The intrinsic radio proper motion of a quasar is predominantly conducted with Very Long Baseline Interferometry (VLBI). These observations have been conducted primarily by the Astronomical Union barycentric reference system standardized by the International Astronomical Union (IAU) 2009. When point-like extragalactic radio sources such as quasars were selected to anchor the ICRF, it was assumed that these sources are approximately fixed on the sky and exhibit no measurable proper motion. However, as the precision of VLBI measurements has improved, it has become clear that quasars are not fixed over human timescales and have proper motions on the order of microarcseconds to milliarcseconds (e.g., Eubanks 1997; Gwinn et al. 1997; Feissel & Gontier 2000). The intrinsic radio proper motion of a quasar is predominantly due to the motion of plasma in relativistic jets produced by the quasars (e.g., Fey et al. 1997). These intrinsic proper motions are random in orientation on the sky. Quasars also show correlated proper motions from cosmological effects (e.g., Gwinn et al. 1997; Quercellini et al. 2009; Nusser et al. 2012; Darling 2013), as well as from observer-induced signatures such as the secular aberration drift (e.g., Fanselow 1983; Bastian 1995; Eubanks et al. 1995; Sovers et al. 1998; Mignard 2002; Kovalevsky 2003; Koepinkin & Makarov 2006; Titov et al. 2011; Xu et al. 2012, 2013; Titov & Lambert 2013). Both cosmological and observer-induced proper motions are often much smaller than the quasars’ intrinsic proper motions, but the correlated nature of these effects allows a statistical detection if the sample size is large enough. Using a large sample of extragalactic proper motions, it is possible to obtain geometrical distances independent of canonical cosmological distance ladders (e.g., Ding & Croft 2009; Broderick et al. 2011), to measure or constrain the deflection of quasar light by a primordial gravitational wave background spanning $10^{-18}$–$10^{-9}$ Hz (Gwinn et al. 1997; Book & Flanagan 2011), to test the isotropy of Hubble expansion (Darling 2014), and to measure the collapse of large-scale structure (e.g., Quercellini et al. 2009; Nusser et al. 2012; Darling 2013).

The secular aberration drift is an observer-induced effect caused by the acceleration of the solar system around the Galactic center. The observed signal can be modeled as a curl-free dipole with an apex at the Galactic center. The observed signal can be modeled as a spheroidal dipole, with the square root of the power equal to 4.89 ± 0.77 μas yr$^{-1}$, and an apex at (275°2 ± 10°0, −29°4 ± 8°8). Our dipole model detects the aberration drift at a higher significance than some previous studies, but at a lower amplitude than expected or previously measured. The full aberration drift may be partially removed by the no-net-rotation constraint used when measuring archival extragalactic radio source positions. Like the cosmic microwave background dipole, which is induced by the observer’s motion, the aberration drift signal should be subtracted from extragalactic proper motions in order to detect cosmological proper motions, including the Hubble expansion, long-period stochastic gravitational waves, and the collapse of large-scale structure.

Key words: astrometry – catalogs – galaxies: distances and redshifts – proper motions – techniques: interferometric

Supporting material: data behind figures, figure set, machine-readable table

1. Introduction

Observations of extragalactic radio sources have been conducted with Very Long Baseline Interferometry (VLBI) since the 1970s with the purpose of measuring the Earth’s orientation and monitoring the terrestrial and celestial reference frames. These observations have been conducted primarily by the United States Navy and the National Aeronautic and Space Administration (NASA), and since 1998, have been coordinated by the International VLBI Service for Geodesy and Astrometry (IVS; Schlüter & Behrend 2007). By measuring group delays—the difference in arrival times of radio wave packets—at widely separated radio antennae, VLBI experiments can produce radio positions typically with milliarcsecond precision or better. These positions are used to determine the International Celestial Reference System (ICRS), a barycentric reference system standardized by the International Astronomical Union (IAU). Currently, the ICRS is defined by the second realization of the International Celestial Reference Frame (ICRF2; Ma et al. 1998; IERS Technical Note No. 35., 2009). ICRF2 contains 3414 total sources, including 295 “defining” sources whose positions are used to fix the axes of the ICRS.

When point-like extragalactic radio sources such as quasars were selected to anchor the ICRF, it was assumed that these sources are approximately fixed on the sky and exhibit no measurable proper motion. However, as the precision of VLBI measurements has improved, it has become clear that quasars are not fixed over human timescales and have proper motions on the order of microarcseconds to milliarcseconds (e.g., Eubanks 1997; Gwinn et al. 1997; Feissel & Gontier 2000).
the Galactic plane to measure that the solar system is 8.4 ± 0.6 kpc from the Galactic center and has a barycentric circular rotation speed of 254 ± 16 km s⁻¹. This yields an acceleration of 0.79 ± 0.11 cm s⁻² yr⁻¹ and a dipole amplitude of 5.40 ± 0.78 μ as yr⁻¹. In previous studies, extragalactic proper motions have been used to measure a solar acceleration of 0.93 ± 0.11 cm s⁻² yr⁻¹ (dipole amplitude of 6.4 ± 1.1 μ as yr⁻¹; TL13) and 0.85 ± 0.05 cm s⁻¹ yr⁻¹ (dipole amplitude of 5.8 ± 0.3 μ as yr⁻¹; Xu et al. 2013).

Although the secular aberration drift signal is small compared to typical extragalactic proper motions, it is important that it be well measured. The detection of the secular aberration drift will give an independent estimate of the solar acceleration without reliance on Galactic objects. If not corrected for in geodetic experiments, the drift can cause a deformation of the celestial reference frame axes, which can lead to inaccurate estimates of other geodetic parameters (Titov 2010). Additionally, the secular aberration drift must be removed from extragalactic proper motions in order to detect and measure cosmological effects.

In this paper, we present the VLBA Extragalactic Proper Motion Catalog containing 713 proper motions created using ~30 years of archival VLBI data and our own NRAO Very Long Baseline Array (VLBA) observations. We then use the catalog to measure the secular aberration drift as a means of demonstrating one of the uses of a large, precise catalog of extragalactic proper motions. This catalog is 66% larger than previous catalogs used to measured the aberration drift— TL13 use 429 quasars—due both to geodetic VLBI observations conducted in the intervening years and to the addition of our own astrometric observations. In addition, we use an analytic least-squares bootstrap technique to determine the proper motions, which provides more accurate estimation of the proper motions and associated uncertainties than previous techniques. Section 2 describes the catalog creation, Section 3 presents our optical redshift measurements, Section 4 presents our VLBA astrometric measurements and derived proper motions, Section 5 presents the completed catalog, Section 6 measures the secular aberration drift, and Section 7 summarizes our findings and suggests future additions to this work.

2. Catalog Creation

We created our catalog of extragalactic radio proper motions using the 2017a Goddard VLBI global solution¹ (e.g., IERS Technical Note No. 35., 2009). The global solution uses group delays and radio wave arrival times of a series of distant compact radio sources (typically quasars) to simultaneously solve for both a terrestrial and celestial reference frame using the fitting program CALC/SOLVE.² Earth orientation parameters are also solved for after each 24 hr session.

