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# A radio detection survey of narrow-line Seyfert 1 galaxies using very long baseline interferometry at 22 GHz

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## Abstract

We conducted a high-sensitivity radio detection survey for 40 narrow-line Seyfert 1 (NLS1) galaxies using a very long baseline interferometry (VLBI) technique at 22 GHz through phase-referencing long-time integration and using a newly developing recorder with a data rate of 8 Gbps, which is a candidate of the next generation VLBI data recording systems of the Japanese VLBI Network. The baseline sensitivity was typically a few mJy. The observations resulted in a detection rate of 12/40 for our radio-selected NLS1 sample: 11 out of the 12 detected NLS1s showed inverted radio spectra between 1.4 and 22 GHz on the basis of the Very Large Array flux densities and the VLBI detections. These high fractions suggest that a compact radio core with a high brightness temperature is frequently associated with NLS1 nuclei. On the other hand, at least half of the sample indicated apparently steep spectra even with the limited VLBI sensitivity. Both the inverted and the steep spectrum radio sources are included in the NLS1 population.

**Key words:** galaxies: active — galaxies: jets — galaxies: Seyfert — radio continuum: galaxies — techniques: interferometric

## 1 Introduction

The radio natures of narrow-line Seyfert 1 (NLS1s) galaxies potentially provide the key to understanding outflowing mechanisms in the growing phase of active galactic nuclei (AGNs). NLS1s as a class are thought to be fed at high mass accretion rates onto relatively small-mass black holes, potentially connecting between stellar-mass and supermassive black hole systems in the mass function. The first systematic studies in radio bands by interferometric observations were carried out at arcsecond resolutions with the Very Large Array (VLA), and indicated little difference between NLS1s and broad-line Seyfert galaxies: similar radio luminosities, steep radio spectra, and scarcely resolved radio morphology suggest the presence of weak nonthermal jets as a radio emitting source (Ulvestad et al. 1995; Moran 2000), although several optical/X-ray properties are clearly different. NLS1s were thought to be radio-quiet objects as a class with only a few exceptions of known radio-loud objects (e.g., Grupe et al. 2000; Oshlack et al. 2001; Siebert et al. 1999); subsequent systematic studies based on large databases, such as the VLA Faint Images of the Radio Sky at Twenty-centimeters (FIRST: Becker et al. 1995) and the NRAO VLA Sky Survey (NVSS: Condon et al. 1998) in radio, and the Sloan Digital Sky Survey (SDSS) in optical, have revealed a lower fraction of radio-loud objects (∼7%; Komossa et al. 2006, see also Zhou et al. 2006; Whalen et al. 2006; Yuan et al. 2008) compared to that of broad-line Seyfert galaxies.

Recently, gamma-ray detections by the Fermi Gamma-Ray Space Telescope toward six NLS1s galaxies with high significance (Abdo et al. 2009a, 2009c; D'Ammando et al. 2012, 2015) have offered a new population of gamma-ray emitting AGNs other than blazars and radio galaxies. The radio observations at high angular resolutions using a very long baseline interferometry (VLBI) technique for the first discovered $\gamma$-ray emitting NLS1 SDSS J094857.31+002225.4 (PMN J0948+0022) revealed the presences of a one-sided pc-scale jet and a rapidly variable, very-high-brightness radio core showing an inverted spectrum at the nucleus (Doi et al. 2006). PMN J0948+0022 also shows a core-dominant structure with two-sided kpc-scale radio emissions (Doi et al. 2012). The combination of these radio/gamma-ray properties is reminiscent of blazars, which are characterized by Doppler-beaming on relativistic jets viewed from pole-on typically on parsec (pc) scales and by decelerated components on scales of from kpc to Mpc. VLBI observations of the several other gamma-ray emitting NLS1s also indicate the presence of beamed jets on pc scales (Doi et al. 2011, 2013; D'Ammando et al. 2012, 2013b; Wajima et al. 2014): some of them also show two-sided kpc-scale radio structures (Antón et al. 2008; Doi et al. 2011, 2012). However, the radio jets are mildly relativistic and their powers are comparable to the least energetic blazars, on the basis of single-dish monitoring (Angelakis et al. 2015).

