A Procedure for Making High Dynamic-range Radio Images: Deep Imaging of the Kiloparsec-scale Radio Structures of a Distant Blazar, NRAO 530, with JVLA Data

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Abstract

Using JVLA data obtained from A-, B-, and C-array observations of Sgr A* and NRAO 530 (as a calibrator) at 5.5, 9, and 33 GHz during the period between 2012 and 2015, we developed a procedure for the reduction of wideband data at high angular resolution. We have demonstrated that, correcting for residual interferometer errors, such as antenna-based errors caused by residual delays as well as baseline-based closure errors, radio astronomers can now achieve high-fidelity radio images with a dynamic range (peak: rms) exceeding 1,000,000:1. We outline the procedure in detail, noting that it can have broad application in the analysis of broadband continuum observations. Here, we apply this procedure to observations of a distant blazar, NRAO 530, revealing the radio structures surrounding the core in unprecedented detail. Our wideband JVLA image of this source at 5.5 GHz (C-band) shows that the kiloparsec radio structure of NRAO 530 is prominently characterized by a moderately curved western jet terminating at a hot spot where the radiation is stretched farther out into a diffuse radio lobe or plume. Close to the radio core, an abrupt bending of the jet is revealed in the high-resolution (<100 mas) images at 33 GHz (Kα band), showing the evolution of the position angle of the jet from the north at the VLBI scale (50 mas, or ~400 pc projected) and increasing toward the west at larger VLA scales (1", or ~10 kpc). The continuation of the jet axis drift forms a curved western jet extending out to 200 kpc. In contrast to the main radio structure, a faint and broad counter-jet is present on the eastern side with a curvature antisymmetric to that of the western jet. The eastern jet terminates at a bright hot spot, forming an edge-brightened diffuse lobe. A newly recognized compact component, located 0°6 east of the radio core, is detected in the A-array images at 9 GHz (X-band), suggesting that a more recent ejection has taken place toward the east. In addition, a lower brightness emission extended N–S from the core is detected at a level of 1–10 K in brightness temperature in our 5.5 GHz C-array data. The observed contrast in surface brightness between the western and eastern jet components suggests that the jets on the VLA scale are mildly relativistic. The radiation from the western jet is boosted while the radiation from the receding eastern jet is plausibly suppressed owing to the relativistic Doppler effect.

Key words: BL Lacertae objects: general – galaxies: active – galaxies: jets – ISM: individual objects (NRAO 530) – radio continuum: galaxies – techniques: image processing

1. Introduction

As a number of radio interferometer systems increase sensitivity by employing large increases in bandwidth, several important corrections must be applied, due to time variations of various instrumental parameters during the observation. An example is antenna-based residual delays that vary across the band and change with time. For wideband data distorted by these time-variable issues, it becomes difficult to restore the true information in the process of imaging the continuum structure of a radio source. Consequently, without corrections for such residual effects, the dynamic range (DR) of the resulting images is limited.

In previous narrowband observations, the DR of continuum observations was typically sensitivity limited, so it was challenging at best to learn about the full spatial structure of the brightest radio sources such as blazars, distant radio galaxies, and QSOs characterized by dominant bright radio cores. Such objects have often served the purpose of being calibrator sources for interferometer data inasmuch as they appear largely as bright point sources. Historically, the emission from their extended environs, as well as background radio sources, was ignored, except at the highest frequencies, where the bright emission components might be partially resolved.

When extended-source signals from such high-contrast regions are sampled with recent wideband techniques, the residual errors (RE) left over from standard calibration procedures from previous eras challenge the imaging reliability, particularly for the faint features in the vicinity of bright radio sources, features that are often confused with artifacts resulting from the uncorrected RE. The DR of the image is therefore limited, and the image fidelity is degraded owing to the RE in phase and amplitude. The DR is a good indicator of image fidelity—the difference between any produced image and the true image (Perley 1999), so the DR can be used as a measure of image quality. In the presence of bright radio sources, the DR is particularly important for reliably capturing the distribution of much fainter extended emission. For example, NRAO 530 was listed in the VLA calibrator catalog accompanied by images showing little more than a dominant radio core at 14.9 and 8.46 GHz (see Figure 9 of this paper). A faint extended structure was revealed by later VLA observations at 1.46 GHz with the A-array, showing east–west radio
lobes and jets (Kharb et al. 2010). With an angular resolution of 1.5 and noise level of 0.34 mJy beam$^{-1}$, this observation achieved a DR of $\sim$18,000:1.

Motivated by our JVLA observations of the Galactic center source, Sgr A (Zhao et al. 2016; Morris et al. 2017), we developed a procedure for restoring the emission structure of the calibrators used for our programs to a substantially greater depth than had previously been accomplished. The image DR was improved by iteratively converging the reference model to the true structure by applying various nonstandard corrections, in addition to eliminating radio frequency interference (RFI). In particular, we corrected for the time-variable residual delays.

In this paper, we illustrate our detailed procedure by applying it to the radio structure of the complex-gain (phase and amplitude) calibrator NRAO 530—a distant radio blazar—using the JVLA data obtained in support of the observations of Sgr A. Using the best DR image model of the calibrator, the solutions for correcting RE were derived and applied to the Sgr A data (Morris et al. 2017). As by-products, an unprecedentedly deep image of NRAO 530 was also obtained. So while we use this source to demonstrate the wideband capability for RE correction to maximize the DR of the image, we also report a new scientific perspective on the blazar itself.

NRAO 530 is a gamma-ray blazar, associated with an optically violent variable source at $z = 0.902$ (Healey et al. 2008) or $D_L = 5.8$ Gpc ($1^\circ = 7.8$ kpc). The radio source was first discovered with the 300 ft telescope of the NRAO (Pauliny-Toth et al. 1966). The VLBI observations show a jet structure to the north of its compact core, suggesting a prominent example of periodic oscillation of the jet axis (Lister et al. 2013) or the helical motion (Lu et al. 2011) that the jet traces on scales of milliarcseconds or parsecs. The northern VLBI jet is superluminal (Lu et al. 2011; Lister et al. 2016, 2018). On kiloparsec scales, NRAO 530 is characterized as having double radio lobes in the E–W direction. The western lobe shows relatively higher intensity, showing a curved jet connecting the western hot spot to the core. NRAO 530 is one of the MOJAVE$^5$ blazar samples mapped with VLA data by Kharb et al. (2010). Based on their kiloparsec-scale radio study of the MOJAVE blazar sample, those authors have questioned the simple radio-loud uni$^{6}$ scheme linking BL Lac objects (i.e., blazars) to FR I galaxies and quasars to FR II sources (Fanaroff & Riley 1974; Urry & Padovani 1995) and have also pointed out that a significant fraction of MOJAVE blazars show parsec-to-kiloparsec-scale jet misalignment. NRAO 530 seems to fall into the FR I/II category because of the $\sim$90° misalignment between the VLBI jet and the VLA structure (Kharb et al. 2010).

In general, given the bright cores of blazars and typically large distances, the relatively faint extended structure of their jets, radio lobes, and halos of radio cores are hidden under the detection limits of the old-generation narrowband telescopes. As an illustrative example for a distant blazar, deep imaging of NRAO 530 with the JVLA endowed with wideband capability is necessary to reveal the puzzles concerning the connection of the morphology on the VLA scale and the powerful core observed with the VLBI.

The rest of this paper is outlined as follows. The details of the procedure for correcting RE and achieving HDR imaging for wideband radio interferometer array data are given and discussed in the Appendix. In the main text, Section 2 describes the data and new images of NRAO 530. Our findings from the blazar NRAO 530 are presented in Section 3, and the astrophysical implications are discussed in Section 4. Section 5 summarizes our astrophysical results.

2. Data Sets and Imaging

Along with the dramatic hardware improvements of the JVLA, data reduction software packages are being developed emphasizing the wideband capability that allows astronomers to make images much deeper than have previously been possible. However, many successive corrections for possible data issues are needed in order to construct VLA images approaching the theoretical image fidelity of the equipped broadband instruments (see the Appendix).

2.1. Observations of NRAO 530 and Data Sets

In the recent study of Sgr A with the JVLA, we developed procedures to demonstrate the possibility of correcting for the data errors and minimizing the instrumental and atmospheric effects. In the following, we discuss the data that were used for the images of J1733–1304 (hereafter NRAO 530) and J1744–3116, both used as calibrators for observations of Sgr A. The relevant C-band, X-band, and Ka-band data sets used in this paper are summarized in Table 1. We have applied the technique of RE-correcting and DR-imaging to the radio study of the Galactic center; e.g., Morris et al. (2017) have published a paper on deep imaging the nonthermal radio filament (SgrAWF) near the Galactic black hole. More papers on nonthermal radio filaments and faint compact radio sources in the radio bright zone (RBZ) at the Galactic center will follow.

2.2. Images of NRAO 530

2.2.1. C-band Images at 5.5 GHz

Our C-band observations are described in a sequence of papers (Zhao et al. 2013, 2016; Morris et al. 2017). NRAO 530 was used as a gain calibrator. Using CASA, we followed the standard calibration for a continuum source. In order to achieve a high dynamic range (HDR) in a high-resolution image (A-array), in addition to the VLA standard calibrations, two further corrections must be made: (1) correction for residual delays across each of the subbands and (2) removal of flux-density variability (Zhao et al. 1991, 2016; Morris et al. 2017). At radio wavelengths, the former is related to antenna-based instrumental issues of unclear origin (see Appendix A.4 for further discussions), and the latter is intrinsic to AGNs.

We processed the C-band data taken in the A- and B-arrays at 5.5 GHz with the JVLA, following the procedure described in the flow chart exhibited in Figure 12 of the Appendix. After

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5 Calculated using the cosmology calculator of Ned Wright, UCLA. http://www.astro.ucla.edu/~wright/CosmoCalc.html, assuming $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Komatsu et al. 2009).

6 Monitoring Of Jets Active galactic nuclei with VLBA Experiments: http://www.physics.purdue.edu/MOJAVE/.

7 Small phase errors, present as slopes across subbands with a typical value of $\sim$2° per 128 MHz, remain in the data after applying JVLA standard calibration. The slopes appear to be caused by residual delays with typical values of $\sim$0.04 ns. The residual delays are antenna based and vary with time but with unpredictable trend.
the first five steps with antenna-based corrections, the rms noise of the image with robustness weighting $R = 0$ is 4.5 $\mu$Jy beam$^{-1}$ in a region far away from the core (>15″), giving a DR exceeding 1,000,000:1. However, within the central 1″ region, the rms noise is about a factor of 10 higher, including RE remaining in the data, including minor baseline-based closure issues. Thus, with the model produced at step 5, we performed a baseline-based correction with a solution interval of 30 s. Figure 1 shows the final image made with natural weighting by combining the A- and B-array data. An rms noise of 3.5 $\mu$Jy beam$^{-1}$ is achieved in the region without source emission (>15″ from the image center), while the rms noise is 4.5 $\mu$Jy beam$^{-1}$ near the core (~4″), comparable to the expected thermal noise of ~3 $\mu$Jy beam$^{-1}$.

Given an observing frequency, the positional errors caused by residual delays are contaminated with the mixed issues of larger uncertainties of the core position owing to the residual delays, additional flux density from extended emission, and lower level RFI, we initially had difficulty converging the RE correction and HDR imaging simply following the procedure outlined in the flow chart (Figure 12). A special procedure was developed with more detailed substeps to complement each of the major correction cycles. A detailed description for the reduction of the C-array data is given in Appendix A.5. At step M8, a decent image was obtained from the antenna-based correction process, showing an N–S extension. At this stage, it is not clear whether the weak N–S feature is a pattern of possible faint residual side lobes likely caused by the postulated baseline-based residual errors. At the final step of the baseline-based correction with the imaging model of the radio core, and E–W lobes and jets excluding any N–S structure, we solved baseline-based solutions with intervals of 120, 60, and 30 s and applied them separately to the data. This final step can effectively eliminate the significant baseline-based errors in comparison to the noise levels corresponding to the solution intervals. Therefore, the final image model is guaranteed to be produced from antenna-based signals. The three trials with different solution intervals all give the same source structure, revealing the faint N–S extended emission. This necessary test excludes the possibility that the N–S pattern is a residual side lobe caused by the baseline-based closure issues on some individual baselines in certain periods, e.g., temporary issues of some correlator chip. Therefore, we conclude that the N–S extension is most likely that the true weak emission extended from the core. Figure 2 (top-left panel) shows the C-array image at 5.5 GHz, revealing a lower brightness feature elongated north–south, labeled N-extension and S-extension, with an rms noise of 6 $\mu$Jy beam$^{-1}$ in the region with no contamination from source emission (20″ away from the core).