The 2017a solution is computed from more than 30 years of dual-band VLBI observations—1979 August 3 to 2017 March 27—and uses a total of 5696 diurnal sessions and greater than 10⁷ measurements of group delays. All sessions with durations of 18 hr and longer and source elevations higher than 5° were used in the fitting process. No net translation and rotation constraints were applied to the positions and velocities of all stations except for stations near Chile and Japan. The recent earthquakes in 2010 and 2011, respectively, caused nonlinear motions for nearby stations, which are modeled using post-seismic deformation models (Altamimi et al. 2016). Atmospheric gradient delays were modeled following MacMillan (1995) and MacMillan & Ma (1997) and the troposphere zenith delay was calculated using logged pressure and temperature (e.g., Saastamoinen 1972).³

In addition to the 2017a global solution, an astrometric time series of 4618 extragalactic radio sources is also produced by Goddard.⁴ Instead of treating the radio source positions as global parameters, which are assumed to be constant with time, the positions are incrementally treated as local parameters and are estimated once for each 24 hr session. Five separate solutions are combined to create the final 2017a time series. In the first solution, the positions of all 295 ICRF2 defining sources are global parameters and are tied to their ICRF2 positions with a a no-net-rotation (NNR) constraint, while the positions of all other sources are solved for at each session. In the second solution, the NNR constraint is removed for a quarter of the defining sources (every fourth source in R.A.) and the positions of this quarter are treated as local parameters and are solved for at each session. In the third, fourth, and fifth solutions, the next successive quarter of the defining sources uses them as local parameters. By incrementally treating all source positions as local parameters, the positions are allowed to vary between sessions and a coordinate time series can be constructed. Then, we can fit a trend line to the coordinate versus epoch for each source and solve for each source’s proper motion.

During the creation of the solutions, an NNR constraint is applied to fix the ICRS axes (IERS Technical Note No. 35., 2009). This constraint is needed to remove degeneracy when solving for the local parameters of each 24 hr observing session. However, Titov (2010) argues that a tight NNR constraint can remove systemic proper motions from the final catalog. To mitigate this effect, the NNR constraint is loosened during the creation of the Goddard 2017a coordinate time series. By creating five separate solutions where only a portion of the sources are required to satisfy the NNR constraint in each solution, all source positions are allowed to rotate with respect to the ICRS axes, while still enabling a non-degenerate local solution.

We fit a line to each coordinate time series (R.A. and decl.) for each radio source using an analytical least-squares parameter estimation. If we assume each source has a constant proper motion (this is a reasonable approximation for most extragalactic sources, with a few exceptions discussed below), then we can solve for the proper motion, μ, by minimizing the χ² statistic,

$$S = \sum_{i=1}^{N} \frac{(r_i - \theta_0 - \mu t_i)^2}{\sigma_i^2},$$

where $r_i$ is the celestial position of the source at time $t_i$, $\sigma_i$ is the uncertainty of the source position, and $\theta_0$ is the y-intercept of the line—a physically meaningless quantity in this application. Because the fitting model is linear, we can directly solve for $\mu$.

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¹ See https://gemini.gsfc.nasa.gov/solutions/2017_astro/2017a_ts.html
² https://lupus.gsfc.nasa.gov/software_calc_solve.htm
³ See https://gemini.gsfc.nasa.gov/solutions/2016a/gsf2016a.eops.txt for further details on initial parameters and assumptions.
and \( \theta_0 \)

\[
\mu = \frac{s_{\nu} - s_{\nu}}{\Delta},
\]

and

\[
\theta_0 = \frac{s_{\nu}^2 - s_{\nu} s_{\nu}}{\Delta},
\]

where

\[
s = \sum_{i=1}^{N} \frac{1}{\sigma_{\nu}^2},
\]

\[
s_t = \sum_{i=1}^{N} \frac{I_t}{\sigma_{t}^2},
\]

\[
s_r = \sum_{i=1}^{N} \frac{I_r}{\sigma_{r}^2},
\]

\[
s_{\nu} = \sum_{i=1}^{N} \frac{I_{\nu} I_r}{\sigma_{\nu}^2},
\]

\[
\Delta = s s_{\nu}^2 - s_{\nu}^2.
\]

We solved for proper motions separately in R.A. and decl.—\( r \) in the above equations is thus \( \alpha \) or \( \delta \), respectively. Proper motions in R.A., and their associated uncertainties, are corrected for decl. We excluded all sources that had been observed for less than 10 years or for fewer than 10 sessions. We also excluded sessions from before 1990 because fewer antennas and fewer monitored radio sources made VLBI data taken before this time less accurate (e.g., Gontier et al. 2001; Feissel-Vernier et al. 2004; Malkin 2004; Lambert & Gontier 2009; Titov et al. 2011). We also removed the 39 “special handling” sources from ICRF2 (IERS Technical Note No. 35, 2009). These sources show significant position instability in either R.A. and/or decl., indicating that their proper motion is largely from relativistic radio jets, rather than from the global effects we hope to measure. Thus, the inclusion of these sources in our catalog would impede our goal of detecting small, correlated proper motions.

There is a large variation in the uncertainties of individual positions within many of the time series. Additionally, some of these positions with high uncertainties are separated from the other measurements by a large gap in time, thereby giving them a disproportionately large influence on the resulting proper motion fit. To assess the influence of individual measurements on each fit and to better estimate the uncertainty of the fits, we employed 500 iterations of a bootstrap re-sampling on each time series. The reported proper motions in our catalog are the median of the bootstrap distribution. The proper motion uncertainties are calculated from the variance of the distribution using

\[
\sigma^2_{\mu} = \frac{1}{N-1} \sum_{i} (\mu_i - \bar{\mu})^2,
\]

where \( \bar{\mu} \) is the mean of the distribution, \( \mu_i \) is the proper motion for an individual bootstrap iteration, and \( N \) is the total number of bootstrap iterations.

3. Optical Redshifts

When available, we include redshifts in our catalog. Although not necessary for measurement of the secular aberration drift, redshifts are crucial for measurement of many of the cosmological effects described in Section 1. The majority of the redshifts were obtained from the 2017 May 31 version of the Optical Characteristic of Astrometric Radio Sources (OCARS; Malkin 2016) Catalog. This catalog contains known redshifts and optical or infrared magnitudes of radio sources observed in astrometric and geodetic VLBI observations. These source characteristics are primarily obtained from the NASA/IPAC Extragalactic Database⁵ (NED) or the SIMBAD Astronomical Database⁶ (Wenger et al. 2000). About 8% of our proper motion catalog is either missing redshifts or the redshifts are listed as “questionable” in OCARS.

We observed 28 catalog objects with either no redshift or a “questionable” OCARS redshift at the Apache Point Observatory (APO) 3.5 m telescope and/or at Gemini North to increase the fraction of our proper motion catalog that is usable in cosmological studies. Table 1 lists the observed objects and their measured redshifts. Ultimately, we measured 10 redshifts, ranging from \( z = 0.21\)–2.86. For cases where no redshift was determined, many of the spectra showed no significant emission or absorption lines. In a few cases, the only detectable lines were consistent with the local standard of rest \( (z = 0) \), even though we expect all of our catalog objects to be extragalactic. With only foreground Galactic absorption features present, we were unable to measure optical redshifts for these extragalactic radio sources. These objects have a redshift of “ Galactic” in Table 1. The spectroscopic observations are described below.

3.1. Apache Point Observatory

We conducted observations on the 3.5 m telescope at Apache Point Observatory from 2015 April 18 to 2016 June 30. We used the Dual Imaging Spectrograph (DIS) with a 1.5” slit and two gratings centered at 4400 Å and 7500 Å with linear dispersions of 1.83 Å pixel⁻¹ and 2.31 Å pixel⁻¹, respectively. The final spectra have a spatial resolution of 0”162 pixel⁻¹. We observed each target for a total of between ~15 and 75 minutes, depending on the target’s optical magnitude.