On the other hand, VLBI observations of radio-loud NLS1s with gamma-ray detections/non-detections have revealed that the radio-loud aspect is possibly attributed not only to a beaming effect but also to an intrinsically large radio power. Intrinsic radio powers that are corrected for the beaming effect using estimated Doppler factors suggest that radio-loud NLS1s include both intrinsically radio-loud and intrinsically radio-quiet cases (Doi et al. 2011, 2012). An extended pc-scale jet showing a steep spectrum dominates a total radio power, which suggests that it is not so relativistic and/or sufficiently inclined with respect to our line of sight for the jet (Gu & Chen 2010; Gu et al. 2015). Seven out of the 10 known NLS1s with kpc-scale radio structures (Richards & Lister 2015, see also Gliozzi et al. 2010; Doi et al. 2012, 2015) are not yet gamma-ray detected. This situation suggests that jet powers may be intrinsically and sufficiently large to escape the core regions of host galaxies, but not so Doppler-boosted because of relatively large viewing angles. For several nearby radio-quiet NLS1s, VLBI observations have also revealed pc-scale jet-like structures showing steep spectra, which are presumably generated through the same process as that of radio-loud NLS1s, but probably with only a little difference in power or viewing angle of nonthermal jets (Giroletti et al. 2005; Doi et al. 2013, 2015). Thus, at least a fraction of NLS1 nuclei has an ability to generate nonthermal jets, which have a wide range of radio powers: in some cases, the signatures of a beaming effect on relativistic jets viewed from pole-on are observed.

However, a limited number of NLS1s have been investigated at milli-arcsecond (mas) resolutions so far, because NLS1s are relatively weak radio sources in comparison with the other AGN classes. Systematic VLBI observations have been started by other authors (Gu et al. 2015), the targets of which are 16 radio-loud NLS1s selected from several parent samples with 105 sources: 14 sources were detected at 5 and 6.7 GHz, which are relatively low frequencies and may tend to be biased to the contribution of extended pc-scale jets. The present paper reports on the result of a new VLBI detection survey as a systematic study for NLS1s in the radio band at a higher frequency (22 GHz), where an inner jet component is potentially focused on. Our observation was planned before the publication of Gu et al. (2015). Our sample selection was relatively similar to theirs: the differences are (1) the combination of parent samples; (2) the inclusion of radio-quiet NLS1s; (3) a higher observing frequency. Section 2 presents the sample selection. In sections 3 and 4, VLBI observations and the procedures of data reductions are described. These results are presented and the implications are briefly discussed in section 5.

## 2 Sample

We selected NLS1 radio sources by position-matching between the catalogue of the VLA 1.4 GHz FIRST survey (Becker et al. 1995) and source lists in the following NLS1 studies: (1) 64 sources in Véron-Cetty, Véron, and Gonçalves (2001); (2) 2011 sources in Zhou et al. (2006); (3) 23 sources in Yuan et al. (2008); (4) 62 sources in Whalen et al. (2006). We found several sources that were counted redundantly: the resulting number of uniquely selected sources was 233 (734–0.8 mJy beam$^{-1}$ at 1.4 GHz). We clipped 41 sources with an intensity higher than 10 mJy beam$^{-1}$ from these sources. The NLS1 radio source catalogue used as a target list in the present study is listed in table 1.

The sample selection criteria are similar to those of the previous systematic VLBI study by Gu et al. (2015), which was also based on the radio-selected samples with flux densities of >10 mJy in the VLA FIRST. The parent samples were restricted to only radio-loud objects from Komossa et al. (2006), Zhou et al. (2006), Yuan et al. (2008), and Foschini (2011), which were slightly different from ours as we include radio-quiet ones as well. Six radio-quiet objects are included in our sample [$\log RL < 1$, see column (7) in table 1].

## 3 Observation

The observations were performed as a part of the experimental observations to test a developing OCTAVE-DAS (Data Acquisition System: Oyama et al. 2012). It is a candidate for the next-generation data recording system of OCTAVE (Optically Connected Array for VLBI Exploration: Kono et al. 2012), JVN (Japanese VLBI Network: Fujisawa 2008), and other VLBI arrays.