Then, with the point source at the core, we aligned the C-array data with the A- and B-array data. The flux density of the core was reduced down to a common value of 0.18 Jy for all six data sets by subtracting a point-source model from the phase center of the data to below the contamination level spread from the wing of the clean beam. A Gaussian taper function was applied to the combined data with OUTERTAPER $^9$ = 300 $\lambda$ to weight down the long-baseline visibilities. The dirty image was cleaned with the multiscale and multifrequency-synthesis (MS-MFS) algorithm (Rau & Cornwell 2011) at CASA, and the clean image (Figure 2, middle) was convolved to a synthesized beam 0″81 × 0″69 (4″). The rms noise is $\sigma = 5$ $\mu$Jy beam$^{-1}$. The top-right panel in Figure 2 shows the central 6″ × 8″ region, revealing a weak extended emission structure stretched out from the core to the north up to four synthesized beams (3″) at an intensity level of 4$\sigma$. The combined A- + B- + C-array image at 5.5 GHz separately to the data.

$^8$ Note: the regions used for statistics may contain faint extended emission near the core.

$^9$ OUTERTAPER is an input parameter of the CASA task “clean,” which sets the boundary for long baselines of the sampled data.

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**Table 1**

Log of Data Set

| Project (PI) | Observing Date | Array | Band$^a$ | $\nu$ (GHz) | $\Delta\nu$ (GHz) | HA Range | Time On Source (hr) | Sources |
|-------------|----------------|-------|---------|-------------|--------------|----------|-------------------|---------|
| 12A-037 (Zhao) | 2012 Mar 29 | C | C$^b$ | 5.5 | 2 | $-3^\circ 9$ to $+3^\circ 8$ | 0.94 | J1733–1304 |
| 12A-037 (Zhao) | 2012 Apr 22 | C | C$^b$ | 5.5 | 2 | $-0^\circ 5$ to $+2^\circ 9$ | 0.82 | J1733–1304 |
| 12A-037 (Zhao) | 2012 Jul 24 | B | C$^b$ | 5.5 | 2 | $-0^\circ 9$ to $+3^\circ 0$ | 0.63 | J1733–1304 |
| 12A-037 (Zhao) | 2012 Jul 27 | B | C$^b$ | 5.5 | 2 | $+3^\circ 4$ to $+3^\circ 9$ | 0.71 | J1733–1304 |
| 14A-346 (Morris) | 2014 May 17 | A | C$^b$ | 5.5 | 2 | $-3^\circ 2$ to $+0^\circ 7$ | 0.31 | J1733–1304 |
| 14A-346 (Morris) | 2014 May 26 | A | C$^b$ | 5.5 | 2 | $-0^\circ 4$ to $+3^\circ 5$ | 0.47 | J1733–1304 |
| 14A-231 (Yusef-Zadeh) | 2014 Mar 1 | A | X$^b$ | 9.0 | 2 | $-3^\circ 0$ to $+3^\circ 2$ | 0.27 | J1733–1304 |
| 14A-232 (Yusef-Zadeh) | 2014 Apr 17 | A | X$^b$ | 9.0 | 2 | $-3^\circ 3$ to $+2^\circ 0$ | 0.19 | J1733–1304 |
| SF-0853 (Haggard) | 2014 Apr 28 | A | X$^b$ | 9.0 | 2 | $-3^\circ 4$ to $+3^\circ 4$ | 1.12 | J1744–3116 |
| 15A-293 (Yusef-Zadeh) | 2015 Sep 11 | A | Ka$^c$ | 33 | 8 | $-2^\circ 6$ to $+0^\circ 8$ | 0.17 | J1733–1304 |

**Notes.** (1) The JVLA program code and PI name. (2) The calendar dates of the observations. (3) The array configurations. (4) The JVLA band codes (see footnote a). (5) The frequencies at the observing band center. (6) The total bandwidth of the observations. (7) The coverage of the hour-angle (HA) range for the data. (8) The time on sources. (9) The source name of the gain calibrators included in the data.

$^a$ The band codes “C,” “X,” and “Ka” used for the JVLA correspond to the receiver bands in the frequency ranges of 4.0–8.0 GHz, 8.0–12.0 GHz, and 26.5–40.0 GHz, respectively (https://science.nrao.edu/facilities/vla/docs/manuals/ao2013B/performance/bands).

$^b$ Correlator setup: 64 channels in each of 16 subbands with channel width of 2 MHz.

$^c$ Correlator setup: 64 channels in each of 64 subbands with channel width of 2 MHz.
evidently shows the detection of the weak component near the bright core, although the brightness of the southern extension is below the detection limit. Our results confirm the N–S extension observed in the A-array image at 1.4 GHz (Figure 2, bottom) taken from Kharb et al. (2010).

2.2.2. X-band Images at 9 GHz

Two gain calibrators, NRAO 530 and J1744–3116, were included in the X-band observations of Sgr A* with the JVLA in the A-array during 2014 March and April (see Table 1). J1744–3116 is 2°5 away from Sgr A while NRAO 530 is 16° away. Applying the calibration solutions derived from closer gain calibrators can more effectively eliminate the RE from the data of the target sources, in particular for the time-variable residual delays (see Morris et al. 2017 and the Appendix below). Following the five-step procedure for the RE-correcting and DR-imaging processes discussed in Appendix A.4, we performed further corrections for the residual gains, residual delays, and flux-density variations after the standard calibration for JVLA data, obtaining deep image models for both calibrators. The final image model of J1744–3116 is presented in the Appendix (Figure 11, right), and is utilized to discuss the consequence of the flux-density variation of the core on imaging and is not discussed in the main text. The images of NRAO 530 are discussed as follows.

Figure 3 shows the image of NRAO 530 made with robustness weight $R = 0$ by combining the three data sets taken on 2014 March 1, and April 17 and 28. The peak of the image is 4.9 Jy beam$^{-1}$, and the rms noise in the outer region is 3.6 μJy beam$^{-1}$, giving a DR of 1,300,000:1 with the synthesized beam of $0^\circ 27 \times 0^\circ 19 (−17^\circ)$. Twelve compact components in the western jet (W2–W13) and two components in the eastern jet (E1 and E5) are detected at the level of >8σ (see Figure 3). These components are fitted with a 2D Gaussian function, and the parameters resulting from the fitting are summarized in Table 2.

Figure 4 shows uniform weighted X-band images at three individual epochs, corresponding to the observations at 9 GHz on 2014 March 1, and April 17 and 28. A comparable rms noise level in the range between 11 and 15 μJy beam$^{-1}$ is achieved. Each of the epoch data sets has been processed independently by following the RE-correcting and DR-imaging procedure (Figure 12). The resulting images agree with each other. However, the UV data were sampled in different hour-angle ranges at the three epochs (Table 1), which resulted in different FWHMs of the synthesized beams (see Figure 4 caption). The detailed difference between the epochal images, e.g., the apparent peak intensity of W4, is attributable to the different UV coverage in the three observations.

2.2.3. Ka-band Images at 33 GHz

The VLA Ka-band data set observed on 2015 September 11 was obtained from the NRAO archive (15A-293). The correlator setup for the data set is described in the footnote of Table 1. The resulting total bandwidth is 8 GHz. The central band frequency is 33 GHz. The data were first calibrated.
3. Description of the Structure of NRAO 530

3.1. Structure on Kiloparsec Scales

Figure 1 shows a remarkably detailed image of the radio emission structure related to this blazar. NRAO 530 appears to share the common radio emission structure observed in radio galaxies and QSOs. From the high-resolution (0′′5) image at 5.5 GHz made with combined A- and B-array data from the JVLA observations (Figure 1) as well as the Gaussian-tapered image at 0′′8 resolution with combined A-, B-, and C-array data (Figure 2, middle), both the dominant bright core and the extended radio structure with an angular size of 10″ show a sequence of slightly resolved emission knots aligned in the well-confined but curved western jet (W-jet). This structure bridges the hot spot (W12) in the western lobe (W-lobe) with the radio core. The eastern jet (E-jet) is delineated by a faint radiation blob (E2) and a plume of slightly curved faint emission (E3 and E4) connecting to the hot spot (E5) in the eastern lobe (E-lobe; see the top panel in Figure 6 for labeling, and also see Figure 1 and the middle panel of Figure 2 for the detailed structure). In contrast to the western jet, in which the emission is well confined within a train of bright spots, the eastern jet (or jet path) is represented by a more diffuse emission ridge with no bright spots. The radio morphology is similar to that of radio galaxies and QSOs (see Bridle & Perley 1984, for example); the radio core of NRAO 530 dominates the power, with intensity ratios of 610:1 and 79,000:1 with respect to the hot spots in the E- and W-lobes, respectively. At 5.5 GHz, the specific power of the core is about $1.1 \times 10^{26}$ W Hz$^{-1}$, dominating the power of $5.6 \times 10^{27}$ W Hz$^{-1}$ obtained by integrating over the extended components as revealed in the C-array image (see Figure 2 and Table 3).

3.1.1. Eastern Jet

The 5.5 GHz images (Figure 1, the middle panel of Figure 2, and the top panel of Figure 6) show the slightly curved eastern jet, or jet path, with no bright spots. Figure 3 shows an image at 9 GHz with angular resolution of 0′′2. At this resolution, two (E2 and E4) of the five features along the eastern jet and lobe (E1, E2, E3, E4, and E5) are detected at 9 GHz. All five features are observed at 5.5 GHz with angular resolution of 0′′5 (see the top panel of Figure 6 for labeling). The brightest component in the eastern jet, E1 ($S_p = 0.12$ mJy beam$^{-1}$), is located 0′′6 east of the core and is detected only at 9 GHz in the A-array observations during the period between 2014 March 1 and April 28 (see Figure 4). The deconvolved size of E1 0″37 × 0″24 (P.A. = 148°) has been determined from 2D Gaussian fitting; the source is slightly resolved at the angular resolution of 0′′2. The component E1 is not detected at 5.5 GHz with angular resolution of 0′′5, or cannot be separated from the core owing to inadequate angular resolution. This component is also not detected at 33 GHz. The 3σ limit ($S_p = 24$ μJy beam$^{-1}$) of the A-array image at 33 GHz is consistent with E1 being a newly ejected jet component with a steep spectral index and an intensity below the detection limit at the angular resolution of 0′′1. Furthermore, the component E1 is detected in all three epochs of the A-array observations at 9 GHz on 2014 March 1, and April 17 and 28. No significant variation in flux density, position, or size is observed during this two-month period.

following the standard JVLA procedure. The corrections for the RE follow our new method. This data set was used to test and demonstrate the procedure for RE correction and HDR imaging discussed in Appendix A.4. Figure 5 shows the image at 33 GHz with natural weighting. An rms noise of 8 μJy beam$^{-1}$ is achieved with a resolution better than 0′′1, revealing the bending transition from the northern VLBI jet to the western VLA jet.
The component E5 appears to mark the hot spot in the eastern lobe where the curved eastern jet terminates, showing the outer edge-brightened structure of the eastern lobe. The surface brightness of E5 is low, with peak intensities at 9 and 5.5 GHz being $\mu S_p = 30$ and $60 \mu$ Jy beam$^{-1}$ as determined from the images convolved to a common beam ($0\farcs27 \times 0\farcs19$, P.A. = $-17\degr$). The intensity contrast to the core is $S_{E5, Core} = 1:160,000$ at 9 GHz and 1:79,000 at 5.5 GHz. At 1.46 GHz, this ratio is less than 1:1,000, determined from the image of Kharb et al. (2010; Figure 2, bottom). In addition, the eastern hot spot E5 is trailed by a fainter emission plume elongated $5\arcsec$ toward the northwest. The spectral index determined from the 9 and 5.5 GHz data is $-1.4 \pm 0.7$.

### 3.1.3. Western Jet

Fourteen compact components in the western jet and lobe are identified as W1 to W14. W1 is only detected in the high-resolution image at 33 GHz and is not distinguishable from the core in the JVLA A-array images at both 9 and 5.5 GHz. The components W1 to W12 are located along a curved jet feature, convex toward north. Table 2 lists emission quantities determined from the high-resolution JVLA images. The components are slightly resolved in the A-array images. The 9 and 5.5 GHz data at an angular resolution of 0\arcsec2 show that the components W2–W11 have peak intensity $\mu S_p$ ranging from 0.06 to 3.07 mJy beam$^{-1}$ at 9 GHz and 0.13–4.70 mJy beam$^{-1}$ at 5.5 GHz. The spectral index determined from these components at 9 and 5.5 GHz is about $\alpha = -1$, consistent with synchrotron radiation. W3, located $0\farcs5$ northwest of W2, appears to be nearly resolved out at 33 GHz, showing a marginal detection at the level of 4$\sigma$. The rest of the components in the western jet appear to be resolved out and not detected at 33 GHz.