We reduced the data using the Image Reduction and Analysis Facility (IRAF) package. The images were over-scan-corrected, trimmed, bias-subtracted, flat-fielded, wavelength-calibrated, and background-sky-subtracted. Then we median-stacked the reduced images for each source and extracted a one-dimensional final spectrum. For objects where a flux calibrator was observed on the same night, we flux-calibrated the reduced, extracted spectra using the IRAF model of the calibrator’s flux density and a mean extinction curve measured at Apache Point.⁷ Figure 1 shows the final, one-dimensional spectra taken at APO. The measured redshifts and key lines used to determine those redshifts are listed on the plots. In the rest of this subsection, we discuss each spectrum individually.

⁵ http://ned.ipac.caltech.edu
⁶ http://simbad.u-strasbg.fr/simbad/
⁷ http://www.apo.nmsu.edu/arc35m/Instruments/DIS/images/apoextinct.dat
had too low of a signal-to-noise ratio (S/N) to extract. Together, these factors prevent us from determining a redshift.

0019+058—We find $z = 2.86$ based on three AGN emission lines—O I, C II, and C IV. There is also a prominent emission line at $\sim 5700$ Å that coincides with a sky emission line. It is likely that this line is an artifact of incomplete sky subtraction. There is a scatter of 10–30 Å in the line identifications at $z = 2.86$. This equates to a redshift uncertainty of $\sigma_z = 0.2$. OCARS gives this object a lower limit of $z > 0.64$, which is in good agreement with our measurement.

0056–001—We find $z = 0.719$ based on several emission lines, including H $\gamma$, H $\beta$, and [O III]. The scatter is <6 Å, which equates to $\sigma_z = 0.001$. After we observed this object at Apache Point, OCARS added a new redshift for this object—$z = 0.719$. Our measurements match this redshift exactly.

Table 1

| IVS Name | Mag | Filter | $z$ | Obs. |
|----------|-----|--------|-----|------|
| 0017+200 | 20.6 | V      | ... | APO  |
| 0019+058 | 18.8 | V      | 2.86 ± 0.02 | APO  |
| 0056–001 | 17.1 | V      | 0.719 ± 0.001 | APO  |
| 0106+138 | 19.0 | V      | 1.697 ± 0.005 | APO  |
| 0159+723 | 19.2 | V      | ...     | APO  |
| 0253+033 | 18.0 | V      | ...     | APO  |
| 0300+470 | 16.6 | V      | ...     | APO  |
| 0302+625 | ...  | ...    | Galactic | APO  |
| 0420+417 | 19.2 | R      | ...     | Gemini |
| 0422+004 | 16.5 | V      | 0.268$^a$ | NED  |
| 0426+273 | 19.6 | R      | ...     | APO  |
| 0549+135 | 20.5 | V      | 0.35 ± 0.01 | APO  |
| 0529+483 | 19.9 | V      | ...     | APO  |
| 1013+127 | 18.6 | V      | ...     | APO  |
| 1147+245 | 15.7 | V      | 0.209 ± 0.001 | APO  |
| 1444+313 | 15.0 | r      | ...     | APO  |
| 1506+591 | 19.9 | V      | 0.310 ± 0.004 | APO  |
| 1525+610 | 19.9 | G      | 0.2456 ± 0.0007 | APO  |
| 1717+178 | 19.9 | V      | 0.14$^b$ | NED  |
| 1754+155 | 17.2 | R      | 2.06 ± 0.04 | APO  |
| 1823+689 | 19.0 | R      | 2.143 ± 0.001 | APO  |
| 2013+163 | 17.3 | R      | ...     | APO  |
| 2021+317 | 19.0 | R      | ...     | Gemini |
| 2051+745 | 20.4 | V      | 0.92 ± 0.01 | APO  |
| 2225+033 | 17.5 | V      | ...     | APO  |
| 2315+032 | 20.4 | R      | ...     | APO  |
| 2319+444 | 20.7 | R      | ...     | APO  |

Notes. Columns from left to right: (a) the IVS name of the target, (b) the magnitude of the object from OCARS, (c) the optical filter in which the magnitude was measured, (d) the redshift of the object if a measurement was possible, and (e) the observatory where the object was observed (both objects observed at Gemini were first observed at APO). An ellipse for the redshift indicates that no redshift was measured. A redshift of “Galactic” indicates that only Galactic ($z = 0$) lines were detected, even though we expect all catalog objects to be extragalactic. We cannot measure optical redshifts for these extragalactic radio sources. For all of our redshifts, we determine the uncertainty based on the scatter in the line identifications. The two redshifts listed without uncertainties were obtained from the literature, where no uncertainties were provided.

$^a$ Shaw et al. (2013).

$^b$ Sowards-Emmert et al. (2005).

Figure 1. Calibrated, one-dimensional spectra obtained from APO. All spectra are smoothed by a 3 Å wide boxcar. Some of the spectra lack flux calibration, as indicated by the y-axis label. In the spectra without flux calibration, there is a large dip at $\sim 5500$ Å due to the sensitivity falloff at the edges of the red and blue CCDs. For objects where only the red half of the spectrum is plotted, the blue continuum was not significantly detected and could therefore not be extracted from the final image. Detected lines and the best-fit identifications are shown in each plot, along with their redshift. There are also two night sky absorption features visible in all plots at 6866 Å and $\sim 7600$ Å. For all of our redshifts, we determine the uncertainty based on the scatter in the line identifications. The two redshifts listed without uncertainties were obtained from the literature, where no uncertainties were provided. Objects labeled “Galactic” have only Galactic ($z = 0$) lines detected. Without any detected extragalactic lines, we cannot measure redshifts for these objects. The data used to create this figure are available. (The complete figure set (27 images) is available.)

0106+138—We find $z = 1.697$ from several emission lines shown in Figure 1. The scatter is 3–7 Å, which equates to $\sigma_z = 0.005$. This is in good agreement with the redshift measured by SDSS: $z = 1.7005 \pm 0.0003$ (Alam et al. 2015). 0159+723—There are several objects in our sample where only local standard of rest ($z = 0$) absorption lines were detected. 0159+723 is an example of one of these. It shows no emission lines and has many $z = 0$ absorption lines (Na I, Mg I, Ca II, etc.). Without the detection of any extragalactic lines, we cannot measure a redshift for this extragalactic radio source.

0253+033—This object has many deep, broad absorption, and/or emission lines. However, none of the typical AGN lines can explain all of the detected features. This object has a photometric redshift of $z = 0.4$ in the Million Quasars (Milliquas) catalog$^8$ (Flesch 2015), but we are unable to confirm this redshift with our spectrum. The line profiles are similar to those seen in broad absorption line (BAL) quasars (e.g., Hazard et al. 1984; Foltz et al. 1987; Weymann et al. 1991), suggesting that some of the lines may be blended and are confusing the identification of line centers. This object is classified as a BL Lacertae object (BL Lac) by D’Abrusco et al. 2014 based on its WISE colors, although the strength of the detected lines in our spectrum casts this classification into doubt. Further study of this object is needed to measure a redshift.

0300+470—No emission or absorption lines were detected for this object. It has a tentative redshift of $z = 0.475$ in NED.

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$^8$ http://quasars.org/milliquas.htm
from Hughes et al. (1992), but the original paper shows that this object is a BL Lac that was assigned the mean redshift of all known BL Lacs in lieu of an actual redshift. Without any detected lines or a measured redshift from previous studies, we cannot assign this object a redshift.