OCTAVE-DAS consists of three key components. The first is a high-speed analog-to-digital (A/D) converter at a sampling rate of 8 gigabits per second (Gbps) of 3-bit quantization. It is called “OCTAD” (OCTave A/D converter). It is able to sample signals at a radio frequency (RF) directly. In addition, it has digital base-band converter (DBBC) functions for the VLBI Global Observing System (VGOS) observation. The second key component is a media converter between a single 10 GigE (gigabit Ethernet) port and four VSI-H (VLBI Standard Interface-Hardware) I/O ports. It is called OCTAVIA (OCTave VLBI Interface Adapter) or OCTAVIA2 depending on its version. The third key component is a recorder. It is able to record the data stream at a rate of from 4.5 to 32 Gbps. It is called OCTADISK (OCTave DISK recorder), OCTADISK2, or VSREC (VLBI Software Recorder), depending on its version. OCTAVE-DAS is being developed at the Mizusawa VLBI observatory, a branch of the National Astronomical Observatory of Japan.

The test observations using OCTAVE-DAS were conducted on 2014 April 21 and 28, with four radio telescopes of the VLBI Exploration of Radio Astrometry project (VERA: Kobayashi et al. 2003): Mizusawa, Ogasawara, Iriki, and Ishigaki stations participated in the experiment. The polarization was the left-circular-polarization. VERA has a dual-beam receiving system. The dual beams are called “A-beam and B-beam”. For the dual beam observation in this paper, A-beam was used for the target sources and B-beam for the reference sources.

Using the current VERA observation system, the received radio signals of dual beams were converted to intermediate frequency (IF) frequency. The bandwidth was 512 MHz. The IF signals were sampled by two A/D converters (ADS-1000s). The sampling rate was 1.024 GHz. The quantization bit number was two. The data streams were recorded by OCTADISK. The aggregated bit rate was 4.096 Gbps.

In addition, we installed OCTAVE-DAS in order to expand the bandwidth. We also installed the analog signal converters with a wider bandwidth. The new system was installed on A-beam for this test observation, to increase the sensitivity of target sources. The received signal of A-beam was divided into two signals for the current and new systems. The signal for the new systems was divided into four IF channels, the bandwidth of which was 512 MHz. The starting frequencies of the four IFs were 21.459, 21.971, 22.483, and 22.995 GHz. The four IF signals were A/D converted by ADS-3000+ which had been developed at NICT (National Institute of Information and Communications Technology) instead of OCTAD for the observation in this paper. The sampled data stream was recorded by VSREC. The aggregated recording rate was 8.192 Gbps.

The dual-beam systems with the current VERA system and OCTAVE-DAS can work simultaneously. We utilized “dual-beam phase referencing” in order to increase coherent integration time by the elimination of the atmospheric phase fluctuation of the targets with the phases of the calibrators. For several targets (SBS 0846+513, SDSS J103727.44+003635.5, B3 1441+476, [HB89] 1519−065, and [HB89] 1546+353), proper calibrators cannot be found within a separation angle of $2\overset{\circ}{.}1$. We used a nodding style phase-referencing. A-beam pointing was switched between a target and a reference calibrator with a cycle of 40 s. On-source tracking was used for PMN J0948+0022, which was expected to be detected without phase-referencing. SDSS J124634.64+023809.0 was mis-allocated in our observation. The resulting number of observed targets was 40.

The A/D converter ADS-1000 at the Ishigaki station was unfortunately unlocked from a reference signal during both of the observations. The solutions of the phase reference from the B-beam were unavailable.