### 3.1.4. Hot Spot of the Western Lobe

After the core, the second brightest component in NRAO 530 is W12, with peak intensities of 5.0 and 7.72 mJy beam$^{-1}$ at 9 and 5.5 GHz, respectively, marking the hot spot in the western jet/lobe structure. A hot spot usually represents the termination of a jet flow (Blandford & Rees 1974, for example), where the jet flow impacts the ambient medium at the outer edge of the lobe. Similar to the northwestern tail of the eastern hot spot E5, a southwestern extension (W13 and W14) appears to be associated with W12 (see Figures 1, 2, and 6). We also point out a detailed difference of the W-lobe from the E-lobe, as follows. The northwestern tail of the hot spot E5 and the hot spot itself, as well the eastern jet that forms the edge-brightened large lobe, all combine to give the appearance that the jet material is flowing back toward the core, at least in projection. The E-lobe appears to be consistent with the typical FR II morphology. The western jet, on the other hand, turns $90\degr$ to the south after passing through the hot spot W12, and then stretches farther out to the west. There appears to be no indication of a similar continuation of the western jet after the hot spot W12 pointing back toward the core. The diffuse western tail of the W-lobe appears to be more like the morphology often observed in FR I type jets, such as the mirror-symmetric jets in 3C 449 (Perley et al. 1979).

### 3.1.5. North–South Extension to the Core

In the C-array image with the low angular resolution of $\sim 4\arcsec$ (Figure 2), a lower surface brightness structure (plume) extending $15\arcsec$ north and $13\arcsec$ south of the core is detected at an intensity level in the range between 0.2 and 2 mJy beam$^{-1}$. This N–S feature is obvious in the 1.46 GHz A-array image at a resolution of 1\arcsec5 from Kharb et al. (2010; see the bottom panel of Figure 2). In the higher angular resolution (0\arcsec8) image with combined A-, B-, and C-array data at 5.5 GHz, an emission plume with intensity in the range between 0.02 and 0.3 mJy beam$^{-1}$ is located a few arcseconds north of the core. The lower surface brightness emission feature of the southern extension appears to be below the detection limit. Table 3 lists the emission quantities of the north–south extension for comparison with the core and eastern and western lobes. The 5.5 GHz flux density integrated over the northern extension is $7 \pm 1$ mJy, about 5 percent of the western lobe, including the jet, and the flux density of the southern extension is $3 \pm 1$ mJy. The flux density integrated over the full N–S extension is about 10% of the total flux density integrated over the overall extended emission, excluding the central core emission.
However, the total flux density from the extended emission in the north–south extension is only ~3% of the core flux density at 5.5 GHz and about 10% at 1.4 GHz.

3.2. The Northern VLBI Jet and Western JVLA Jet
3.2.1. J—The Vector of the Jet Axis

Figure 6 shows the high-resolution images obtained from the JVLA wideband data at 5.5, 9, and 33 GHz compared to the VLBA image at 15 GHz. The JVLA images trace the western jet on scales from 200 kpc (5.5 GHz) to 700 pc (33 GHz). At the resolution of 0″1, the components W1 and W2 detected at 33 GHz show an elongation to the NW. This structure begins at the core, linking to the large-scale western jet. The position angles of the major axis (from 2D Gaussian fitting) indicate P.A. = 146° ± 7° for W1 at an angular offset Δθ = 0″31 from the core and P.A. = 111° ± 3° for W2 at Δθ = 0″69 (see Table 2). The change in P.A. between W1 and W2 suggests that the projected jet axis bends toward the west as the scale increases from a few hundred parsecs to a few kiloparsecs.

At the size scale of the VLBA structure of <200 pc, the axis of the jet is oriented toward the north (see Lu et al., 2011, for example).

To quantitatively investigate the relationship between the jet on the VLA scale and the VLBI jet, we defined a jet vector J as the vector that connects the core to a jet component. The vector J can be quantitatively described by its position angle (P.A.) and its angular offset from the core (Δθ). For a jet with linear motion or no precession involved, its trajectory is a straight line, i.e., no changes in P.A. are expected as Δθ increases. Table 2 lists Δθ and P.A. in columns 7 and 8, respectively, for all components.

Figure 7 (top) plots the position angle P.A. as a function of Δθ. The western (eastern) jet components are represented in green (red); the quantities P.A. and Δθ on angular scales between 0″1 and 20″ are determined from the JVLA data (see Table 3). The northern jet components observed with the VLBA (Lu et al. 2011) are in blue. From this plot, the following obvious conclusions can be drawn:

(1) The JVLA western jet (green) is the continuation of the VLBI northern jet (blue). The P.A. of the jet axis J is
essentially to the north on the scale of the VLBA component (<50 mas) and gradually changes to the west as $\Delta \theta$ increases the angular distance. The transition where P.A. changes rapidly occurs in the range between $0^\circ.05$ and $1^\circ$ in $\Delta \theta$. The northern VBLI jet and the western JVLA jet belong to one astrophysical entity, hereafter referred to as the northwestern jet.

On scales <50 mas, the P.A. changes by >50°. According to proper motion measurements based on multiple VLBA observations by Lu et al. (2011), those authors conclude that the motion on VLBA scales is dominated by the E–W swing of the jet components at a rate of 3.4 yr$^{-1}$. They suggest that the observed angular motion is evidence for helical motion of the jet.

Figure 4. The images of NRAO 530 made with uniform weighting, corresponding to $R = -2$, from the JVLA observations at 9 GHz in the A-array at three epochs. Top: 2014 March 1, $\sigma_d = 11\mu$Jy beam$^{-1}$, beam = $0^\circ.26 \times 0^\circ.18$ ($-6^\circ$). Middle: 2014 April 17, $\sigma_d = 15\mu$Jy beam$^{-1}$, beam = $0^\circ.30 \times 0^\circ.18$ ($-23^\circ$). Bottom: 2014 April 28, $\sigma_d = 12\mu$Jy beam$^{-1}$, beam = $0^\circ.26 \times 0^\circ.18$ ($-33^\circ$). The compact components are labeled with the same identifications as in Figure 3. The contours are $2\sigma_d \times (-2, 2)$, for $n = 1, 2, 3, \ldots, 18$.

Figure 5. Image of NRAO 530 at 33 GHz made with the A-array data observed on 2015 September 11. Applying natural weighting ($R = 2$) produces a synthesized beam of size $0^\circ.11 \times 0^\circ.075$ ($-23^\circ$). The peak intensity of the image is 3.4 Jy beam$^{-1}$ with rms noise of $\sigma = 8\mu$Jy beam$^{-1}$, achieving a dynamic range of 420,000:1. The contours are $\sigma \times (-4, 3, 2)$, for $n = 2, 3, 4, \ldots, 18$.

Figure 6. Images of NRAO 530 made with JVLA combined A- and B-array data at 5.5 GHz (top) and A-array data at 9.0 GHz (middle). Bottom left is the Ka-band image of NRAO 530 made with JVLA A-array data at 33 GHz. Bottom right is the VLBA image of NRAO 530 at 15 GHz from Lu et al. (2011).
component on scales from a few milliarcseconds to a few tens of milliarcseconds. Such an E–W swing in which P.A.θ changes by >50° is not observed in the JVLA data. Plausibly, the rapid swing motion occurs only at small angular scales <50 mas, and the angular resolution of the JVLA is not adequate to detect such small-scale angular motions, such as jet component rotation around the jet axis or the inferred helical motion. We note that the helical motion of the jet material that occurred on the VLBI scale does not appear to be the same thing as a precession of the jet axis characterized by the jet curvature on VLA scales. The slow precession of the jet axis can also result in the observed VLBI and VLA jet misalignments.

(3) It is obvious that over the lifetime of the northwestern jet, the P.A.θ changes by about ~90° over the scale of ~10° (or ~100 kpc).

Unlike the western jet in which the bright emission spots clearly delineate the projected jet trajectory, the eastern jet components are determined from the enhanced emission peaks along the relatively diffuse, elongated ridge that likely delineates the eastern jet path. The uncertainties in the parameters of the eastern components could be larger than the errors quoted in Table 2 concerning the issue in identifying jet components, given the strong likelihood that the eastern jet is receding and the radiation from the jet components is therefore suppressed, due to the relativistic Doppler effect, assuming implicitly that the jet is relativistic given that the VLBI apparent motions are superluminal.

### Table 3

Extended Components in NRAO 530

| ID      | Size  | Sflux | Pcore | (mJy) | (°) | (10²⁻⁷ W Hz⁻¹) |
|---------|-------|-------|-------|-------|-----|-----------------|
| Core    | 4450 ± 5 | ...   | 1     | 5     | 11  |                 |
| W-lobe  | 96 ± 10  | 19    | 46    | 0.36  |     |                 |
| E-lobe  | 42 ± 5   | 18    | 106   | 0.16  |     |                 |
| N-extension | 7 ± 1  | 15    | 636   | 0.03  |     |                 |
| S-extension | 3 ± 1  | 13    | 1480  | 0.01  |     |                 |
| Extended| 148 ± 13 | 37    | 30    | 0.56  |     |                 |
| Total   | 4598 ± 14 | ...   | 0.968 | 11.6  |     |                 |

**Notes.** Column 1 is the ID. Column 2 is the integrated flux density. Column 3 is the maximum linear size. Column 4 is the ratio of the core flux density to the integrated flux density for each component. Column 5 is the radio power $P_c = S_{4.8} / (1 + z)^{1.7}$, assuming $D_L = 5.8$ Gpc.

a The values are determined from the C-array image at 5.5 GHz (Figure 2).

b Kharb et al. (2010).

c The spectral index $\alpha_{1.46,5.5} = (\lambda_{5.5} / \lambda_{1.46})^{\alpha}$.

d The uncertainty in $\alpha$ is dominated by the 6% variation in flux density at 5.5 GHz observed in the period between 2012 March 29 and 2014 May 26.

---

**Figure 7.** Top: position angle (P.A.) of the jet axis vector projected on the sky (J) as a function of $\Delta\theta$, where the jet axis vector $J$ for a given jet component is defined as the vector pointing to the component from the core with length $\Delta\theta$ (the angular offset from the core) and position angle P.A.$\theta$. The data for the western jet (green) and the eastern jet (red) are from this paper (Table 2). The data for the VLBI jet components d, e, f, g, i, and j (blue) are from Lu et al. (2011). Bottom: position angle (P.A.$\theta$) of the unit vector (T) of the direction of the jet transverse velocity as a function of the distance measured along the projected jet trajectory from the core to a jet component ($D_{jet}$); see Section 3.2.2 for the definition of the quantities. The vertical bars indicate 1σ uncertainties. The uncertainties for the horizontal axis are smaller than the symbols. The straight line (red) indicates a linear fit of a logarithmic function of $P.A._{jet} = -40.4\log_{10}(D_{jet}) - 52.5$ to the data. The red dots along the bottom indicate residuals of $\Delta P.A._{jet}$ (= data fit minus a constant of 200°). The mean and rms of the residuals are $-3.8°$ and 1″ for all data included. Eliminating VLBI and VLA components that are highly deviated from the fitted curve, i.e., excluding the VLBI components d and g and the VLA components beyond W9 in the statistics, the mean becomes 0° and the rms stays at a value ~1″2. The residuals in statistics are weighted by the 1σ uncertainties of the data. The residuals for the components d, g, and W13 are out of the plot range.

### 3.2.2. T—The Unit Vector of the Jet Transverse Velocity

The apparent projected direction of motion of the northwestern jet can also be described quantitatively. We can determine the direction of the transverse velocity with a unit vector $T$ defined as the direction change of the vector $J$ between consecutive jet components: at the $i$th jet component $T_i = (J_{i+1} - J_i) / |J_{i+1} - J_i|$, where $J$ is the vector pointing from the core to the jet component, defined in the previous section. The direction of $T_i$ can be described by $P.A._{jet}$, the position angle of $T_i$. For a curved jet, $P.A._{jet}$ is a function of $D_{jet}$, the distance measured along the projected jet trajectory.
from the core to the location of the \(i\)th component. The quantity \(D_{\text{jet}}\) can be computed approximately as the sum of the lengths of the connecting lines between consecutive jet components from the core to the location of the \(i\)th component:

\[
D_{\text{jet}}^i = \sum_{k=1}^{i} |J_{k+1} - J_k|,
\]

where, \(i = 1, 2, \ldots, n\) (see the caption of Figure 7 for more details). Figure 7 (bottom) plots P.A.\(\text{Jet}\) as a function of \(D_{\text{jet}}\) with a logarithmic scale in the \(D_{\text{jet}}\) axis to facilitate visualization of the P.A.\(\text{Jet}\) changes in the transition from the northern jet on the VLBI scale to the western jet on the VLA scale. Within a scale of 25 mas, P.A.\(\text{Jet}\) varies between \(-6^\circ\) and \(59^\circ\) based on the six brighter VLBI components d, e, f, g, i, and j. The function P.A.\(\text{Jet}(D_{\text{jet}})\) indicates that the overall VLBI jet displays east–west wiggles as it moves northward. The result is consistent with VLBI observations (Lu et al. 2011). In fact, based on the VLBA observations of NRAO 530 at 27 epochs between 1994 and 2011, the innermost jet P.A. can be fit to a periodic oscillation with amplitude of 20° and a period of 9.4 yr (Lister et al. 2013).