0302+625—This object’s spectrum only contains Galactic absorption lines. A few of the detected absorption lines are marked in the plot—notably, the Balmer series. We are unable to measure a redshift for this object because no extragalactic lines are detected.

0420+417—This object shows no significant emission or absorption lines. Additionally, the continuum is not detected on the blue CCD and has a low S/N on the red CCD. Because of these two factors, we selected this object for additional observation on Gemini North. These observations are discussed in Section 3.2.

0422+004—In the literature, Shaw et al. (2013) find \( z = 0.268 \) based on Ca II H & K and G-band absorption lines (no uncertainty is given on the redshift). We do not detect these lines—or any other significant lines—in our spectrum, but the continuum S/N is much lower. Based on the spectrum provided in Shaw et al. (2013), we accept their redshift of \( z = 0.268 \) for inclusion in our catalog.

0426+245—There are three emission lines detected for this object. From these lines, we find two possible redshifts, both of which only fit two of the three lines. The first option is \( z = 0.59 \) based on the [O III] doublet. The scatter for this option is \( \sim 4 \, \text{Å} \) (\( \sigma_z = 0.001 \)). The second option is \( z = 3.12 \) based on C IV and C III] (using the first half of the doublet at 7900 Å). The scatter for this option is \( \sim 7 \, \text{Å} \) (\( \sigma_z = 0.003 \)). Because neither of these redshifts can explain all three emission lines, we cannot assign a redshift to this object. A higher S/N spectrum is needed to detect additional lines and determine the correct redshift.

0459+135—We find \( z = 0.35 \) using four lines—H\( \beta \), He II, H\( \delta \), and [Ne V]. It is possible that H\( \alpha \) is also present, but lies in the noisy red end of the spectrum at \( \approx 8860 \, \text{Å} \). There is an overall scatter of \( \sim 20–40 \) Å in the line identifications at \( z = 0.35 \). This equates to a redshift uncertainty of \( \sigma_z = 0.01 \). 0529+483—This object is a blazar and has a redshift of \( z = 1.162 \) from Halpern et al. (2003). This redshift is based on a single line detection, which the authors identified as Mg II (2798 Å). No other information is given about their redshift determination, but it is likely they assumed this line is Mg II because it is one of the most common optical emission lines seen in blazars. We also detect this line in our spectrum, but no other lines are significantly detected. Without any other lines, we are unable to measure a statistically viable redshift, despite the conclusions of Halpern et al. (2003). Their redshift determination, although possible, should be regarded as tentative and is therefore not included in our catalog.

1013+127—This object has a redshift in NED of \( z = 0.463 \), but no references are given. An additional literature search revealed no potential sources for the redshift identification. A spectrum is available in SDSS (Alam et al. 2015), from which their algorithms measured a tentative redshift of \( z = 3.0140 \pm 0.0005 \). However, examination of the SDSS spectrum shows no clear emission or absorption lines on which to base their measurement. There are also no clear lines in our APO spectrum, nor any indication of non-significant lines that support either reported redshift. Therefore, we conclude that no reliable redshift can be determined for this object from the available data.

1147+245—This object has a redshift in NED of \( z = 0.2 \), but no references are given. There is also a spectrum in SDSS with a redshift of \( z = 3.9 \pm 9.0 \) (Alam et al. 2015). The SDSS spectrum shows no statistically significant lines, which, combined with the large redshift uncertainty, leads us to disregard this redshift. Based on our APO spectrum, we find a redshift of \( z = 0.209 \pm 0.001 \) using a cluster of three lines identified as H\( \alpha \) flanked by the [N II] doublet. This is in good agreement with the NED redshift. The large bump at \( \sim 4000 \, \text{Å} \) is an artifact of flux calibration that can be seen to a lesser extent in other spectra (e.g., 0529+483 and 1013+127).

1444+313—This object’s spectrum only contains Galactic absorption lines. A few of the detected absorption lines are marked in the plot. We cannot measure a redshift for this object without any detected extragalactic lines.

1506+591—We find \( z = 0.310 \) using seven AGN emission lines, shown in Figure 1. There is a scatter of \( \sim 6–20 \) Å in the expected line locations. This equates to a redshift uncertainty of \( \sigma_z = 0.004 \).

1525+610—We find \( z = 0.2456 \) from four AGN emission lines. Only the long-wavelength halves of the [N II] and [O III] doublets are visible, but it is assumed that the other half of each is lost in the surrounding noise. There is a scatter of \( 3–5 \, \text{Å} \), indicating \( \sigma_z = 0.0007 \). The emission line at 7540 Å is an artifact from background subtraction.

1717+178—No significant emission lines are detected for this object. OCARS gives this object a “tentative” redshift of \( z = 0.137 \) from an observation by Sowards-Emmerd et al. (2005). This redshift is based on the Ca II H & K doublet and Mg I absorptions lines. We do not detect any of these lines, but examination of the higher S/N spectrum in Sowards-Emmerd et al. (2005) confirms their redshift. Thus, we use \( z = 0.137 \) in our catalog. No uncertainty was given in the source paper.

1754+155—We find \( z = 2.06 \) (from O I, N IV), O II, and Fe II. There is a scatter of \( \sim 50 \, \text{Å} \), indicating \( \sigma_z = 0.04 \). This spectrum is also well fit by \( z = 0.05 \pm 0.02 \), where the lines from blue to red are [O II], H\( \gamma \), H\( \beta \), and H\( \alpha \). However, images of this object in the National Geographic Society Palomar Observatory Sky Atlas (POSS-I), ALLWISE (Cutri et al. 2013), and VLA observations at 1.45 and 43.3 GHz, all show a point-like object. A quasar at \( z = 0.05 \) should be near enough for the host galaxy to be resolved in at least one of these wavelength regimes. Thus, we conclude that \( z = 2.06 \pm 0.04 \) is the most likely redshift.

1823+689—We find \( z = 2.143 \) from Ly\( \alpha \) and C IV emission lines. The sudden decrease in continuum flux leftward of Ly\( \alpha \) may indicate the beginning of the Ly\( \alpha \) forest, but it is too close to the edge of the spectrum (where the CCD sensitivity also decreases) to make a definitive statement. There is a scatter of 2 Å between the two lines, which equates to a redshift uncertainty of \( \sigma_z = 0.001 \).

2013+163—This object’s spectrum only contains Galactic absorption lines. A few of the detected absorption lines are marked in the plot. We cannot measure a redshift for this extragalactic object because no extragalactic lines are detected.