## 4 Data reduction

The correlations were processed with the software correlator OCTACOR2 (OCTAve CORrelator), which was developed at the Mizusawa VLBI observatory and NICT (Oyama et al. 2012). The correlated data were integrated

**Table 1.** Samples and results of observations.*

| NED name (1) | $z$ (2) | RA (J2000.0) ($^{\rm h\ m\ s}$) (3) | Dec (J2000.0) ($^{\circ}\ '\ ''$) (4) | $I^{\rm FIRST}_{\rm 1.4GHz}$ (mJy beam$^{-1}$) (5) | Sample (6) | log $RL$ (7) | Ref. (8) | Mode (9) | Calibrator (10) | $F_{\rm VLBI}$ (mJy) (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 2MASX J03474022+0105143 | 0.031 | 03 47 40.195 | +01 05 14.25 | 38.85 | a | 0.99 | | 2B | J0352+0238 | <7 |
| FBQS J0713+3820 | 0.123 | 07 13 40.291 | +38 20 40.08 | 10.43 | b | 0.33 | | 2B | J0709+3737 | <7 |
| 2MASS J07440228+5149175 | 0.46 | 07 44 02.242 | +51 49 17.48 | 11.89 | b | 1.62 | | 2B | J0733+5022 | <7 |
| FBQS J075800.0+392029 | 0.096 | 07 58 00.047 | +39 20 29.09 | 10.8 | b | − 0.19 | | 2B | J0752+3730 | <7 |
| SDSS J081432.11+560956.6 | 0.510361 | 08 14 32.135 | +56 09 56.55 | 69.18 | c | 2.53 | e | 2B | J0824+5552 | 117 |
| SBS 0846+513 | 0.584701 | 08 49 57.990 | +51 08 28.83 | 344.09 | c | 3.16 | f | ND | J0905+4850 | 454 |
| SDSS J085001.16+462600.5 | 0.524316 | 08 50 01.171 | +46 26 00.41 | 20.9 | c | 2.23 | e | 2B | J0847+4609 | <7 |
| SDSS J090227.16+044309.5 | 0.533025 | 09 02 27.152 | +04 43 09.40 | 152.59 | c | 3.02 | e | 2B | J0901+0448 | 244 |
| PMN J0948+0022 | 0.585102 | 09 48 57.295 | +00 22 25.60 | 107.53 | c | 2.55 | ghi | 1B | — | 501 |
| MRK 1239 | 0.019927 | 09 52 19.099 | −01 36 43.63 | 58.64 | a | 1.33 | jk | 2B | J0945−0153 | <7 |
| SDSS J095317.09+283601.4 | 0.65891 | 09 53 17.106 | +28 36 01.63 | 44.58 | c | 2.71 | e | 2B | J1001+2911 | <7 |
| SDSS J103123.73+423439.3 | 0.377167 | 10 31 23.728 | +42 34 39.40 | 16.57 | c | 2.34 | | 2B | J1038+4244 | <7 |
| KUG 1031+398 | 0.042443 | 10 34 38.599 | +39 38 28.17 | 23.98 | a | 1.67 | | 2B | J1033+4116 | <7 |
| SDSS J103727.44+003635.5 | 0.595596 | 10 37 27.454 | +00 36 35.76 | 27.23 | c | 2.66 | e | ND | J1048+0055 | <12 |
| [HB89] 1044+476 | 0.79902 | 10 47 32.654 | +47 25 32.24 | 734.02 | c | 3.87 | e | 2B | J1051+4644 | <7 |
| SDSS J111005.03+365336.3 | 0.62995 | 11 10 05.034 | +36 53 36.12 | 18.62 | c | 2.97 | e | 2B | J1104+3812 | <7 |
| 2MASX J11193404+5335181 | 0.105975 | 11 19 34.026 | +53 35 18.45 | 15.49 | d | 1.96 | | 2B | J1120+5404 | <7 |
| SDSS J113824.54+365327.1 | 0.356743 | 11 38 24.545 | +36 53 26.99 | 12.54 | c | 2.34 | e | 2B | J1130+3815 | <7 |
| 2MASX J11404788+4622046 | 0.11439 | 11 40 47.897 | +46 22 04.82 | 78.85 | b | 1.36 | | 2B | J1138+4745 | <7 |
| FBQS J114654.2+323652 | 0.4658 | 11 46 54.298 | +32 36 52.24 | 14.67 | c | 2.11 | | 2B | J1152+3307 | 104 |
| FBQS J1151+3822 | 0.334575 | 11 51 17.757 | +38 22 21.75 | 10.93 | b | 0.54 | | 2B | J1146+3958 | <7 |
| 2MASX J12022678−0129155 | 0.150694 | 12 02 26.806 | −01 29 15.54 | 11.37 | d | 1.49 | | 2B | J1207−0106 | <7 |
| NGC 4051 | 0.002336 | 12 03 09.594 | +44 31 52.52 | 12.3 | a | 0.47 | lj | 2B | J1203+4510$^{\S}$ | <17 |
| NGC 4253 | 0.012929 | 12 18 26.516 | +29 48 46.52 | 38.16 | a | 1.19 | | 2B | J1217+3007 | <7 |
| SDSS J123852.12+394227.8 | 0.622668 | 12 38 52.147 | +39 42 27.59 | 10.36 | c | 2.23 | | 2B | J1242+3751 | <7 |
| SDSS J124634.64+023809.0 | 0.362629 | 12 46 34.683 | +02 38 09.02 | 37.05 | c | 2.38 | e | — | J1250+0216 | — |
| MRK 0783 | 0.0672 | 13 02 58.925 | +16 24 27.49 | 18.53 | a | 1.36 | j | 2B | J1300+141B | <9 |
| SDSS J130522.74+511640.2 | 0.787552 | 13 05 22.746 | +51 16 39.55 | 83.87 | c | 2.34 | e | 2B | J1259+5140 | <9 |
| FBQS J1421+2824 | 0.539978 | 14 21 14.075 | +28 24 52.23 | 46.79 | b | 2.14 | e | 2B | J1419+2706 | 117 |
| SDSS J143509.49+313147.8 | 0.502218 | 14 35 09.523 | +31 31 48.30 | 39.26 | c | 2.87 | | 2B | J1435+3012$^{\S}$ | <23 |
| B3 1441+476 | 0.705472 | 14 43 18.578 | +47 25 56.53 | 164.79 | c | 3.07 | e | ND | J1452+4522 | <16 |
| [HB89] 1502+036 | 0.407882 | 15 05 06.467 | +03 26 30.83 | 365.39 | c | 3.19 | mn | 2B | J1458+0416$^{\S}$ | 697 |
| [HB89] 1519−065 | 0.083121 | 15 22 28.758 | −06 44 41.83 | 11.8 | a | $0.56^{\ddagger}$ | | ND | J1510−0543 | <16 |
| [HB89] 1546+353 | 0.479014 | 15 48 17.924 | +35 11 28.37 | 140.94 | c | 2.84 | eo | ND | J1602+3326 | 22 |
| IRAS 15462−0450 | 0.099792 | 15 48 56.806 | −04 59 34.26 | 10.68 | a | $1.05^{\ddagger}$ | | 2B | J1550−0538 | <9 |
| FBQS J1629+4007 | 0.272486 | 16 29 01.315 | +40 07 59.62 | 11.97 | b | 1.46 | pqr | 2B | J1623+3909$^{\S}$ | 145 |
| 2MASX J16332357+4718588 | 0.116054 | 16 33 23.585 | +47 18 58.96 | 62.63 | c | 2.22 | pqr | 2B | J1637+4717 | 163 |
| FBQS J1644+2619 | 0.145 | 16 44 42.536 | +26 19 13.19 | 87.53 | c | 2.65 | prs | 2B | J1642+2523 | 62 |
| B3 1702+457 | 0.0604 | 17 03 30.379 | +45 40 47.09 | 115.44 | a | 2.17 | pqr | 2B | J1658+4737 | <9 |
| FBQS J1713+3523 | 0.083 | 17 13 04.476 | +35 23 33.43 | 11.13 | b | 1.05 | | 2B | J1708+3346$^{\S}$ | 138 |
| SDSS J172206.02+565451.6 | 0.425967 | 17 22 06.081 | +56 54 52.00 | 36.91 | c | 2.37 | | 2B | J1722+5856 | <9 |