Then, on the scale transitioning from VLBI to VLA, the abrupt northwestern bending of the jet occurs as P.A.\(\text{Jet}\) changes from \(-7^\circ\) (j) to \(-54^\circ\) (W2) on angular scales from 25 to 700 mas. The corresponding change rate is 70 deg arcsec\(^{-1}\). Then, after the following \(7^\circ\) along the jet route, the jet turns westward at \(D_{\text{jet}} = 7^\circ 8\) (P.A.\(\text{Jet} = -90^\circ\) at W8) with a rate of 5 deg arcsec\(^{-1}\). Advancing the next \(3^\circ 1\), at W10 before encountering the hot spot region (W12), the jet turns southward at a rate of 14 deg arcsec\(^{-1}\). Then, the jet appears to terminate at W12 followed by a rapid change in P.A.\(\text{Jet}\) 30 deg arcsec\(^{-1}\). The rapid change in P.A.\(\text{Jet}\) indicates that the jet loses its stiffness (or collimation for straight line jets), likely owing to the impact onto the ambient medium at the hot spot. The jet disruption for an FR I source could also be due to an unstable growing mode, such as a Kelvin–Helmholtz instability (Blandford & Pringle 1976; Ferrari et al. 1978; Hardee 1979; Hardee & Norman 1988; Norman & Hardee 1988; Zhao et al. 1992a, 1992b, for example).

In short, from the diagram of P.A.\(\text{Jet} - D_{\text{jet}}\), the change in P.A.\(\text{Jet} - D_{\text{jet}}\) seems to scale with jet kinematics, i.e., a larger change in P.A.\(\text{Jet}\) occurs in the inner region of the core, where the helical motion of the jet material dominates the P.A.\(\text{Jet}\) change while the P.A.\(\text{Jet}\) change appears to be caused by the slow precession of the jet axis over the VLA scales. On the VLBI scale, the change rate in P.A.\(\text{Jet}\) drops from 83 deg mas\(^{-1}\) at \(D_{\text{jet}} \sim 1\) mas to 2 deg mas\(^{-1}\) at 25 mas. The rapid change in P.A.\(\text{Jet}\) on the VLBI milliarcsecond scale is consistent with the jet undergoing helical motion (Lu et al. 2011) or periodic swing (Lister et al. 2013). However, as compared to the rate on the VLBA scale, the rate on the VLA scale is about three orders of magnitude smaller. In the course of the jet moving from the core to the hot spot W12 over its route length of 10\(^\circ\), overall the P.A.\(\text{Jet}\) changes by about 90°. We made a linear fit to the plotted data and found that

\[
P.A.\text{Jet} = -40^\circ 4 \log_{10}\left(\frac{D_{\text{jet}}}{\text{arcsec}}\right) - 52^\circ 5,
\]

where the uncertainties of the coefficients in the linear fitting are equivalent to \(1^\circ 2\), the rms of the residuals (see Figure 7).

The fitted straight line, a logarithmic spiral, can be expressed in polar coordinates if (P.A.\(\text{Jet}, D_{\text{jet}}\)) is substituted by (\(\theta, r\)):

\[
r = a e^{\theta/b},
\]

where the variables \(\theta\) and \(r\) are in units of degrees and arcseconds, and the coefficients \(a = 0^\circ 0502\) and \(b = -17^\circ 5\).

A similar logarithmic spiral function can also be fit to the projected trajectory, which may serve as evidence for a slow precessing jet from the core in NRAO 530.

3.3. Spectral Fitting to the Low Flux-density State

The blazar NRAO 530 exhibits a remarkable degree of flux-density variations over a wide frequency range from 5 GHz to 375 GHz (Aller et al. 1985; Teräsranta et al. 1992; Bower et al. 1997; Robson et al. 2001; Feng et al. 2006; Hovatta et al. 2008; Jenness et al. 2010; Aller & Aller 2012; An et al. 2013, and the F-GAMMA monitoring program\(^{10}\)). Superluminal motions of the northern jet components within the VLBI core have been detected with apparent transverse velocities ranging from 2.3c to 26.5c (Lu et al. 2011), which agree with the more accurate determination of a maximum of 27.37c ± 0.97c and a median of 13.74c ± 0.40c based on the inner six components by the MOJAVE project\(^{11}\) (Lister et al. 2013, 2016, 2018). Thus, the core-dominated emission is highly enhanced via the relativistic Doppler-boosting effect. Table 4 lists the total flux densities of NRAO 530. Figure 8 plots the spectrum of NRAO 530, implying two discernible states: (1) the high state characterized by highly fluctuating flux densities at the wavelengths from short centimeter to submillimeter, and (2) the low state that appears to be delineated by the minimum values of the flux densities determined at each of the observing frequencies \(\nu > 1\) GHz. The minimum flux density in each of monitoring programs appears to depend on the length of monitoring time. A model composed of a synchrotron self-absorption component and an optically thin component is used to fit the low-state spectrum. Allowing for the emission from the core, the synchrotron self-absorption can be described as

\[
S_c = S_0 \left(\frac{\nu}{\nu_0}\right)^{\alpha_c} \left[1 - \exp\left(-\frac{\nu}{\nu_0}\right)^{\alpha_c - 5/2}\right].
\]

where \(\nu_0\) is the turnover frequency at which the synchrotron optical depth becomes unity, \(S_0\) is the flux density at \(\nu_0\) multiplied by a factor of \(e/(e - 1) = 1.58\), and \(\alpha_c\) is the spectral index when the core emission becomes optically thin.

The emission from the extended lobes and jets is assumed to be optically thin synchrotron radiation with spectral index \(\alpha_{e}\), and the flux density of the extended emission at 1 GHz of \(S_1\) for \(\nu\) in units of GHz is

\[
S_{\text{ext}} = S_1 \nu^{\alpha_e}.
\]

There are five parameters (\(S_0, \nu_0, \alpha_c, S_1, \text{and } \alpha_e\)) to fit. The spectral index \(\alpha_e\) can be determined from the extended emission. With \(\alpha_c = -0.94\), determined from the VLA images at 1.46 GHz (Kharb et al. 2010) and 5.5 GHz (this paper; see Table 3), the number of free parameters is then reduced to four. We fit the low-state flux-density data in Figure 8 (open circles) to derive the parameters. The turnover frequency is \(\nu_0 = 0.16\) GHz, \(S_0 = 6.2\) Jy or \(S_c = 3.9\) Jy at \(\nu = \nu_0\), and \(\alpha_c = -0.19\),

\(^{10}\)https://www.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html

\(^{11}\)https://www.physics.purdue.edu/MOJAVE/sourcepages/1730-130.shtml
Table 4
Total Flux Density of NRAO 530

| ν (GHz) | S_ν (Jy) | For Fitting | Duration | Reference | ν (GHz) | S_ν (Jy) | For Fitting | Duration | Reference |
|--------|----------|-------------|----------|-----------|--------|----------|-------------|----------|-----------|
| 0.076  | 9.93 ± 0.20 | Yes | ... | [18] | 0.080 | 7.00 | Yes | ... | [1] |
| 0.084  | 9.49 ± 0.15 | Yes | ... | [18] | 0.092 | 9.52 ± 0.14 | Yes | ... | [18] |
| 0.099  | 9.09 ± 0.12 | Yes | ... | [18] | 0.107 | 8.71 ± 0.12 | Yes | ... | [18] |
| 0.115  | 8.68 ± 0.09 | Yes | ... | [18] | 0.122 | 8.60 ± 0.08 | Yes | ... | [18] |
| 0.130  | 8.23 ± 0.07 | Yes | ... | [18] | 0.143 | 8.09 ± 0.07 | Yes | ... | [18] |
| 0.150  | 7.65 ± 0.77 | Yes | ... | [17] | 0.151 | 7.96 ± 0.06 | Yes | ... | [18] |
| 0.158  | 7.65 ± 0.05 | Yes | ... | [18] | 0.166 | 7.61 ± 0.05 | Yes | ... | [18] |
| 0.174  | 7.92 ± 0.06 | Yes | ... | [18] | 0.181 | 7.63 ± 0.06 | Yes | ... | [18] |
| 0.189  | 7.61 ± 0.07 | Yes | ... | [18] | 0.197 | 7.66 ± 0.08 | Yes | ... | [18] |
| 0.200  | 7.49 ± 0.04 | Yes | ... | [18] | 0.204 | 6.83 ± 0.14 | Yes | ... | [18] |
| 0.212  | 6.72 ± 0.09 | Yes | ... | [18] | 0.220 | 6.93 ± 0.15 | Yes | ... | [18] |
| 0.227  | 7.26 ± 0.18 | Yes | ... | [18] | 0.327 | 7.42 ± 0.34 | Yes | ... | [19] |
| 0.365  | 8.44 ± 0.35 | Yes | ... | [22] | 0.408 | 6.58 | Yes | ... | [1] |
| 0.750  | 6.73 ± 0.21 | Yes | ... | [2] | 1.400 | 5.99 ± 0.14 | ... | ... | [2] |
| 1.41   | 5.2 | Yes | ... | [1] | 1.46 | 6.648 ± 0.047 | ... | ... | [13, 15] |
| 1.5    | 5.2 | Yes | ... | [16] | 2.64 | 3.79–5.41 | Yes | 8 yr | [20, 21] |
| 2.7    | 4.3 | Yes | ... | [1] | 4.8 | 4–9 | Yes | 46 yr | [9] |
| 4.85   | 6.991 ± 0.099 | ... | ... | [3] | 5.0 | 4.1 | Yes | ... | [1] |
| 5.0    | 5.0 | ... | ... | [16] | 5.5 | 4.74±0.13 | ... | ... | [15] |
| 8.0    | 3.5–12.5 | Yes | 46 yr | [9] | 8.1 | 10.5 | ... | ... | [16] |
| 8.4    | 6.2 | ... | ... | [1] | 9.0 | 5.002 ± 0.050 | ... | ... | [15] |
| 14.5   | 2.5–15 | Yes | 46 yr | [9] | 15 | 11.0 | ... | ... | [16] |
| 22     | 8.22–11.78 | ... | 0.3 yr | [10] | 33 | 3.426 ± 0.017 | ... | ... | [15] |
| 37     | 2.25–15.55 | Yes | 25 yr | [4] | 37 | 10.5–12.20 | ... | 0.1 yr | [10] |
| 43     | 8.98 ± 1.87 | ... | ... | [16] | 43 | 16.6 ± 0.5 | ... | ... | [6] |
| 86     | 11.2 ± 0.3 | ... | ... | [7] | 86 | 2.10–6.11 | Yes | 8 yr | [21] |
| 88     | 7.8 ± 0.5 | ... | ... | [8] | 90 | 3–15 | ... | 11 yr | [9] |
| 95     | 12.6 ± 0.7 | ... | ... | [6] | 107 | 13.2 ± 0.4 | ... | ... | [8] |
| 150    | 7.09 ± 0.35 | ... | ... | [11] | 215 | 6.2 ± 1.1 | ... | ... | [7] |
| 230    | 2.4–13.0 | ... | 1 yr | [12] | 230 | 0.857–3.868 | Yes | 16 yr | [14] |
| 270    | 5.66 ± 0.30 | ... | ... | [11] | 345 | 0.604–2.41 | Yes | 15 yr | [14] |
| 350    | 0.73–0.48 | Yes | 8 yr | [5] | 375 | 4.67 ± 0.47 | ... | ... | [11] |

