0.006 mas yr\(^{-1}\) in the northerly direction.

4. CONCLUSIONS AND OUTLOOK

We have improved the absolute position and proper motion of Sgr A* using the reference sources with accurate positions. These calibrators are separated from Sgr A* by ≈ 2\(^{\circ}\) and are much less scatter broadened than the more nearby sources J1745–2820 and J1748–2907 (≈0.7\(^{\circ}\) from Sgr A*) previously used to determine Sgr A*’s position (Reid & Brunthaler 2004, 2020). Correcting for a local reference frame offset about 30 mas, we find the position of Sgr A* at the reference epoch 2020.0 to be at α(J2000) = 17\(^{h}\)45\(^{m}\)40\(^{s}\)032863±0\(^{s}\)000016 and δ(J2000) = −29°00′28″24260±0″00047.

Transforming the reference epoch from 2020.0 to 2000.0 using Sgr A*’s proper motion, results in a position of α(J2000) = 17\(^{h}\)45\(^{m}\)40\(^{s}\)037669±0\(^{s}\)000023 and δ(J2000) = −29°00′28″13088±0″00049.

By extending the time series of measurements by Reid & Brunthaler (2020) of Sgr A* relative to J1745–2820 and J1748–2907, we improved the accuracy of Sgr A*’s proper motion yielding −3.152 ± 0.011 and −5.586 ± 0.006 mas yr\(^{-1}\) in the easterly and northerly directions.
Our improved absolute position for Sgr A* should be used in high angular resolution interferometric observations, including VLBI, VLTI and ALMA observations of the Galactic center region. If Sgr A* is used as the interferometer phase reference, this will allow higher dynamic-range imaging and a more accurate registration of images between radio, millimeter, and infrared observations. In addition, as shown in Figure 2, the errors in relative position measurements due to the second-order effect of the inaccurate absolution position can lead small extra position shifts, which are dependent on the sky positions of target and calibrator. This can degrade relative astrometry accuracy. Thus, an accurate absolute position for Sgr A* will be important for μas relative astrometry in the Galactic center region, e.g., measuring the parallax of Sgr A* with μas accuracy using the next generation instruments (Rioja & Dodson 2020).

In addition, the astrometric reference frame for the stars seen orbiting an unseen mass in the Galactic center at IR wavelengths is established using common stellar sources seen in radio and infrared images (Menten et al. 1997; Reid et al. 2003; Ghez et al. 2008; Gillessen et al. 2009; Sakai et al. 2019). Our improved absolute position for Sgr A* provides an accurate origin for the astrometric reference frame in the Galactic centre region. For example, using IR measurement of Sgr A* flares, this would allow transfer of the absolute radio to the IR position of Sgr A* directly at the mas level.

Finally, we note that the IAU definition of Galactic coordinates (Blaauw et al. 1960) places the Galactic center at α⊙(B1950) = 17h42m26s603, δ⊙(B1950) = −28°55′00″.445 (Lane 1979) in B1950.0 coordinates. Converting the B1950.0 coordinates to J2000.0 coordinates, Reid & Brunthaler (2004) obtained a J2000 origin α⊙(J2000) = 17h45m37s224, δ⊙(J2000) = −28°56′10″.23. However, the IAU definition of Galactic coordinates was based on early HI observations, prior to the discovery of Sgr A*. Given the strong evidence that Sgr A* is a supermassive black hole at the dynamical center of the Galaxy, one could consider a revised definition which places Sgr A* at the origin of Galactic coordinates. Note, however, that owing to the Sun’s Galactic orbit, the apparent position of Sgr A* drifts by over 6 mas yr$^{-1}$, which would require a time-dependent coordinate system.