2021+317—This object shows no significant emission or absorption lines. Additionally, the continuum is not detected on the blue CCD and has a low S/N on the red CCD. Because of

http://archive.nrao.edu/nvss/
these two factors, this object was selected for additional
observation on Gemini North. These observations are discussed in
Section 3.2.

\[ \text{2051+745} \]—We find \( z = 0.92 \) from \( \text{Fe II} \) and \( [\text{O II}] \). The
\( \text{Fe II} \) feature is very broad (FWHM \( \sim 100 \) Å) and has no clear
peak. This is a good fit for the large group of \( \text{Fe II} \) emission
lines present at \( \sim 2600 \) Å (rest wavelength) for some quasars.
Because the \( \text{Fe II} \) feature is several blended lines, we are unable to
use the line scatter to estimate the redshift uncertainty.
Instead, we use the FWHM of the \( [\text{O II}] \) feature—\( \sim 50 \) Å—to
estimate a redshift uncertainty of \( \sigma_z = 0.01 \).

\[ \text{2225+003} \]—This object shows no significant absorption or
emission lines. It has a flagged redshift of \( z = 3.823 \pm 0.001 \)
as measured by the SDSS BOSS survey (Dawson et al. 2013).
This redshift is based primarily on \( \text{Ly}\alpha \) in absorption and \( \text{C IV} \),
\( \text{He II} \), and \( \text{C III} \) in emission, none of which are strong lines in
the SDSS spectrum. In the APO spectrum, the absorption
feature is non-significantly detected and none of the other lines
are visible. With only one low-S/N absorption feature and a
weak SDSS redshift, we cannot assign this source a reliable
redshift. Note that the strong emission line at 5581 Å is a
skyline.

\[ \text{2315+032} \]—This object shows no significant lines and the
continuum was not detected on the blue CCD. We are unable to
measure a redshift.

\[ \text{2319+444} \]—There is only one significant emission line in
this spectrum. The object has a redshift in NED of \( z = 1.31 \)
(Xu & Han 2014), but the original paper gives no previous
source or additional data to support this redshift. There are no
common AGN lines that correspond with the detected line at
this redshift, nor are there any other low-S/N lines to support
the redshift. Additionally, if we try other redshifts where the
significant emission line corresponds with common AGN lines,
there are no other low-S/N lines to add validity to any of these
redshifts. With only one reliable emission line, we cannot
assign a redshift to this object.

3.2. Gemini North

Several of the objects observed at Apache Point Observatory
showed weak continua and no significant emission or
absorption lines. We chose two of these objects (0420+417
and 2021+317) for additional observations with the Gemini
Multi-Object Spectrograph—North (GMOS-N; Hook et al.
2004) at Gemini North Observatory.\(^{10}\) 2021+317 was
observed on 2016 June 26 and 28, while 0420+417 was
observed on 2016 November 8 and 26. We observed both
objects with a 1\( ^{\prime} \) slit and two grating setups: the B600 grating
with no filter and the R400 grating with a OG515 filter to
prevent order overlap (gratings centered at 4880 and 7640 Å,
respectively). We used 2 \( \times \) 2 binning, which, combined with
the grating setup, resulted in final spectra with linear
dispersions of 0.9 Å/pixel\(^{-1} \) and 1.4 Å/pixel\(^{-1} \) and wavelength
coverage of 3500 Å—6250 Å and 6250 Å—9000 Å,
respectively. Sixteen exposures of 632 s each were taken for
both objects—eight for each grating.

To reduce the Gemini North observations, we used the
Gemini IRAF package, a package written specifically for
reducing Gemini observations.\(^{11}\) The reduction process is the
same as for the images taken at Apache Point Observatory—the

\(^{10}\) Program ID GN-2016B-Q-81.

\(^{11}\) http://www.gemini.edu/sciops/data-and-results/processing-software
session, depending on the source flux density. We used 2 bit sampling at the Nyquist rate and an aggregate bit rate of 1024 megabits s\(^{-1}\). To maximize the S/N, which directly correlates with the resulting astrometric uncertainty, all of our observations used at least 9 out of 10 VLBA antennas. The longest baseline, Maunakea to St. Croix, was always used in our observations to maximize angular resolution.

We included 45-minute geodetic blocks before and after each observing session to improve measurement of phase errors induced by the troposphere. For the geodetic blocks, we used a similar setup to our main observations, but with more widely spaced baseband channels in order to better model the tropospheric delay as a function of frequency (total bandwidth of 480 MHz). Additionally, we repeated each observing session within 3–24 days so that each target was observed twice within a month and the final astrometric measurements are based on two independent observations. Previous VLBA astrometric campaigns (e.g., Reid & Brunthaler 2004) have found that a second set of observations can increase astrometric precision by \(\sqrt{2}\) and provide an important verification of the astrometry. The period between repeated observations must be long enough that weather conditions are not correlated (>3 days) but short enough that the proper motions of the extragalactic objects are negligible (<24 days). For all targets, the astrometry obtained from the two separate observations were in statistical agreement.

The data were reduced using standard VLBA reduction procedures in the Astronomical Image Processing System (AIPS; Associated Universities 1999), including self-calibration. For each target and phase reference, we created CLEANed images with a resolution of 0.9 mas pixel\(^{-1}\), using uniform weighting. The images have an average sky rms of 0.5 mJy beam\(^{-1}\) and an S/N of \(\sim\)2200 (based on the integrated flux of the object and the sky rms). We found the positions of each target and its phase reference through least-squares fitting of a two-dimensional Gaussian in the image plane. The resulting position accuracies are, on average, 4 \(\mu\)as. We used the relative angular separation between the target and its phase reference with known proper motion to calculate the target’s absolute position, then added the new position to the target’s time series. We then fit the time series using the analytic maximum likelihood parameter estimation described in Section 2. For these new proper motions, we did not use a bootstrap resampling to calculate the proper motions because the majority have too few epochs to correctly implement a bootstrap. The new proper motions have a mean amplitude precision of 49.7 \(\mu\)as yr\(^{-1}\). Table 2 lists the measured proper motions. Figure 3 shows an example time series for one of the new proper motion measurements.

5. The VLBA Extragalactic Proper Motion Catalog

The final extragalactic proper motion catalog contains 713 proper motions. The first ten entries of the catalog are shown in the Appendix. Figure 4 shows the sky distribution of our catalog, along with the proper motion of each object. Proper motions range from 0.01–1359.25 \(\mu\)as yr\(^{-1}\). On average, objects were observed for 21.9 years (\(\sigma = 4.4\) years) and the proper motion measurements were made based on an average of 249 group delays (\(\sigma = 513\) delays). Figure 5 shows the catalog redshift distribution. The mean redshift is \(z = 1.20\) and the standard deviation is \(\sigma_z = 0.84\).

Figure 6 shows histograms of the catalog proper motions and errors, along with the equivalent histograms for the TL13 proper motion catalog. The median proper motion amplitude of our objects is 14.7 \(\mu\)as yr\(^{-1}\) and the standard deviation is 82.5 \(\mu\)as yr\(^{-1}\). For the TL13 catalog, the median proper motion amplitude is 36.0 \(\mu\)as yr\(^{-1}\), with a standard deviation of 29.8 \(\mu\)as yr\(^{-1}\). The large difference in standard deviations is primarily because TL13 remove large proper motions that deviate from their iteratively fit dipole by more than 7\(\sigma\). For completeness, we have published all of our calculated proper motions without any clipping.

There is a large difference in the proper motion uncertainty distributions of the two catalogs—the mean proper motion uncertainty of our catalog is 26.8 \(\mu\)as yr\(^{-1}\), while it is
51.8 μas yr⁻¹ for the TL13 catalog. The lower uncertainty in our proper motions is due in part to the additional epochs of observations that have been added to the time series in the intervening years. It is also due to our new method of calculating the proper motions from the time series. Most curve-fitting programs use a nonlinear parameter estimation, which arrives at the best-fit parameters through a series of guesses. The uncertainties of the best-fit parameters are estimated using a similar iterative approach. Instead of using this approximate technique, we derived the analytic equations for the maximum likelihood estimators. By directly calculating the best-fit line to the time series using an analytic calculation, we are also able to directly calculate the uncertainties of the best-fit parameters, rather than using an iterative method to approximate the uncertainties. However, due to the large variation in the uncertainties of individual positions within each time series, we report the standard deviation of a bootstrap distribution as the uncertainty of each proper motion (Section 2). These standard deviations are larger than the calculated uncertainties of the maximum likelihood estimators but are a better reflection of the true parameter uncertainties. Despite this increase to the catalog proper motion uncertainties, our mean proper motion uncertainties remain significantly lower than those in TL13, demonstrating the significant effect our analytic calculations and additional epochs have on the proper motion uncertainties.