Note. Columns 1 and 6: the observing frequencies. Columns 2 and 7: the flux densities and 1σ error for the individual epochs’ measurements, or the range between the minimum and maximum flux density determined from the monitoring programs. Columns 3 and 8: if “Yes,” the mean values determined from the individual epochs’ observations or the minimum values determined from the monitoring programs are used to create a low-state spectrum. These values are marked with open circles in Figure 8 and are used in the spectral fitting. Columns 4 and 9: the duration length in years are given for the flux-density monitoring programs. Columns 5 and 10: references—[1] Wright & Otrupcek (1990), The Parkes Survey. [2] Pauliny-Toth et al. (1966), The Green Bank 300 foot Survey. [3] Griffith et al. (1994). [4] Hovatta et al. (2008). [5] Jenness et al. (2010), Robson et al. (2001). [6] Falcke et al. (1998), Feng et al. (2006). [7] Kirchbaum et al. (1997), Feng et al. (2006). [8] Reuter et al. (1997), Feng et al. (2006), [9] Bower et al. (1997), Aller et al. (1985), Aller & Aller (2012), An et al. (2013), [10] Bower et al. (1997), Teräsranta et al. (1992), [11] Bower et al. (1997), Stevens & Robson (1994), [12] Bower et al. (1997), [13] Kharb et al. (2010), [14] Gurwell (2018), The SMA Calibrator Catalog. [15] This paper. The 1σ errors are mainly due to the core variations. [16] Van Moorsel & Spieweck (2018) and Test Memo #192 of NRAO, C. Chandler (1995). [17] Interna et al. (2017), The GMRT-TGSS Survey. [18] Hurley-Walker et al. (2017), The WMA-GLEAM Survey.[19] This paper; derived from VLA archival data AP327_A951127.xp1 assuming the flux density of 3C 286 to be 26.3 Jy at 327 MHz. [20] Angelakis et al. (2019), Effelsberg 100 m Monitoring for the F-GAMMA program. [21] E. Angelakis (2019, personal communication) on F-GAMMA: Multifrequency radio monitoring of Fermi blazars: https://www3.mpifr-bonn.mpg.de/div/vlbi/ljamma/Light_Curves_%26_Spectra.html. [22] Douglas et al. (1996), The Texas Survey.

which is consistent with the value determined from the core. The extended flux density at 1 GHz, S_1 = 0.739 Jy, is also consistent with the value extrapolated from the VLA measurement for the extended flux density at 1.46 GHz (Kharb et al. 2010). We note that the core in this paper refers to the region within 50 mas from the source center, and the emission from the outside of the region is included in the extended component. The spectral index of α_c = −0.19 appears to be consistent with the result derived from the VLBI core (Lu et al. 2011). A few notes on the spectral fitting follow:

(1) At ν = 142 MHz, the contributions to flux density from the core and extended emission are comparable. At ν < 142 MHz, the extended emission becomes prominent, e.g., at 80 MHz the flux density from the extended emission is 88% of the total flux density. At ν ≳ 142 MHz, the core becomes dominant, having 88% and 99% of the total flux densities at 1.4 and 90 GHz, respectively. The corresponding total radio power in the low state is 1.0 × 10^{28} and 4.5 × 10^{27} W Hz^{-1} at 1.4 and 90 GHz, respectively.

(2) At most times, the core appears to be in the high flux-density state. Higher variability in flux density tends to occur toward high frequencies. This result is consistent with the VLBI determinations of the variation in superluminal velocity at different angular scales,
suggested that the high-state flux density at high frequencies is relativistically Doppler boosted (e.g., Lu et al. 2011).

4. Implication and Discussion

Extragalactic radio sources with jets and lobes can be classified into two morphological classes, FR I and FR II (Fanaroff & Riley 1974). The FR I sources appear to get weak at large distances from the radio core, e.g., 3C 449 (Perley et al. 1979) while the FR II sources, e.g., 3C 47 (Bridle et al. 1994), show edge-brightened lobes that are characterized by a hot spot. These two different classes in apparent radio morphology appear to be related to the powers of the radio sources and absolute isophotal magnitude (Ledlow & Owen 1996). In the logarithmic diagram of the radio power at 1.4 GHz ($P_{1.4\text{GHz}}$) and absolute isophotal magnitude ($M$), the authors find that a nonzero-slope line divides FR I from FR II sources, which corresponds to $L_{\text{radio}} \propto L_{\text{opt}}^{1.8}$. Based on their nearby sample ($z < 0.5$), the FR II division appears to occur over a range in $P_{1.4\text{GHz}} \approx 10^{24} - 10^{25.6} \text{W Hz}^{-1}$.

On the other hand, studies of the correlation between radio power at 1.4 GHz and optical luminosity (Ledlow & Owen 1996) lead to the conclusion that all radio galaxies live in similar environments in that optical luminosity and other properties of the host galaxy are the most important parameters affecting radio source formation and evolution. Relating the absolute optical $R$-band magnitude $M_R$ of the host galaxy to the central black hole mass $M_{\text{BH}}$ (McLure & Dunlop 2001) and the radio power at 1.4 GHz, $P_{1.4\text{GHz}}$, to the kinetic luminosity of the jet, $L_{\text{jet}}$ (Willott et al. 1999), Ghisellini & Celotti (2001) found that the dividing line of the radio power at 1.4 GHz between FR I and FR II corresponds to a constant ratio, $L_{\text{jet}}/M_{\text{BH}}$. The statistical analysis of the FR I/II dividing line suggests that for radio sources situated on the FR I/II boundary, higher radio powers imply a larger mass of black holes harbored in their cores (e.g., Ghisellini & Celotti 2001; Willott et al. 1999).

4.1. FR II or FR I Type Source?

Based on 1.4 GHz VLA observations of the extended radio structures associated with the blazars in the complete flux-density-limited MOJAVE sample, Kharb et al. (2010) found that a substantial fraction of MOJAVE sources fall into the FR I/II category according to their luminosities and morphologies. Either the total power of $P_{1.4\text{GHz}} = 1.0 \times 10^{28} \text{ W Hz}^{-1}$ determined from the spectral fitting to the low flux-density state or the power from the extended emission in kiloparsec scale $P_{\text{ext,1.4 GHz}} = 2.1 \times 10^{27} \text{ W Hz}^{-1}$ suggests that NRAO 530 has a high optical luminosity if it falls on the FR I/II dividing line (Owen & Ledlow 1994; Ledlow & Owen 1996; Ghisellini & Celotti 2001). Therefore, the energetic jets in NRAO 530 might imply a high accretion rate (Ghisellini et al. 2014) onto a very massive black hole (Rawlings & Saunders 1991) at the blazar core.

However, the radio power at 1.4 GHz from the core is a factor of 5 greater than that of the extended emission even in the low state. The flux density from the core is boosted, due to the relativistic Doppler effect as superluminal motions have been observed with the VLBA (Lu et al. 2011; Lister et al. 2013, 2016), becoming highly variable. Taking the median value determined from the inner core components with the VLBA, the apparent transverse velocity $v_c$ in units of $c$ (the speed of light) is $\beta_a = 14$, giving a lower limit on the Lorentz factor of $\gamma_{\text{min}} = \sqrt{1 + \beta_a^2} \approx 14$, assuming the jet to be viewed at a critical angle $\theta_c$. Then, the corresponding view angle $\theta_v$, the angle between the direction of the jet velocity and the line of sight to the observer, can be determined as $\theta_v = \arcsin(1/\gamma_{\text{min}}) \approx 4^\circ$ (Lu et al. 2011). Thus, the minimum Doppler factor, $\delta \equiv \frac{\gamma_{\text{min}}}{\gamma_{\text{min}} - 1}$, would be $\delta_{\text{min}} = \gamma_{\text{min}} \approx 14$. The enhanced factor of observed luminosity for a relativistic jet is $\delta^p$ with $p = 3 - \alpha_c$ for a spherical core and $p = 2 - \alpha_{\text{jet}}$ for an optically thin jet (e.g., Cawthorne 1991; Urry & Padovani 1995). Therefore, the radiation from the core is enhanced, due to the Doppler-boosting by an amount of $\gamma_{\text{min}}^3(1 - \beta_a \cos \theta)$ (Kellermann & Owen 1988; Cawthorne 1991; Urry & Padovani 1995). In the case of $\gamma = \gamma_{\text{min}} = 14$, the flux densities from the inner components of the core can be boosted by $\sim 3$ times, about three orders of magnitude, assuming $\alpha_c = 0$. The Doppler-boosting effect explains why only the northern jet components (approaching the observer) are detected if the emission from the receding southern jet is suppressed by $\sim 3$ orders, and the bipolar jet is intrinsically symmetric.

Taking account of the Doppler-boosting, we find that the actual intrinsic radio power at 1.4 GHz of NRAO 530 is likely on the order of the power from the extended emission, or a few times $10^{27} \text{ W Hz}^{-1}$. Although the edge-brightened eastern lobe with a barely visible jet is very consistent with the FR II morphology, the relatively bright western jet with a faint emission lobe stretching farther out appears to be more like an FR I type radio source. Some of the extremely misaligned MOJAVE blazar jets could be hybrid morphology sources, with an FR I jet on one side and an FR II jet on the other.
4.2. Mildly Relativistic Jets on the VLA Scale?

On the VLBI scale, the jet axis lies essentially north of the core on angular scales 1–25 mas. The jet axis of the northern jet components in the inner core rapidly swings at a rate of 3°/4 yr⁻¹ in change of the position angle (Lu et al. 2011), which can be modeled with a periodic oscillation of the jet position angle for the innermost component (amplitude of 20° and period of 9.4 yr; Lister et al. 2013). On VLA scales, over the angular scale 0°−1°, the position angle of the northwestern jet drifts toward the west. In addition, ignoring the contrast in the brightness of the western and eastern jets, the curvature of the eastern jet appears to be antisymmetric with respect to the western jet. The twin jet in NRAO 530 can be characterized as an S-shaped structure.

The S-shaped morphology differs from the U-shaped narrow-angle-tailed and wide-angle-tailed twin-jet sources that are often observed in the environment of rich clusters of galaxies (O’Dea & Owen 1986; O’Donoghue et al. 1993). Such mirror-symmetric jet structures are usually associated with FR I radio sources, e.g., 3C 449 (Perley et al. 1979). The ram pressure owing to the motion of the jet-parent galaxies through the intracluster medium is suggested to be responsible for the observed, symmetrically curved radio trails (Begelman et al. 1979). Unlike the collinear twin jet observed in many FR II sources in which the view angle of the jet axis keeps constant, the projected S-shaped jet indicates that the jet axis in those cases likely drifts on the sky slowly over the jet lifetime. Consequently, the view angle of the jet axis also changes over time. The S-shaped antisymmetric jet is a feature predicted by precessing jet models, discussed in detail by Gower et al. (1982) via their extensive numerical simulations and used for the interpretation of the VLBI features observed in AGNs, such as 4C+12.50 (Lister et al. 1982).

For the case of NRAO 530, if the mean intensity ratio of the western jet hot spot (W12) to the eastern one (E5) at 5.5 and 9 GHz, \( R_{\text{hspt}} = 150 \), is due to the relativistic Doppler effect, then we can estimate the bulk Lorentz factor \( \gamma \) (e.g., Laing & Bridle 2015). The emission from the western jet, plausibly moving toward the observer, is enhanced by \( \delta^{2.94} \) for a continuous jet with spectral index \( \alpha_{\text{jet}} \approx \alpha_c \approx -0.94 \). If we further assume that the western jet is viewed at a critical angle and the eastern jet is antisymmetric to the western jet, the enhancement factor is \( \gamma_{\text{min}} (1 - \beta^2) \approx 2.94 \) for the approaching western jet while the receding eastern jet is suppressed by a factor of \( \gamma_{\text{min}} (1 + \beta^2) \approx 2.94 \). From the intensity ratio \( R_{\text{hspt}} \) for W12 and E5, the bulk Lorentz factor of \( \gamma_{\text{min}} \approx \sqrt{\frac{R_{\text{hspt}}^{2.94} + 1}{2 \gamma_{\text{min}}^2}} \) can be inferred. Then, the view angle of the hot spot W12 can be estimated as \( \theta_{\text{w}} = \sin^{-1}(1/\gamma_{\text{min}}) \approx 34° \). Compared to \( \theta_{\text{w}} = 4° \), determined for the inner jet in the VLBI core, the large view angle of the hot spot and the curvature of the western jet imply that the jet axis has precessed, presumably in concert with the rotation axis of an accretion disk, changing the critical view angle from 34° at the earlier epoch to 4° at the recent epoch. The slow precession of the jet axis could occur if the jet nozzle has been subject to a torque as has been postulated in many theoretical models of accreting black holes (e.g., Ghisellini et al. 2014). The simple model adopted in this paper, which assumes an intrinsic bidirectional symmetry in a mildly relativistic bipolar jet coupled with a slow precession of the jet axis, accounts for the observed asymmetry of the curved, large-scale twin-jet morphology and the intensity ratio of the oppositely directed jets. The observed properties of the northwestern jet seem to fit also into the theoretical model for the hybrid FR I/II sources, in which the jets become transonic in the core and decelerate to mildly relativistic velocities from moderately relativistic or ultrarelativistic jets (Bicknell 1995).