*Col (1): source name in NED. Col. (2): redshift. Col. (3): right ascension. Col. (4): declination. Col. (5): peak intensity in mJy beam$^{-1}$ at 1.4 GHz in VLA FIRST. Col. (6): parent sample. Col. (7): radio loudness from reference listed in col. (6), except for sources from Véron-Cetty, Véron, and Gonçalves (2001) which includes no value for radio loudness. Note that the definition of radio loudness differs from reference to reference. We calculated radio loudness for sources in Véron-Cetty, Véron, and Gonçalves (2001) by the ratio of FIRST 1.4 GHz radio to SDSS $g$-band PSF optical flux densities, according to Zhou et al. (2006). Sources denoted by "‡" represent the use of $B$-band magnitudes listed in Véron-Cetty, Véron, and Gonçalves (2001) because their SDSS results are not available. Col. (8): reference of previous VLBI observation. Col. (9): observation mode in the present study. "ND" and "2B" represent nodding-style and VERA's dual-beam phase referencing, respectively. "1B" represents an on-source observation with a single beam. SDSS J124634.64+023809.0 was mis-allocated in our observation. Col. (10): phase-referencing calibrator used in the present study. Calibrators denoted by "§" represent non-detection in B-beam. Col. (11): correlated flux density in mJy measured in the present study.