There are several systematic effects present in our catalog. First, there is a bias toward objects with positive decl.: 61% of the catalog objects lie above the celestial equator. This is due to the higher concentration of VLBI telescopes in the Northern Hemisphere than in the Southern Hemisphere. We find that this systematic does not have a significant effect on measuring the
secular aberration drift (see Section 6). If this bias affected the measurement, we would expect to see a significant deviation in decl. of the dipole apex from its expected location at the Galactic center. Section 6.1 shows that this is not the case and that our fitted apex is within 1σ of the Galactic center.

Second, the decl. proper motions and associated uncertainties are systematically larger than those in R.A. Figure 7 shows histograms illustrating this bias. The majority of our catalog was created using geodetic experiments conducted with the VLBA, which is more than twice as long in longitude than it is in latitude (east to west the VLBA is \( \sim 8600 \) km, and north to south it is \( \sim 3400 \) km), causing the primary telescope beam to be an ellipse that is, on average, longer in decl. than in R.A. Thus, the ellipticity of the primary beam allows R.A. to be measured more precisely than decl. for most point-like objects.

6. Secular Aberration Drift

Following the formalism in Mignard & Klioner (2012), the secular aberration drift can be expressed as the curl-free portion of a first-order vector spherical harmonic, resembling an electric (E) field dipole. The extragalactic proper motions due to the drift can then be expressed as an E-mode dipole as a function of sky position \((\alpha, \delta)\) by

\[
\mu_\alpha = \frac{1}{2 \sqrt{\pi}} \left( s_1^{\text{Re}} \sin \alpha + s_1^{\text{Im}} \cos \alpha \right)
\]
where $s_{lm}$ are the amplitudes of the “spheroidal” E-mode vector spherical harmonics of degree $l$ and order $m$. These can be converted to the $d_1$, $d_2$, and $d_3$ amplitudes used in TL13 by

$$
\begin{pmatrix}
    d_1 \\
    d_2 \\
    d_3
\end{pmatrix}
= 2 \sqrt{\frac{3}{\pi}}
\begin{pmatrix}
    -s_{11}^{Re} \\
    s_{11}^{Im} \\
    \sqrt{2} s_{10}
\end{pmatrix}
\cos \delta.
$$

(12)

In addition, a divergence-free first-order vector spherical harmonic, resembling a magnetic (B) field dipole, can also be fit to the extragalactic proper motions using the equations

$$
\mu_\delta = \frac{1}{2} \sqrt{\frac{3}{\pi}} \left( t_{10} \sqrt{\frac{1}{2}} \cos \delta \\
+ t_{11}^{Re} \cos \alpha \sin \delta - t_{11}^{Im} \sin \alpha \sin \delta \right),
$$

(13)

and

$$
\mu_\alpha = \frac{1}{2} \sqrt{\frac{3}{\pi}} \left( t_{10} \sqrt{\frac{1}{2}} \cos \delta \\
- t_{11}^{Re} \sin \alpha - t_{11}^{Im} \cos \alpha \right),
$$

(14)

where $t_{lm}$ are the “toroidal” B-mode vector spherical harmonic amplitudes and the conversion between these and the toroidal amplitudes used in TL13 is

$$
\begin{pmatrix}
    t_1 \\
    t_2 \\
    t_3
\end{pmatrix}
= 2 \sqrt{\frac{3}{\pi}}
\begin{pmatrix}
    t_{11}^{Re} \\
    -t_{11}^{Im} \\
    -\sqrt{2} t_{10}
\end{pmatrix}
\cos \delta.
$$

(15)

### 6.1. Data Processing and Results

We simultaneously fit the E-mode and B-mode dipoles to our extragalactic proper motions using a Markov Chain Monte Carlo (MCMC) Bayesian sampling of the posterior probability distribution function with the Python package lmfit.\(^\text{12}\) (Newville et al. 2014). The probability distributions for each dipole parameter are estimated through sampling of the log-likelihood functions where we assume the coefficients are drawn from a Gaussian distribution. Table 3 lists the maximum likelihood solution for each dipole E-mode and B-mode vector spherical harmonic coefficient and the 68% confidence interval spread of the probability distributions in both the spherical harmonic formalism and the TL13 formalism. Figure 8 shows the maximum likelihood secular aberration drift (E-mode dipole) model and Figure 9 shows the estimated posterior probability distributions. We detect the secular aberration drift at a 6.3$\sigma$ significance level, with the square root of the power equal to $4.89 \pm 0.77 \mu\text{as yr}^{-1}$, an amplitude of $1.69 \pm 0.27 \mu\text{as yr}^{-1}$, and an apex of $(275^\circ.2 \pm 10^\circ.0, -29^\circ.4 \pm 8^\circ.8)$. The apex of our E-mode dipole is within $1\sigma$ of the Galactic center $(266^\circ.4, -28^\circ.9)$ and the amplitude is within $5\sigma$ of the predicted amplitude of $5.40 \pm 0.78 \mu\text{as yr}^{-1}$.

We do not detect the B-mode dipole at a 2.2$\sigma$ significance level. We find that including the B-mode dipole increases the significance of the E-mode dipole by $\sim 0.63\sigma$ when compared to fitting just the E-mode dipole without a rotational component. The presence of a non-significant toroidal dipole indicates that we are detecting some residual Earth rotation that is not completely removed during data processing. Table 4 shows the correlations between the coefficients of our fit. There is a strong correlation between several coefficients of the E-modes and B-modes, which accounts for the necessary inclusion of the B-mode dipole.

\(^{12}\) https://lmfit.github.io/lmfit-py/
Table 3
Secular Aberration Drift Model

| Y_{hi} Formalisma | TL13 Formalismb |
|------------------|------------------|
| Order            | Amplitude (μas yr⁻¹) | Term | Amplitude (μas yr⁻¹) |
| E-mode Dipole    |                   |      |                     |
| \( s_{10} \)     | -2.40 ± 0.75      | \( d_1 \) | -6.94 ± 2.17        |
| \( s_{20} \)     | -0.27 ± 0.52      | -\( d_1 \) | 0.55 ± 1.06        |
| \( s_{21} \)     | -3.00 ± 0.55      | \( d_2 \) | -6.13 ± 1.13        |
| \( \sqrt{P_i} \) | 4.89 ± 0.77       | Amplitude | 1.69 ± 0.27 |
| B-mode Dipole    |                   |      |                     |
| \( r_{10} \)     | -0.55 ± 0.59      | -\( r_3 \) | 1.59 ± 1.71        |
| \( r_{11} \)     | 1.12 ± 0.54       | \( r_1 \) | 2.29 ± 1.11        |
| \( r_{21} \)     | -0.06 ± 0.65      | -\( r_2 \) | 0.12 ± 1.33        |
| \( \sqrt{P_i} \) | 1.68 ± 0.75       | Amplitude | 0.58 ± 0.26 |
| E-mode Apex      |                   |      |                     |
| (275±2° ± 10°, -29°±4 ± 8°) | | | |

Notes. \( \sqrt{P_i} \) and \( P_i \) are the square root of the first-order vector spherical harmonic powers. They can be converted to the TL13 amplitudes (right column) by dividing by \( \sqrt{2/3\pi} \).

a Vector spherical harmonic coefficients using the formalism presented in Mignard & Klioner 2012.
b The same dipole model as presented in the left column, but converted into the formalism used in TL13 for comparison. See Section 6 for conversions between the two formalisms.