5. Conclusion

With a procedure developed within the CASA software package, we show that the time-variable residual delay in the JVLA data can be effectively eliminated for deep imaging of faint, extended radio structures associated with dominant cores. Applying the technique that is described in the Appendix, sensitivities or DRs of images made with wideband interferometric array data can be improved by a factor of several tens to over a hundred. As an example for demonstration, the data for NRAO 530, a gain calibrator used in the JVLA observations of Sgr A at 5.5, 9, and 33 GHz during the period between 2012 March 29 and 2015 September 11, have been processed following the procedure of RE correction and high-DR imaging discussed in this paper. Deep images of NRAO 530 at 5.5, 9, and 33 GHz at angular resolutions from 0′′1 to 4′′ have been achieved with DRs on the order of 1,000,000: 1. The detailed emission structure revealed on scales of 1−100 kpc suggests that the edge-brightened eastern lobe/jet structure appears to fit with the FR II category. The observed morphology of the western jet, with the western extension, seems to more likely fall into the FR I category. The classification for the western jet perhaps is owing to a specific viewing angle. The apparent antisymmetric, curved twin-jet morphology, and the observed contrast of their radiation intensity suggest that the twin jets in NRAO 530 on VLA scales is mildly relativistic and that the view angle of the jet axis likely evolves over time.

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Appendix

Procedure for HDR Imaging

Wideband capability enabled by recent technology advancements has enhanced the power of interferometer arrays at radio, millimeter, and submillimeter wavelengths. Sensitivities of radio telescopes have been dramatically improved in recent years. Source structure and variability of core-dominant radio
objects such as blazars and quasars have become noticeable issues in calibration and imaging. Less attention has been paid to the effects of these radio properties in handling radio data when the image DR is limited by the telescope’s sensitivity. For example, the image of NRAO 530 observed with the VLA in 1997 (see Figure 9) indicates that the blazar is a point-like source at an angular resolution of $\sim 1''$ when the DR is below 10,000:1. In addition, at subarcsecond resolution, residual delays ($\delta\tau_A$), varying with time, become a noticeable issue in high-DR imaging with wideband data taken with modern telescopes. The corresponding phase gradient across a wide frequency band causes side lobe smearing of a dirty beam which is difficult to clean with the algorithms that have been widely used in radio astronomy (Högboom 1974; Clark 1980; Steer et al. 1984) as well as the newer algorithms developed for multifrequency-synthesis (MFS) and multiple-scale (MS) imaging (Rau & Cornwell 2011). The effect becomes aggravated and significantly degrades the image quality in the field near a strong compact source. For example, Figure 10 shows residual bandpass solutions in phase, solved from JVLA A-array data of NRAO 530 at 9 GHz after the standard delay corrections derived from 3C 286 are applied. A phase slope of 2$^\circ$ across a subband of bandwidth (BW) 128 MHz is present, suggesting that a typical residual delay of 0.04 ns or 1/3λ remains in the data. A time variation of the residual delays is also evident from the time-dependent bandpass solutions. A larger phase slope of 4$^\circ$ per 128 MHz is present occasionally on some antennas (see Antenna = “ea08” Time = “11:12:35:1” of Figure 10, bottom left). As a consequence, the presence of residual delays in the deep image has several implications.

1. Residual phase delays generate errors in the position of a radio core that is supposed to be placed at the phase center or the delay center. For example, phase errors ($\Delta\phi$) caused by residual delays ($\delta\tau_A$) across a subband (BW = $\Delta\nu$) could be due to pointing errors or can propagate to the positional uncertainty of the radio core at the sampling channel frequencies in synthesis imaging with MFS algorithms. For example, given fixed baselines, positional errors ($\Delta\theta$) on the radio core can be related to the quality of data described by the residual delays ($\delta\tau_A$) remaining after the calibration process, $\Delta\theta = c\delta\tau_A/B$, where $c$ is the speed of light and $B$ is the separation between two antenna elements, or the baseline length. In the case of JVLA A-array observations at 9 GHz, corresponding to the longest baselines, the positional errors of the core caused by RE are $\sim 0''07$, about a quarter of the synthesized beam width, $\theta_{\text{syn}}$. The main side-lobe pattern in the dirty image will be smeared owing to the small deviation in phase between the channels, corresponding to the positional errors caused by residual delays. The consequence of the residual delays will limit the benefits of deep cleaning in the process of multiple-frequency synthesis imaging. Given a fixed residual-delay error $\delta\tau_A$, the positional error $\Delta\theta$ is inversely proportional to the baseline length. The shorter baselines of the small array configurations produce larger uncertainties in source positions. On the other hand, the synthesized beam of the array is also inversely proportional to the baseline length, $\theta_{\text{syn}} = \lambda/B$, where $\lambda$ is the observing wavelength. The baseline term is canceled in the ratio of the positional error to the size of the synthesized beam, namely, $\frac{\Delta\theta}{\theta_{\text{syn}}} = \frac{c\delta\tau_A}{\lambda}$. Therefore, the issue in deep cleaning of wideband imaging caused by dirty beam smearing due to the residual delay is not dependent on the size of the array configuration, given a fixed observing wavelength. However, for the same array configuration, the issues in deep imaging due to the residual delay become worse for the data observed at shorter wavelengths, due to the difficulty in achieving a reliable model from the contaminated visibility data.

2. Vector-averaging subband data along with self-calibration can eliminate the residual-delay issue but only at the cost of increasing the noise in the data. This approach has been used in handling earlier generation, narrow-bandwidth VLA continuum data for each of the intermediate frequencies (IFs), or by creating “ch0” data to form the continuum data from spectral line observations. The “ch0” is simply produced from vector-averaging the channels across a spectral band. Indeed, the frequency-dependent phase errors due to $\delta\tau_A$ can be eliminated completely. The remaining phase errors related to source position can be further removed by applying additional self-calibration solutions derived from the “ch0” data. However, the trade-off using the vector-averaging technique for subbands is that the phase variation is effectively turned into signal noise, producing a coherence loss. For a visibility function $V(\nu) = A(\nu)\exp[i\phi(\nu)]$, the ratio of the vector-averaged amplitude to the actual amplitude drops with the amount of phase changes in phase across the subband ($\Delta\phi$), due to a residual delay: $A = 1 - \frac{\Delta\phi^2}{2\sqrt{n}}$. This ratio can be used for quantitative assessment of the coherence loss. The maximum loss in fringe intensity owing to a residual delay of 0.04 ns is $\sim 0.06\%$ of the core flux density ($F_{\text{core}}$). The uncertainty of the vector-averaged amplitude is $\sigma = A - \frac{\Delta\phi^2}{2\sqrt{n}}$, where $n$ is the number of independent data channels in a given subband. Thus, the process of vector-averaging produces an uncertainty in the calibration modeling and generates additional noise in the data as well.

3. The method of vector-averaging subband data is subject to bandwidth smearing if a residual delay is present. The resultant fringes of vector-averaged subband data are modulated by a sinc function $\frac{\sin(\pi \Delta\nu_{\text{BW}} \tau_{\text{syn}}) - \sin(\pi \Delta\nu_{\text{BW}} \tau_{\text{rs}})}{\pi \Delta\nu_{\text{BW}} \tau_{\text{rs}}}$, the delay beam, or the bandwidth pattern (Thompson 1986).
The residual delay here ($\tau_{rs}$) is considered from two aspects. (1) The residual delay $\delta\tau_A$; as discussed above, this delay term is referred to as the time delay from an unknown source when the target source is placed at the phase center that is presumed to be accurately tracked. (2) The geometrical delay, $\delta\tau_{\text{pnt}} = \frac{B}{c} \Delta\theta_{\text{pnt}}$, for a source offset by $\Delta\theta_{\text{pnt}}$ from the phase-tracking center or the array-pointing center. Hereafter, we refer to the geometrical delay, $\delta\tau_{\text{pnt}}$, as the source delay. Both delay terms, $\delta\tau_A$ and $\delta\tau_{\text{pnt}}$, are time variable. Given the unclear origins, the behavior of $\delta\tau_A$ appears unpredictable in time. The term $\delta\tau_{\text{pnt}}$ is traceable. The phase compensation of the source delay at each of the spectral frequencies can be computed with a high-precision interferometer model if no subband averaging is applied. The MFS algorithms have incorporated such corrections in the imaging process.

However, the shortcut with subband averaging will lead to a loss of valuable frequency-dependent information, and therefore the image fidelity will be substantially degraded. For a subbandwidth of $\Delta\nu_{\text{BW}} = 128 \text{ MHz}$ and the maximum baseline of the JVLA, at an angular distance of 5″ from the delay center or phase center, the fringe amplitude will drop to 75% of the value in the spectral data without subband averaging. In addition, the structure of the source will be distorted, due to the bandwidth-smearing effect. At the radial distance of
The rms noise of made from the same uncorrected data but adding a value of 0.06 Jy at the core to the data of Day 1, establishing a constant improvement. The rms noise level in the region far from the core is \( \sigma_{\text{far}} \sim 45 \mu\text{Jy beam}^{-1} \). Middle: the image made from the same uncorrected data but adding a value of 0.06 Jy at the core to the data of Day 1, establishing a constant flux density of the core in both data sets. The rms noise of \( \sigma_{\text{far}} \) is improved to the level of \( \sigma_{\text{far}} \sim 6 \mu\text{Jy beam}^{-1} \). Right: the image made with both data sets with further corrections for the residual errors using the improved model. The rms noise \( \sigma_{\text{far}} \) is \( \sim 2 \mu\text{Jy beam}^{-1} \). The contours are \( 2\sigma_{\text{far}} \times (2, 2') \) with \( n = 1, 2, 3 \), until the peak is reached. The synthesized beam is \( 0''120 \times 0''739 \) (\( 31'' \)).

\( \Delta \theta_{\text{pass}} \) away from the phase center, a point source will be smeared to an angular extent of \( \Delta \theta_{\text{pass}} = \frac{\Delta \nu_{\text{BW}}}{\nu} \) (Thompson 1986). For example, at \( \Delta \theta_{\text{pass}} = 10'' \) from the phase center, the angular distortion of a point source can be \( \sim 0''14 \), more than half of the A-array synthesized beam, if subband averaging is applied to a 128 MHz subband data at 9 GHz.

4. The residual delay, \( \delta \tau_{\text{A}} \), varies with time in an unpredictable way. The unclear origin of \( \delta \tau_{\text{A}} \) causes difficulties in eliminating such frequency-dependent phase errors from the data of target sources. The phase issue caused by \( \delta \tau_{\text{A}} \) can be corrected partially by applying the frequency-dependent phase corrections interpolated from the time-dependent bandpass solutions derived from a reference calibrator close to the target. A more sophisticated technique using modern computing resources that can extract the requisite information from the data of the target source itself is needed. Development of new technique for data calibration and deep imaging with wideband data appears to be imperative.

In addition to the phase errors caused by residual delays, the variation in visibility amplitude as a function of both time and frequency leads to detrimental effects in deep imaging with wideband data if this variability is not accounted for. The source activity as a function of time and the distribution of the radiative energy as a function of frequency or source spectrum are not unusual among astronomical sources. The issues related to the amplitude variation in DR imaging with wideband data include the following:

1. Source spectrum. For a given spectral energy distribution, the visibility amplitude varies as a function of frequency across a broad frequency band. For a source having a steep power-law spectrum (\( \sim \nu^\alpha \)) with \( \alpha = -1 \), the fractional amplitude changes by \( \Delta S/S = \Delta \nu/\nu \sim 36\% \) across the 2 GHz JVLA wideband at 5.5 GHz. Unlike the former VLA continuum data with narrow IF bandwidth, the amplitude variation across such a wide band challenges traditional imaging techniques. In order to cope with the spectral issues, a new algorithm for imaging the first two terms in the Taylor expansion of the visibility spectra has been developed and has been used in the clean program within CASA (Rau & Cornwell 2011). This technique has been successfully employed for deep imaging of the first term, the intensity distribution.

2. Time variation. Figure 11 shows the issue in deep imaging owing to the time variation of the core flux density. A variation of 10\% in flux density of a 1 Jy core can reduce the DR by a factor of 6–7, limiting deep imaging. In addition, artifacts around the core can be generated in the “cleaned” image if the variability during the observation is not removed from the data (Zhao et al. 1991). A procedure for removal of the time variation of a compact radio core has been described using the software tools in CASA (Zhao et al. 2016).

The rest of the content in this appendix concerning the method of RE-correcting and DR-imaging is organized as follow. Appendix A.1 formulates a general model of the radiation structure and the variable components for given a source. Appendix A.2 describes a set of formulas for transforming extended-source structure into a point-source model. Appendix A.3 discusses the JVLA standard data reduction procedure. Based on the modeling discussed in these three sections, we develop a procedure for RE correction and DR imaging utilizing CASA software. Appendix A.4 outlines five major steps involved in the RE-correcting and DR-imaging process, with a demonstration using JVLA Ka-band data from
the A-array observation of NRAO 530 at 33 GHz. Appendix A.5 introduces a case involving a more sophisticated procedure for handling the JVLA C-array data of NRAO 530 observed at 5.5 GHz. Appendix A.6 discusses the application of residual-delay corrections derived from gain calibrators to target sources. A summary is given in Appendix A.7. The techniques discussed here can be applied to general interferometer array data, although the suggested procedures are based on JVLA data and CASA algorithms.