†References—a: Véron-Cetty, Véron, and Gonçalves (2001); b: Whalen et al. (2006); c: Yuan et al. (2008); d: Zhou et al. (2006); e: Gu et al. (2015); f: D'Ammando et al. (2013a); g: Doi et al. (2006); h: Abdo et al. (2009b); i: Giroletti et al. (2011); j: Doi et al. (2013); k: Doi et al. (2015); l: Giroletti and Panessa (2009); m: Fey and Charlot (2000); n: D'Ammando et al. (2013b); o: Orienti et al. (2015); p: Doi et al. (2007); q: Gu and Chen (2010); r: Doi, Asada, and Nagai (2011); s: Doi et al. (2012).

every one second. The frequency channel number per IF channel was 512.

Data reduction procedures were performed by using the Astronomical Image Processing System (AIPS: Greisen 2003). Amplitude calibration using a priori gain values together with the system noise temperatures measured during the observations were applied. The calibration accuracy had not been evaluated in this new system; it was inferred as being probably less than 20%, in comparison with results of known strong sources in the data. The delay differences among the four IF channels were calibrated using the fringe-fitting solutions of a bright calibrator ("manual-pcal"). This solution allowed us to adopt a small fringe-finding window in subsequent fringe-fitting procedures.

For dual-beam phase-referencing, the fringe-fitting solution in phase for the reference calibrator was obtained with the B-beam data at first. Next, we applied the solution to the four channels of the A-beam. Calibrators for five targets were not detected. The difference between the center frequencies of two beams is 256 MHz (∼1% with respect to the radio frequency). In the case of residual phase variation of $\sim 100^\circ$ (typically observed during VERA dual-beam observations) after a fringe-rate removal, the coherence loss is expected to be only 0.02% when we apply fringe-phase solutions to data at an ∼1%-different frequency. With the dual-beam phase-referencing, we were able to extend the fringe-fitting solution interval to 720 s. The interval is equivalent to a scan duration of the antenna schedule. As a result, six targets out of 29 were detected at signal-to-noise ratios ($S/N$) higher than 3 in this observing mode.

We also performed to apply fringe-fitting solutions of calibrators to the five targets observed in the manner of nodding-style phase-referencing with a cycle of 40 s (Mode in table 1). The solution interval was 720 s with a net accumulation of 240 s on a target. As a result, two out of the five targets were detected at $S/N > 3$ in this observing mode.

PMN J0948+0022, which was observed without phase-referencing, was detected with a solution interval of 120 s. Fringe findings for five targets whose calibrators were not detected in B-beam were also attempted with a solution interval of 120 s (Calibrator in table 1). As a result, three out of the five were detected at $S/N > 3$.

## 5 Result and discussion

Correlated flux densities averaging out through baselines with a detection are listed in the last column of table 1; the table includes the references to sources where previous VLBI studies exist. Upper limits of correlated flux density, ranging from 7 to 23 mJy depending on the observing mode (section 4), were determined by $S/N = 3$ on the most sensitive baseline during the observations.[1] Twelve out of 40 observed targets were detected with VERA baselines ranging from ∼1000 to ∼2300 km, which imply a brightness temperature of the order of $10^7$ K or more for high-frequency radio emissions associated with these NLS1s.