Before fitting, we removed all objects with proper motion amplitudes greater than 500 μas yr⁻¹ (three objects). The proper motions of these outliers are likely dominated by intrinsic radio jet motions and obscure the small signal from the secular aberration drift. To ensure that our choice of proper motion cutoff did not significantly affect the resulting dipole model, we fit the E-mode and B-mode dipoles for a wide range of cutoff values. Figure 10 shows the results of this experiment for proper motion cutoffs between 5 and 50 μas yr⁻¹ (in steps of 1 μas yr⁻¹). We also performed the same experiment for cutoffs between 50 μas yr⁻¹ and 1000 μas yr⁻¹ (in steps of 50 μas yr⁻¹). We found that the Z-score (calculated following Mignard & Klioner (2012), Equation (85)) is relatively constant and the fit remains statistically significant for all cutoffs greater than 9 μas yr⁻¹. Fits with cutoffs below 9 μas yr⁻¹ include less than 226 proper motions and the decrease in significance can be attributed to the small number of data points. Additionally, we found that the apex remains within 2σ of the Galactic center for all cutoffs—all apex locations more than 1σ from the Galactic center were again for low cutoffs (<15 μas yr⁻¹) with a small number of data points. Combined, these factors indicate that our model of the dipole is robust and insensitive to our choice in maximum proper motion amplitude. Therefore, we chose to use a cutoff of 500 μas yr⁻¹ to include the majority of the catalog in our fit.

The secular aberration drift has been measured by several previous studies, most notably TL13 and Xu et al. (2013). TL13 measured a spheroidal dipole with an amplitude of 6.4 ± 1.1 μas yr⁻¹ pointed toward (266° ± 7°, -26° ± 7°) and a toroidal component with an amplitude of 1.9 ± 0.8 μas yr⁻¹. Our model has a lower spheroidal dipole amplitude (1.7 ± 0.3 μas yr⁻¹) than that measured in TL13, making their amplitude a better match for the predicted amplitude (5.40 ± 0.78 μas yr⁻¹; see Section 1). However, our uncertainties are also much smaller, yielding a more significant detection. The apexes of both fits are statistically consistent with the Galactic center.

One possible cause of our lower spheroidal dipole amplitude is the inclusion of a no-net-rotation (NNR) constraint in our catalog (see Section 2). To allow for some rotation of the radio source positions with respect to the ICRS axes, the NNR constraint was incrementally relaxed for subsets of the objects when creating the Goddard 2017a coordinate time series. On the other hand, TL13 used a more relaxed constraint that allowed sources to rotate by <2 arcseconds with respect to the ICRS axes. The difference in our E-mode amplitudes may be due, in part, to the different techniques used to handle the NNR constraint. The NNR constraint affects the toroidal dipole, which affects the spheroidal dipole because of the correlation between several of the E-mode and B-mode coefficients (Table 4). To this effect, Titov et al. (2011) found that their spheroidal amplitude decreased and the E-mode apex shifted away from the Galactic center when sources were more closely fixed to the ICRS axes and only allowed to rotate by <2 milliarcseconds. Our E-mode amplitude is lower than expected, but the associated apex is still in close alignment with the Galactic center, indicating that our model is only slightly affected by the NNR constraint and that the aberration drift is still detectable.

Xu et al. (2013) measured the secular aberration drift using a similar data set to TL13 but with a different estimation method. Instead of solving for individual proper motions and then fitting a dipole to these motions, Xu et al. (2013) added a three-dimensional solar acceleration vector to the global parameters in CALC/SOLVE and directly solved for this acceleration. They found a solar acceleration vector of (7.47 ± 0.46, 0.17 ± 0.57, 3.95 ± 0.47) mm s⁻¹ yr⁻³, which is equivalent to a dipole with a root-power of 16.8 ± 0.8 μas yr⁻¹ (5.8 ± 0.3 μas yr⁻¹ using the convention in TL13) pointed toward (243°, -11°). Their dipole is offset from the Galactic center by approximately 18° north and 23° west. The offset equates to a significant acceleration component perpendicular to the Galactic plane. Our dipole model contains no significant out-of-plane acceleration (0.27 ± 0.51 mm s⁻¹ yr⁻³). Because our dipole apex is statistically consistent with the Galactic center, our solar acceleration vector does not contain a significant perpendicular component.
Since the secular aberration drift is a small component of the overall proper motion of many sources, there is a concern that individual large intrinsic proper motions with small uncertainties could have a significant effect on the dipole fit. Titov et al. (2011) used several subsets of their data, including only ICRF2 defining sources, sources with low structure indices, and sources with more than 1000 sessions, to assess the robustness of their fit. They found that the resulting dipole did not vary significantly for any of the data subsets. We performed a similar analysis to ensure that individual outliers in proper motion do not significantly influence our model. Figure 11 shows the results of a test where we clipped our data to only include objects whose proper motions were determined from a minimum number of observing sessions. We find that our model remains significant regardless of the number of observing sessions per object.

To further assess the effect of large intrinsic proper motions on our secular aberration drift model, we performed 1000 bootstrap re-samplings of the fit. Table 5 lists the median

Figure 9. Two-dimensional and one-dimensional posterior probability distributions for the dipole coefficients plotted using the Python module Corner (Foreman-Mackey 2016). All coefficients are in units of $\mu$as yr$^{-1}$. The dashed lines on the one-dimensional histograms show the 68% confidence intervals for each parameter.
values and 68% confidence intervals from the bootstrap distribution. We find a median root-power of 5.11 μas yr⁻¹ with a 68% confidence interval of 3.61–6.71 μas yr⁻¹. Our dipole model has a root-power of 4.89 ± 0.77 μas yr⁻¹, which is in good agreement with these values, indicating that our model is not significantly influenced by individual data points. Figure 12 shows the location of the E-mode apex for all bootstrap iterations. This plot demonstrates that the location of the E-mode apex is not significantly influenced by individual proper motions.

7. Conclusions

In this paper we presented the VLBA Extragalactic Proper Motion Catalog containing 713 proper motions with average uncertainties of 24 μas yr⁻¹. The catalog is created primarily from archival Goddard VLBI data, with redshifts obtained from OCARS. In addition, we added or updated 40 extragalactic proper motions and 10 redshifts through our own VLBA and APO observations, respectively.

We used the resulting catalog to measure the secular aberration drift at a 6.3σ significance. An accurate measurement of the aberration drift is important so that it can be fully removed from extragalactic proper motions before using those proper motions to study cosmological effects. We detect a spherical dipole with a root-power of 4.89 ± 0.77 μas yr⁻¹ and an apex at (275°2 ± 10°0, −29°4 ± 8°8). We simultaneously fit a toroidal dipole with low significance (2.2σ) to increase the significance of the E-mode dipole. Overall, our model of the E-mode dipole proves robust to a number of tests and remains statistically significant for many subsets of the data.

Although the E-mode dipole is significant, its amplitude is much lower than expected. This difference may be caused by the NNR constraint used when the majority of our radio source positions were calculated. Even if the NNR constraint has prevented us from recovering the full dipole, our catalog can still be used for cosmological studies by removing the residual dipole.