A.1. Modeling Structure and Variability of a Radio Source

The visibility function on the \([u, v]\) plane of a radio source sampled with a wideband interferometer at observing time \(t\) and frequency \(\nu\) can be written as

\[
V(u, v, \nu, t) = V^S(u, v, \nu, t)e^{2\pi\nu\tau_A(t)}G_A(\nu, t),
\]

where \(\tau_A(t)\) and \(G_A(\nu, t)\) correspond to time delays and time-dependent complex gains, respectively. Both terms are antenna based, containing instrumental errors and atmospheric effects. The source function, \(V^S(u, v, \nu, t)\), composed of numerous emission components, can be described as

\[
V^S(u, v, \nu, t) = \sum_{i=0}^{m-1} V^E_i(u, v, \nu) + \sum_{i=0}^{n-1} V^C_i(u, v, \nu, t),
\]

where \(V^E_i(u, v, \nu)\) is the source visibility function of the \(i\)th extended component, and \(V^C_i(u, v, \nu, t)\) is the visibility function of the \(i\)th unresolved compact or point source. The integers \(m\) and \(n\) are assumed to be the total numbers of extended and unresolved components in the field of view, respectively. The extended components are presumably stable during the observing period, while the flux densities of the compact components can vary with time. In practice, for a QSO or a blazar in which a dominant radio core is present, the source function can be simplified as a strong point-source function \(V^C(u, v, \nu, t)\) and an arbitrary extended emission \(V^E(u, v, \nu)\), so that

\[
V^S(u, v, \nu, t) = V^C(u, v, \nu, t) + V^E(u, v, \nu).
\]

For the MOJAVE sources at 1.4 GHz, the ratio of the integrated flux density from the extended components to that of the core is distributed across a very wide range between a few thousand to less than a thousandth (Kharb et al. 2010). For the two gain calibrators NRAO 530 and J1744–3116 at 5.5 and 9 GHz, the integrated flux density of the extended portion is only a few percent that of the core. In core-dominant sources such as most blazars and QSOs at high frequencies, \(V^S(u, v, \nu, t) \sim V^C(u, v, \nu, t)\) can be used in the initial approach.

As interferometer arrays improve in both sensitivity and angular resolution, the previous assumption of a calibrator (a QSO or a small planet) as a point source is no longer suitable. The extended structure and variability of a calibrator appear to generate significant effects, limiting both the calibration precision and the image quality as well as fidelity. Given a celestial object, a time-invariant structure of the source emission can be constructed, as was shown in the analysis of the radio observations and wideband imaging of the complex region Sgr A after fixing the variable component of Sgr A* to a constant value (Zhao et al. 2016). Then, a model for the structure of stable emission from a calibrator or a radio source can be expressed as

\[
V^S(u, v, \nu) = V^C(u, v, \nu) + V^E(u, v, \nu).
\]

A.2. Building a Point-source Model

Dividing the observed complex visibility \(V(u, v, \nu, t)\) of Equation (1) by the source model \(V^S(u, v, \nu)\) of Equation (4), one can approach a point-like visibility function,

\[
V^P(u, v, \nu, t) = V(u, v, \nu, t)/V^S(u, v, \nu),
\]

where the normalized source function \(V^P(u, v, \nu, t)\) is an initial calibration model in which the deviations from a point source are due to atmospheric effects, such as amplitude attenuation and phase distortion, and the antenna-based instrumental errors in both amplitude and phase, as well as error due to imperfections of the initial source model. The process of calibrations for various effects will eventually converge the normalized source function to a point-source function. For example, the linear changes in phase as a function of frequency across the sampling band can be fit by time delays and then be removed from the data. In addition, for QSOs or blazars, time variations of the flux densities from their radio cores often become significant. Special attention is needed in the calibration and imaging processes (Zhao et al. 1991, 2016). Thus, when a variable core is present, the source function can be separated into two components, a component \(V^C_0(u, v, \nu)\) of the flux density at the beginning of the observation, \(t_0\), and a time-variable term giving the deviations from that initial value, \(\Delta V^C(u, v, \nu, t)\):

\[
V^C(u, v, \nu, t) = V^C_0(u, v, \nu) + \Delta V^C(u, v, \nu, t).
\]

For calibration concerns, the radio-dominant core is placed at the phase-tracking center of the interferometer. Given a variable intensity \(I_0 + \Delta I(t)\) of the radiation from its core, the complex function (Equation (6)) of the compact source can be simplified as a real function, \(V^R(u, v, \nu, t) = I_0 + \Delta I(t)\). If the extended component \(V^E(u, v, \nu)\) is not time variable, then the normalized source function of Equation (5) can be expressed as

\[
V^P(u, v, \nu, t) = \left[1 + \frac{\Delta I(t)}{I_0 + V^E(u, v, \nu)}\right]e^{2\pi\nu\tau_A(0)}G_A(\nu, t),
\]

where the spectrum of the core is further assumed to be flat for simplicity. Removing the time-variable term is necessary prior to further calibration of complex gains (Zhao et al. 2016). For a calibrator with no time variations and a simple-enough source structure, the normalized source function \(V^P(u, v, \nu, t)\) is essentially a complex function tracing the antenna gains multiplied by the antenna-based delay term, i.e.,

\[
V^P(u, v, \nu, t) = e^{2\pi\nu\tau_A(0)}G_A(\nu, t),
\]

the right-hand side of Equation (8) can be defined as the overall antenna-based complex gain \(g_A(u, v, \nu, t)\) of \(G_A(\nu, t)\). Furthermore, the antenna-based delay can be further separated into two terms, a constant delay \(\tau_0\) and a time-dependent residual delay:

\[
\tau_A(t) = \tau_0 + \delta\tau_A(t).
\]
For data from the JVLA, $\tau_0$ can be removed by the standard delay correction in the beginning of the data calibration or in a pipeline process, and $\delta\tau_A(t)$ is the residual time-dependent delay. Furthermore, the frequency-dependent and time-dependent functions in the complex gain can be decoupled if the instrumental bandpass is stable enough in time, i.e., $G_A(\nu, t) = G_A(t)B_A(\nu)$, in which case the overall antenna-based gains becomes

$$G_A(\nu, t) = G_A(t)B_A(\nu)e^{2\pi i \delta\tau_A(t)},$$

where $G_A(t)$ is the antenna-based complex gain, a function of time; with a scaling factor of the amplitude $\mathcal{F}$, the antenna gain can be expressed as

$$G_A(t) = \mathcal{F} g_A(t)e^{i \phi_A(t)},$$

and $B_A(\nu)$ is the antenna-based, instrumental complex bandpass, a function of frequency,

$$B_A(\nu) = b_A(\nu)e^{i \phi_A(\nu)}.$$  \hfill (12)

A.3. The Standard Data Reduction Procedure for JVLA Data

In principle, the calibrations of delay, bandpass, complex gain, and flux scale with the JVLA standard data reduction procedure or in the VLA pipeline\(^{12}\) are essentially to correct for the parameter terms $\tau_0$, $b_A(\nu)$, $\phi_A(\nu)$, $g_A(t)$, and $\mathcal{F}$, respectively (Figure 12, top box). After going through the standard data reduction procedure, various errors discussed above are corrected, ignoring the extended emission structure. Then, RE remaining in $G_A(t)$ and $B_A(\nu)$, or Equations (11) and (12), can be assessed by the normalized gains, $g_A(t) = 1 + O[g_A(t)]$ and $b_A(\nu) = 1 + O[b_A(\nu)]$, for the amplitude, as well as $e^{i \phi_A(t)}$ and $e^{i \phi_A(\nu)}$ for the phase. The RE are small, i.e., the residual amplitude errors $O[g_A(t)] \ll 1$ and $O[b_A(\nu)] \ll 1$ and the residual phase error $\phi_0 \equiv \phi_A(t) + \phi_A(\nu)$ fluctuates around zero as a function of time and frequency. The point-source model as described in Equation (8) is reduced to be a function of RE,

$$V^P(u, \nu, t) \approx e^{2\pi i \delta\tau_A(t) + i\phi_0}(1 + O[g_A(t)] + O[b_A(\nu)]).$$

ignoring the terms with high order of RE in amplitude. If the RE $O[b_A(\nu)]$ in the frequency-dependent gains are much smaller than the RE $O[g_A(t)]$ in the time-dependent gains and the phase term owing to residual delay dominates the frequency-dependent RE in phase, ignoring $O[b_A(\nu)]$ and $\phi_0$ in Equation (13), the first order of the RE is reduced to

$$V^P(u, \nu, t) \approx e^{2\pi i \delta\tau_A(t)}(1 + O[g_A(t)]).$$

\(^{12}\) See https://science.nrao.edu/facilities/vla/data-processing/.
related to the variations in the telescope back-end electronics and the telescope front end. The latter includes pointing drifting owing to weather conditions such as a strong wind as well as the gravitational deformation of telescope beams as a function of sky position as the telescope tracks a celestial source. The changes are dependent on the conditions of the individual telescope elements across the array. Based on the analysis discussed in Appendices A.1–A.3, a procedure for RE-correcting and DR-imaging can be developed with the tasks and modules in the CASA software. Figure 12 outlines the basic steps in corrections for the residual delays, residual gains, and time-variable issues. The method for removing the time-variable portion of the core flux density has been discussed (Zhao et al. 2016). The essence of the procedure is to provide a high-precision source model using steps for correcting RE. We use the JVLA Ka-band data of NRAO 530 as an example to illustrate the process. A description of the steps is outlined in the caption of Figure 12.

The image created after applying the JVLA standard calibration (step 1) is a point-like source with a DR of 6800:1 (top image in Figure 12). With this model, the subband or spectral window (spw) based RE of antenna gains in phase (time-dependent) are corrected with self-calibration. Then, alignment of the time-dependent offsets in both phase and amplitude between the subbands is carried out with the solution (time-dependent) derived from the CASA task “bandpass” by averaging all the channels in each of the subbands. Solutions for both gains and bandpass are derived from time intervals equal to each of the observing scans. The “bandpass” solutions are equivalent to the scan-based offsets in amplitude and phase between the “ch0” data of each subband. Correcting for the residual phase errors from self-calibration with the task gaincal, along with applying the “bandpass” solutions of spectral window alignment for each of the 64 subbands (step 2), produces a better image model. With the updated model, further “bandpass” solutions are solved in a shorter time interval, 30 s, by averaging every four channels in each of the subbands. The phase slopes across each of the subbands present in the “bandpass” solutions suggest that the residual delays have not been fully corrected in the data. Following application of the new “bandpass” solutions to the data (step 3), the improved image is constructed, with DR ~57,000:1 (the middle image in Figure 12). The reference model is converging to the true source model. With the updated image model produced from the previous iteration, the corrections for the residual gains in both phase and amplitude can be solved with gaincal using the integration time, the shortest time interval of the data. Applying the new gain solution (step 4), a further corrected data set is generated. Then, the variability of the core is inspected with a light curve showing the variability index in flux density

$$2 \left( \frac{S_{\text{max}} - S_{\text{min}}}{S_{\text{max}} + S_{\text{min}}} \right)^2 = 0.1\% \text{ within the observing period of 2.7 hr.}$$

A model for the variable component is built on a scan-averaged basis with the value derived from the first scan as the reference flux density. The offsets from the reference flux density in the following scans are computed. This variability model is then subtracted from the data using the method discussed by Zhao et al. (2016). After step 5, the antenna-based issues as well as the flux density variation have been corrected. A new model image can be constructed. In the region, a few arcseconds from the core, the rms noise in the new model image appears to be at the level of the thermal noise. One may go back to step 2 and redo the procedure if the image DR is not limited by telescope sensitivity. If baseline-based residual closure errors are present, the baseline-based corrections may need to be applied to the data. For the case of NRAO 530 Ka-band data, we redo the procedure from step 2 and apply baseline-based corrections with bcal. The resulting image is consistent with the image made in step 5. The rms noise of the final image made with robustness weight (R = 0) is ~10 µJy beam⁻¹, reaching the sensitivity limit of the JVLA. The image DR of the final image (the bottom-right image in Figure 12) is 340,000:1.