The two sources, FBQS J114654.2+323652 and FBQS J1713+3523, are for the first time detected with very long baselines. FBQS J114654.2+323652 was presumably detected with the MIZUSAWA–IRIKI baseline in the dual-beam phase-reference mode; we also confirmed the fringe detection in a normal fringe fitting, without a calibrator, with a shorter integration (2 min). Around this source, there is no strong source that could be potentially confusing to our observation. FBQS J1713+3523 was positively detected with baselines of all the four antennas in fringe fitting without a calibrator (because its calibrator was not detected in the B-beam). Around this source, there is no strong source that could be potentially confusing to our observation. Both the sources are weak radio sources at 1.4 GHz in the FIRST [15.42 mJy for FBQS J114654.2+323652 (1994.4) and 11.24 mJy for FBQS J1713+3523 (1994.5)]; on the other hand, they are relatively strong at 22 GHz in our observation (104 and 138 mJy). These sources should be inverted spectrum sources with $\alpha = +0.7$ and $\alpha = +0.9$, where $\alpha$ is the spectral index ($F_\nu \propto \nu^\alpha$), assuming that the 1.4 GHz FIRST (and the 22 GHz) fluxes do not vary significantly for ∼20 years. Such a weak source showing an inverted spectrum has also been previously reported by Doi et al. (2007) for FBQS J1629+4007, which is also in the list of the present study and has been detected [11.95 mJy at 1.4 GHz (1994.6) and 145 mJy at 22 GHz]. In the first place, relatively weak radio emissions at 1.4 GHz and a limited baseline sensitivity at 22 GHz were supposed to bias VLBI detections strongly toward inverted spectrum sources. In fact, all the detected sources except for one (11/12) show flat or inverted spectra ($\alpha = -0.1$–$+0.9$) between 1.4 and 22 GHz, if the variability in the time interval between measurements at 1.4 and 22 GHz is assumed insignificant. Although this is a sort of artificial effect, it is noteworthy that not a very small fraction of NLS1 radio sources (12/40) have been detected at such a high frequency even with very long baselines.

On the other hand, at least half of the sources indicate apparently steep spectra ($\alpha < -0.2$) between 1.4 and 22 GHz on the basis of the FIRST flux densities and the VLBI upper limits. Both inverted and steep spectrum radio sources are included in the NLS1 population, as previously

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[1] Even if we adopted a detection limit of $5\sigma$ instead of $3\sigma$, only [HB89] 1546+353, which is the weakest detection in our sample, would move into non-detection.

pointed out by several authors (Doi et al. 2007, 2011; Gu & Chen 2010). Particularly, [HB89] 1044+476 is the strongest radio source [767.44 mJy at 1.4 GHz in the FIRST (1997.2)] in our sample, but is not detected with the VLBI at 22 GHz ($<$7 mJy). Only a weak radio emission (19.4 mJy) with a core-jet structure in the east–west direction has been previously found in VLBI images at 5 GHz, while VLA images at 8.4 and 22 GHz show significantly large radio flux densities: a bulk of total flux must be resolved out with very long baselines and originate in extended components of a compact steep spectrum source (Gu et al. 2015). B3 1702+457 is in a similar situation [118.64 mJy at FIRST 1.4 GHz (1997.2) and $<$9 mJy at VLBI 22 GHz]: the previous VLBI studies revealed an extended radio structure with a steep spectrum for B3 1702+457 (Doi et al. 2007, 2011). Hence, our negative detections in a limited sensitivity at 22 GHz are genuine even for these sources that are relatively strong at 1.4 GHz.

Consequently, the systematic study by on VLBI detection survey has revealed that NLS1s are an AGN subclass that can possess compact radio components with high brightness temperatures ($\gtrsim 10^7$ K) even at the high frequency (22 GHz). These compact components show inverted spectra in almost all the VLBI-detected cases, which account for a significant fraction in our radio-selected NLS1 sample. These properties may be related to blazer-like aspects of NLS1s, such as gamma-ray detections in several NLS1s, in contrast to normal broad-line Seyfert galaxies.

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