In an upcoming paper, we subtract this dipole and use the remaining proper motions to search for relative proper motions between close-separation extragalactic objects following Darling (2013). The relative proper motions of extragalactic objects contain signatures of both the Hubble expansion and the collapse of large-scale structure, enabling a detection or
measurement of both effects. In a second paper, we fit a quadrupolar pattern to the catalog proper motions in order to obtain limits on the stochastic gravitational wave background (J. Darling et al. 2017, in preparation).

With continued geodetic observations and new Gaia VLBI global solutions, the number of available extragalactic proper motions is expected to continue to increase in the coming years. Additional observing epochs of existing proper motions will also increase the overall accuracy of future catalogs. Both of these will contribute to more accurate measurements of the secular aberration drift and enable more detailed cosmological studies. In the near future, with the release of Gaia (Gaia Collaboration et al. 2016) proper motions, we expect to significantly expand our catalog. The Gaia proper motions will be less precise—astrometry of ~1.69 mas for objects in the secondary data set of DR1 (Lindegren et al. 2016)—than those produced by VLBI, but there will be ~10^6 new extragalactic proper motions (Robin et al. 2012). The dramatic increase in sample size should enable statistically significant detections of the secular aberration drift with relative precision of 10% (Mignard 2002) and cosmological effects despite the decrease in overall catalog proper motion accuracy. The Gaia proper motions will also be less affected by intrinsic proper motion, which will enable a higher significance detection of correlated motions like the secular aberration drift and cosmological effects (see J. Darling et al. 2017, in preparation for further discussion). Additionally, the Next Generation Very Large Array (ngVLA) with VLBA baselines is expected to obtain proper motions of ~10 μas yr^{-1} (Bower et al. 2015). The addition of a central array with a large collecting area to be used in conjunction with the VLBA will enable rapid, high-S/N detections of many radio sources within a single observing epoch and is expected to increase the number of epochs for many catalog objects, thereby increasing the overall proper motion precision of the catalog.

Table 5

| Median$^{b}$ | 68% Confidence Interval |
|--------------|-------------------------|
| $\sqrt{R_{1}}$ | 5.11 | 3.61–6.71 |
| $\sqrt{R_{2}}$ | 2.85 | 1.65–4.45 |
| E-mode Apex R.A. | 284°6 | 274°1–302°9 |
| E-mode Apex Decl. | −29°2 | −48°2–9°1 |

Notes. $^{a}$ All values are in units of μas yr^{-1}, except for the E-mode apex, which is in units of degrees. $^{b}$ Square root of the first-order vector spherical harmonic power. Can be converted to the TL13 amplitude by dividing by 2$\sqrt{3π/3}$.

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Facilities: NMSU:1m, Gemini:Gillett, VLBA.

Software: AIPS (Associated Universities 1999), Corner (Foreman-Mackey 2016), IRAF (including Gemini IRAF), LMFIT (Newville et al. 2014), STILTS (Taylor 2006).

Appendix

The VLBA Extragalactic Proper Motion Catalog Sample

Table 6 shows the first 10 objects from the VLBA Extragalactic Proper Motion Catalog. The entire catalog contains 713 radio sources with the same columns and is available online and at http://vizier.u-strasbg.fr/. From left to right, the columns are the IVS name of the source, the source’s R.A. and associated uncertainty (in milliseconds) from the most recent VLBA observing epoch, the decl. and associated uncertainty (in milliseconds) from the most recent VLBA observing epoch, the proper motion in R.A. and associated
Table 6
The VLBA Extragalactic Proper Motion Catalog Sample

| IVS   | R.A. (J2000 h:m:s) | Decl. (J2000 d:':") | \(\sigma_{\alpha}\) (mas) | \(\sigma_{\delta}\) (mas) | \(\mu_{\alpha}\) (\(μ\)as yr\(^{-1}\)) | \(\mu_{\delta}\) (\(μ\)as yr\(^{-1}\)) | \(N_\delta\) | \(\chi^2_{\delta}\) | Length (years) | Last Obs. (MJD) | New PM | Source |
|-------|-------------------|---------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------|-------------|----------------|----------------|----------|--------|
| 2358+189 | 00:01:08.621513 | -19:14:33.800894 | 1.93 | 5.59 | 8.49 | 97 | 1.5 | -1.12 | 9.45 | 97 | 1.1 | 21.2 | 57819.9 | 3.10 | OCARS |
| 0002−478 | 00:04:35.655473 | -47:36:19.60493 | 0.26 | -24.75 | 13.45 | 45 | 1.4 | -47.34 | 20.18 | 45 | 1.1 | 22.8 | 57659.8 | 0.88 | OCARS |
| 0003+380 | 00:05:57.175296 | +38:20:15.157041 | 17.96 | -13.99 | 9.58 | 29 | 2.4 | -2.21 | 11.12 | 29 | 1.7 | 22.9 | 57102.7 | 0.23 | OCARS |
| 0003−066 | 00:06:13.892882 | -06:23:35.335489 | 0.05 | 0.27 | 1.29 | 1437 | 2.0 | 3.64 | 1.80 | 1437 | 2.2 | 23.5 | 57840.9 | 0.35 | OCARS |
| IIIZW2 | 00:10:31.005918 | +10:58:29.504257 | 1.35 | 5.17 | 12.17 | 62 | 2.8 | -10.08 | 12.58 | 62 | 1.7 | 26.7 | 57776.2 | 0.09 | OCARS |
| 0007+171 | 00:10:33.991756 | +17:24:18.762349 | 0.49 | 132.71 | 26.67 | 26 | 3.8 | 9.21 | 14.77 | 26 | 1.3 | 20.0 | 55244.7 | 1.60 | OCARS |
| 0008−264 | 00:11:01.246780 | -26:12:33.377442 | 0.23 | 0.43 | 7.31 | 180 | 1.9 | 0.26 | 9.41 | 180 | 2.0 | 24.6 | 57840.9 | 1.10 | OCARS |
| 0010+405 | 00:13:31.130193 | +40:51:37.144086 | 0.12 | -3.90 | 3.06 | 67 | 1.2 | 7.63 | 4.64 | 67 | 1.6 | 25.6 | 57784.9 | 0.26 | OCARS |
| 0013−005 | 00:16:11.083362 | -00:15:12.449556 | 2.57 | 1.61 | 5.51 | 59 | 1.4 | 3.95 | 7.81 | 59 | 1.3 | 23.7 | 57751.0 | 1.58 | OCARS |
| 0017+200 | 00:19:37.854481 | +20:21:45.644651 | 0.03 | -19.24 | 9.99 | 214 | 2.7 | -0.74 | 4.25 | 214 | 2.2 | 21.2 | 57840.9 | OCARS |

(This table is available in its entirety in machine-readable form.)
uncertainty (both in μas yr⁻¹), the number of sessions used to determine the source’s proper motion in R.A., the reduced χ² of the derived proper motion in R.A., the same quantities for the proper motion in decl., the number of years of VLBI observations used in determining the proper motion, the Modified Julian Date of the most recent VLBI session used to measure the object’s position, a flag to indicate proper motions added or updated by this paper, the redshift of the source, a flag indicating the quality of the reported redshift, and the sources from which the redshift data were obtained. The redshift flag is obtained from the OCARS catalog (Malkin 2016) and indicates the following potential limitations to the reported redshift: (a) photometric, (b) unreliable or doubtful identification, (c) substantially different estimates in the literature, (d) lower limit, and (e) imaging.” See the OCARS catalog for more information about the redshift of a particular source.

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