A.5. A Note Regarding the 5.5 GHz C-array Data

The above procedure appears to be quickly converging for the high-resolution data sets used in this paper. Owing to the large positional uncertainty generated from the residual delays in the shorter baselines or lower resolution data as well as contamination by low-level RFI, the initial model is poorly determined from our JVLA C-array data taken at 5.5 GHz in the spring of 2012. The process of RE-correcting and DR-imaging is difficult to converge following the steps outlined in Figure 12. Consequently, a more elaborate procedure has been developed based on the C-array data, adding substeps to complement the major correction steps of the procedure.

Figure 13 (top) shows a flow chart of the more elaborate RE-correcting and DR-imaging procedure. The details of this procedure appear to be necessary to obtain convergence in the imaging process while fixing data issues using software in CASA. In the data-correcting flow, eight progressive imaging models, marked with a capital “M” followed by a serial number (the filled light-blue circles in Figure 13), are created. The imaging model is needed for two purposes: (1) to be utilized as an input imaging model to generate solutions from the data processed in the previous step and (2) to generate statistics for comparison with the model in the previous step to judge whether the process is converging; if it failed in converging, adjusting the input parameters and redoing the step; if converging, then comparing the data with the improved imaging model to further edit and flag the data to eliminate the lower level RFI and the erroneous data owing to inconvertible telescope issues. Thus, the details of each step might be different for different data sets. For the C-array data at 5.5 GHz used in this paper, we summarize the eight substeps marked in the flow chart after the initial process that includes the JVLA standard calibrations and fixing the core flux density to a constant. The output data from the initial calibration are averaged to 15 s in integration, and the frequency configuration remains the original, namely 64 spectral channels with a uniform width in each of 16 subbands. A brief description of the substeps in the process, identified with the serial number of the imaging model, is provided below:

M1—A model created from the data calibrated initially. Using this model, the data are edited; then using the edited data, solutions for bandpass correction are obtained by

$$13 \text{ The closure errors referred here are baseline-based errors from the possible origins discussed in Cornwell (1986) and Clark (1981) for the former VLA. Unlike antenna-based errors that vanish when using the well-known closure relationships, e.g., Equation (9.104) and Equation (10.44) of Thompson et al. (2017) for phase and amplitude, and can be corrected with the self-calibration technique (Schwab 1980; Cornwell 1986), the baseline-based errors remain in the closure relationships and the self-calibration will fail to correct them. Baseline-based corrections for the closure errors can be done, however (Perley 1986).}$$
averaging the 64 channels in each of the subbands with a time interval of 60 s. The solutions are applied to data to align the subbands in both phase and amplitude; self-calibration is applied to the aligned data for residual gain corrections.

M2—A model produced from the data processed in step M1; the process in this step is similar to step M1 except the bandpass solutions are computed by averaging every eight channels in each of the subbands. A shorter interval of 30 s is used in the averaging. The bandpass solutions are applied to the data to correct the RE in the delay.

M3—A new model created from the data after steps M1 and M2. Using this model, the residual gain errors are further corrected with self-calibration using an interval of 15 s. Then, light curves for each of the two epochs are produced to fix the residual variations in flux density with the module composed of add.component, ft, and uvsub in CASA.

M4—This substep is similar to the substeps M1 and M2, except for the shorter time interval (15 s) used for solving bandpass solutions in a spectral bin of every two channels. The remaining residual delays are further corrected.

M5—M6—M7—The three substeps to average 64 channels into a single channel by vector-averaging the data in each of the subbands, producing “ch0” data in each of the subbands. Every four channels are averaged in each of the three substeps; consequently, the signal-to-noise ratio $(S/N)$ of the new channel data in each of the substeps increases by a factor of 2, which helps to discern the lower level RFI. Data editing is applied to reject the erroneous data that are hidden in the noise. Further self-calibration is carried out, ensuring the previous gain corrections are not affected by bad data and lower $S/N$ issues. Post M7, the output data become single channel (continuum) in each of the subbands. We note that one needs to be cautious about possible distortions of the source structure owing to the bandwidth-smearing effect at a large distance from the phase center when applying the vector-averaging across each of the subbands.

M8—A new imaging model created from the data corrected for antenna-based error. This model is used to correct for baseline-based errors. The scan-averaged solutions are applied to the data. After flagging the data with large deviation from the baseline-based fringe curve, the output is the final data.

Figure 13 (bottom) shows a comparison between the image of M1 (left panel) made from the initial input data (red box) and the image (right panel) from the final output data (green box). The process of RE-correcting and DR-imaging is converged. The residual error correction appears to be the key process in the restoration of the image from radio interferometer array data in addition to FFT and deconvolution or cleaning process.

A.6. Applying Residual-delay Corrections to Target Sources

The time-dependant bandpass solutions for the residual delays derived from calibrators can be applied to target sources. In Morris et al. (2017), we demonstrated that the residual-delay corrections derived from NRAO 530 at 5.5 GHz and J1744−3116 at 9 GHz can be applied to Sgr A*, producing HDR images. However, the resultant images of Sgr A* suggest that the corrected data at 9 GHz produce a better image than the one at 5.5 GHz. We note that both NRAO 530 and J1744−3116 were frequently scheduled as a gain calibrator for Sgr A* in the observations at 5.5 GHz and 9 GHz, respectively. However, J1744−3116 is $2.5\degree$ away from Sgr A* while NRAO 530 is $16\degree$ away. The difference between the 9 and 5.5 GHz images might suggest that the accuracy in the correction for the residual delay is sensitive to the magnitude of the positional offsets between target and calibrator.

A.7. Summary

In short, implementing the algorithms and methods for processing wideband data in addition to the fundamental technology developed during the former, narrow-bandwidth VLA operation, CASA has successfully provided users a software platform for handling JVLA data. With the procedures discussed in this appendix, we have demonstrated that, within
CASA, it is possible to achieve HDR images, reaching the telescope sensitivity limits. However, the approach is tedious and time consuming. Various input parameters for the CASA programs used in the procedures require specific adjustments in the RE-correcting and DR-imaging process. With the modern computing power available, it becomes possible to have a better way of using more advanced algorithms to cope with these issues that we have confronted in the operation of wideband telescopes and handling big data. Therefore, improvements in programming are needed to arrange and manipulate the computer units in a more efficient way for processing wideband data from the combination of advanced statistical algorithms and knowledge that radio astronomers have developed over the past decades.

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**References**

Aller, H. D., & Aller, M. F. 2012, UMRAO Database (Ann Arbor, MI: Univ. Michigan), [https://dept.astro.lsa.umich.edu/data_sets/umrao.php](https://dept.astro.lsa.umich.edu/data_sets/umrao.php)

Begelman, M. C., Rees, M. J., & Blandford, R. D. 1979, *Nature*, 279, 770

Bicknell, G. V. 1995, *ApJS*, 101, 23

Blandford, R. D., & Rees, M. J. 1974, *MNRAS*, 169, 395

Bower, G. C., Backer, D. C., Wright, M., et al. 1997, *ApJ*, 484, 118

Cawthorne, T. V. 1991, in Beams and Jets in Astrophysics, ed. P. A. Hughes (Cambridge: Cambridge Univ. Press), 187

Clark, B. G. 1980, *A&A*, 89, 377

Clark, B. G. 1981, in Orders of Magnitude of Some Instrumental Effects, VLA Scientific Memorandum 137, [http://library.nrao.edu/public/memos/vla/comp/VLAC_137.pdf](http://library.nrao.edu/public/memos/vla/comp/VLAC_137.pdf)

Condon, J. J. 1974, *ApJ*, 188, 279

Crawthorne, T. V. 1991, in beams and jets in Astrophysics, ed. P. A. Hughes (Cambridge: Cambridge Univ. Press), 187

Feng, S.-W., Shen, Z.-Q., Cai, H.-B., et al. 2006, *A&A*, 456, 97

Ghisellini, G., Tavecchio, F., Maraschi, L., et al. 2014, *Natur*, 515, 376

Gower, A. C., Gregory, P. C., Hutchings, J. B., & Unruh, W. G. 1982, *ApJ*, 262, 478

Griffith, M. R., Wright, A. R., Burke, B. F., & Ekers, R. D. 1994, *ApJS*, 90, 179

Gurwell, M. 2018, Submillimeter Calibrator List (Cambridge, MA: The Smithsonian Astrophysical Observatory), [http://sma1.sma.hawaii.edu/callist/callist.html](http://sma1.sma.hawaii.edu/callist/callist.html)

Hardee, P. E. 1979, *ApJ*, 254, 47

Hardee, P. E., & Norman, M. L. 1988, *ApJ*, 334, 70

Healey, S. E., Romani, R. W., Cotter, G., et al. 2008, *ApJS*, 175, 97

Högbom, J. 1974, *ApJS*, 15, 417

Hovatta, T., Nieppola, E., Tornikoski, M., et al. 2008, *A&A*, 485, 51

Hurley-Walker, N., Callingham, J. R., Hancock, P. J., et al. 2017, *MNRAS*, 464, 1146

Intema, H. T., Jagannathan, P., Mooley, K. P., & Frail, D. A. 2017, *A&A*, 598, A78

Jennings, T., Robson, E. I., & Stevens, J. A. 2010, *MNRAS*, 401, 1240

Kellermann, K. I., & Owen, F. N. 1988, in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur & K. I. Kellermann (New York: Springer), 563

Kharb, P., Lister, M. L., & Cooper, N. J. 2010, *ApJ*, 710, 764

Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, *ApJS*, 180, 330

Krichbaum, T. P., Graham, D. A., & Greve, A. 1997, *A&A*, 323, 17

Laing, R. A., & Bridle, A. H. 2015, in IAU Symp. 313, Extragalactic Jets from Every Angle, ed. F. Massaro et al. (Cambridge: Cambridge Univ. Press), 108

Ledlow, M. J., & Owen, F. N. 1996, *AJ*, 112, 9

Lister, M. L., Aller, M. F., Aller, H. D., et al. 2013, *ApJ*, 146, 120

Lister, M. L., Aller, M. F., Aller, H. D., et al. 2016, *ApJ*, 152, 12

Lister, M. L., Aller, M. F., Aller, H. D., et al. 2018, *ApJS*, 234, 12

Lister, M. L., Kellermann, K. I., Vermeulen, R. C., et al. 1982, *ApJ*, 854, 135

Lu, R.-S., Krichbaum, T. P., & Zensus, J. A. 2011, *MNRAS*, 418, 2260

McLure, R. J., & Dunlop, J. S. 2001, *MNRAS*, 327, 199

Morris, M. R., Zhao, J.-H., & Goss, W. M. 2017, *ApJL*, 850, L23

Norman, M. L., & Hardee, P. E. 1988, *ApJ*, 334, 70

O’Dea, C. P., & Owen, F. N. 1986, *ApJ*, 301, 841

O’Donoghue, A. A., Eilek, J. A., & Owen, F. N. 1993, *ApJ*, 408, 428

Owen, F. N., & Ledlow, M. J. 1994, in ASP Conf. Ser. 54, The First Stromlo Symp.: The Physics of Active Galaxies, ed. G. V. Bicknell, M. A. Dopita, & P. J. Quinn (San Francisco, CA: ASP), 319

Pauliny-Toth, I. I. K., Wade, C. M., & Heezen, D. S. 1966, *ApJS*, 13, 65

Perley, R. A. 1986, in Synthesis Imaging, NRAO Workshop, Course Notes from a NRAO Summer School, ed. R. A. Perley, F. R. Schwab, & A. H. Bridle (Green Bank, WV: NRAO), 161

Perley, R. A. 1999, ASP Conf. Ser. 180, Synthesis Imaging in Radio Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San Francisco, CA: ASP), 275

Perley, R. A., Willis, A. G., & Scott, J. S. 1979, *Natur*, 281, 437

Rawlings, S. G., & Saunders, R. 1991, *Natur*, 439, 138

Reuter, H. P., Kramer, C., Sievers, A., et al. 1997, *A&A*, 122, 271

Robson, E. I., Stevens, J. A., & Jenness, T. 2001, *MNRAS*, 327, 751

Schwab, F. R. 1980, *Proc. SPIE*, 231, 18

Stevens, J. A., & Robson, E. I. 1999, *MNRAS*, 270, L75

Teräsranta, H., Tornikoski, M., Valtaoja, E., et al. 1992, *A&AS*, 94, 121

Thompson, A. R. 1986, in Synthesis Imaging, NRAO Workshop, Course Notes from a NRAO Summer School, ed. R. A. Perley, F. R. Schwab, & A. H. Bridle (Green Bank, WV: NRAO), 161

Willott, C. J., Rawlings, S., Blundell, K. M., & Lacy, M. 1999, *MNRAS*, 309, 1017

Zhao, J.-H., Morris, M. R., & Goss, W. M. 2013, *ApJ*, 777, 146

Zhao, J.-H., Morris, M. R., & Goss, W. M. 2016, *ApJ*, 817, 171