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Facilities: VLBA

Software: AIPS (Greisen 2003), Astropy (Astropy Collaboration et al. 2013)

REFERENCES

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Beasley, A. J., & Conway, J. E. 1995, in Astronomical Society of the Pacific Conference Series, Vol. 82, Very Long Baseline Interferometry and the VLBA, ed. J. A. Zensus, P. J. Diamond, & P. J. Napier, 327

Blaauw, A., Gum, C. S., Pawsey, J. L., & Westerhout, G. 1960, MNRAS, 121, 123, doi: 10.1093/mnras/121.2.123

Blandford, R. D., & Königl, A. 1979, ApJ, 232, 34, doi: 10.1086/157262

Bower, G. C., Deller, A., Demoerst, P., et al. 2015, ApJ, 798, 120, doi: 10.1088/0004-637X/798/2/120

Deller, A. T., Tingay, S. J., Bailes, M., & West, C. 2007, PASP, 119, 318, doi: 10.1086/513572

Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2022, ApJ, 930, L12, doi: 10.3847/2041-8213/ac6674

Genzel, R., Schödel, R., Ott, T., et al. 2003, Nature, 425, 934, doi: 10.1038/nature02065

Ghez, A. M., Salim, S., Weinberg, N. N., et al. 2008, ApJ, 689, 1044, doi: 10.1086/592738

Gillessen, S., Eisenhauer, F., Trippe, S., et al. 2009, ApJ, 692, 1075, doi: 10.1088/0004-637X/692/2/1075

Gordon, D., Jacobs, C. S., & de Witt, A. 2022, in Proc. 12th IVS General Meeting, 1

Gravity Collaboration, Abuter, R., Accardo, M., et al. 2017, A&A, 602, A94, doi: 10.1051/0004-6361/201730838

Gravity Collaboration, Abuter, R., Amorim, A., et al. 2019, A&A, 625, L10, doi: 10.1051/0004-6361/201935656
Greisen, E. W. 2003, in Astrophysics and Space Science Library, Vol. 285, Information Handling in Astronomy - Historical Vistas, ed. A. Heck, 109, doi: 10.1007/0-306-48080-8_7

Hada, K., Doi, A., Kino, M., et al. 2011, Nature, 477, 185, doi: 10.1038/nature10387

Lane, A. P. 1979, PASP, 91, 405, doi: 10.1086/130508

Lo, K. Y., Shen, Z.-Q., Zhao, J.-H., & Ho, P. T. P. 1998, ApJ, 508, L61, doi: 10.1086/311726

Ma, C., Arias, E. F., Eubanks, T. M., et al. 1998, AJ, 116, 516, doi: 10.1086/300408

Marcaide, J. M., Alberdi, A., Bartel, N., et al. 1992, A&A, 258, 295

Menten, K. M., Reid, M. J., Eckart, A., & Genzel, R. 1997, ApJ, 475, L111, doi: 10.1086/310472

Pradel, N., Charlot, P., & Lestrade, J.-F. 2006, A&A, 452, 1099, doi: 10.1051/0004-6361:20053021

Reid, M. J., & Brunthaler, A. 2004, ApJ, 616, 872, doi: 10.1086/424960

—. 2020, ApJ, 892, 39, doi: 10.3847/1538-4357/ab76cd

Reid, M. J., & Honma, M. 2014, ARA&A, 52, 339, doi: 10.1146/annurev-astro-081913-040006

Reid, M. J., Menten, K. M., Genzel, R., et al. 2003, ApJ, 587, 208, doi: 10.1086/368074

Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2019, ApJ, 885, 131, doi: 10.3847/1538-4357/ab4a11

Rioja, M. J., & Dodson, R. 2020, A&ARv, 28, 6, doi: 10.1007/s00159-020-00126-z

Rogers, A. E. E., Doeleman, S., Wright, M. C. H., et al. 1994, ApJ, 434, L59, doi: 10.1086/187574

Sakai, S., Lu, J. R., Ghez, A., et al. 2019, ApJ, 873, 65, doi: 10.3847/1538-4357/ab0361

Scoville, N. Z., Stolovy, S. R., Rieke, M., Christopher, M., & Yusef-Zadeh, F. 2003, ApJ, 594, 294, doi: 10.1086/376790

Thompson, A. R., Moran, J. M., & Swenson, George W., J. 2017, Interferometry and Synthesis in Radio Astronomy, 3rd Edition, doi: 10.1007/978-3-319-44431-4

Tsuboi, M., Tsutsumi, T., Miyazaki, A., Miyawaki, R., & Miyoshi, M. 2022, arXiv e-prints, arXiv:2204.06778.

https://arxiv.org/abs/2204.06778

Yusef-Zadeh, F., Choate, D., & Cotton, W. 1999, ApJ, 518, L33, doi: 10.1086/312058