WMAP extragalactic point sources as potential Space VLBI calibrators

Katinka Geréb*
Department of Astronomy, Eötvös University, Pázmány P. sétány 1/A, H-1117 Budapest, Hungary
Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

Sándor Frey
FÖMI Satellite Geodetic Observatory, P.O. Box 585, H-1592 Budapest, Hungary
MTA Research Group for Physical Geodesy and Geodynamics, P.O. Box 94, H-1521 Budapest, Hungary

Abstract

The point source list of the Wilkinson Microwave Anisotropy Probe (WMAP) is a uniform, all-sky catalogue of bright sources with flux density measurements at high (up to 94 GHz) radio frequencies. We investigated the five-year WMAP list to compile a new catalogue of bright and compact extragalactic radio sources to be potentially studied with Very Long Baseline Interferometry at millimeter wavelengths (mm-VLBI) and Space VLBI (SVLBI). After comparing the WMAP data with the existing mm-VLBI catalogues, we sorted out the yet unexplored sources. Using the 41, 61 and 94 GHz WMAP flux densities, we calculated the spectral indices. By collecting optical identifications, lower-frequency radio flux densities and VLBI images from the literature, we created a list of objects which have not been investigated with VLBI at 86 GHz before. With total flux density at least 1 Jy and declination above $-40^\circ$, we found 37 suitable new targets. It is a nearly 25% addition to the known mm-VLBI sources. Such objects are also potentially useful as phase-reference calibrators for the future Japanese SVLBI mission ASTRO-G.

*Corresponding author

Email addresses: gereb@astro.rug.nl (Katinka Geréb), frey@sgo.fomi.hu (Sándor Frey)
at its highest observing frequency (43 GHz). The phase-referencing capability of ASTRO-G would allow long integrations and hence better sensitivity for observing faint target sources close to suitable phase calibrators in the sky.

**Keywords:** Compact extragalactic radio sources, Active galactic nuclei, Radio spectrum, mm-VLBI, Space VLBI

1. Introduction

The Wilkinson Microwave Anisotropy Probe (WMAP) is a NASA Explorer mission, launched in June 2001 to make fundamental measurements of cosmology (Bennett et al., 2003). Its main aim is to measure the Cosmic Microwave Background (CMB) temperature anisotropies at five different frequencies between 23 and 94 GHz. The foreground emission – galactic emission, galactic and extragalactic point sources – is a cause of a major complication because it contaminates the CMB maps. In order to separate the CMB data and the foreground emission, extragalactic point source catalogues were created for each WMAP data release. Here we use another, more extended point source catalogue constructed by Chen & Wright (2009) based on the five-year WMAP sky maps at three different frequencies (41, 61 and 94 GHz), using a method that favours the selection of flat-spectrum sources. This catalogue offers an opportunity to study the population of the brightest flat-spectrum radio sources in the millimeter wavelength range. Unlike any ground-based instrument limited by the observable sky at a given geographic location, WMAP in fact provides a homogeneous all-sky mm wavelength survey.

The technique of Very Long Baseline Interferometry (VLBI) employs a network of radio telescopes that simultaneously observe the same radio source. By combining the measurements recorded at the stations (or transferred directly to a central processing facility in real time), the angular resolution of the synthesized large radio telescope is determined by the maximum separation (baseline) between the individual telescopes. VLBI allows the imaging of bright and compact radio sources, including radio-emitting active galactic nuclei (AGN) at extremely high angular resolution. The first successful 89 GHz VLBI observation on a single baseline was done by Readhead et al. (1983). Since then, several other VLBI experiments have been made at mm-wavelengths in order to investigate the physical proper-
ties of quasars and other AGN. For example, using the 100 and 86 GHz observations made with the Coordinated Millimeter VLBI Array (CMVA) in 1990 and 1993, Rantakyrö et al. (1998) created a catalogue of 16 radio sources, to probe the physics of the innermost jets in AGN. They achieved up to 50 micro-arcsecond (µas) angular resolution while imaging 12 sources. Lobanov et al. (2000) presented 86 GHz VLBI observations of 28 radio sources. This catalogue contains 26 AGN, the remaining two sources are the center of our Galaxy (Sgr A*) and the Cygnus X-3 X-ray binary star.

The catalogue of Lee et al. (2008) was a great leap forward, containing 127 compact radio sources (88 quasars, 25 BL Lac objects, 11 radio galaxies, 1 star and 2 unidentified sources). To define the target list for their survey, Lee et al. (2008) selected sources which (i) have not been investigated before at 86 GHz with VLBI, (ii) have declination δ > −40° to ensure a good radio station coverage, and (iii) have 86 GHz flux density $S_{86}>0.3\ Jy$. They produced images for 109 objects. Twelve others were also detected but could not be imaged due to insufficient data.

At lower frequencies (24 and 43 GHz), the United States Naval Observatory (USNO) maintains an extensive catalogue.1 It contains AGN that are being studied for assessing their astrometric suitability for use in a high-frequency celestial reference frame (Charlot et al., 2010).

Space VLBI (SVLBI) involves an orbiting radio telescope as one of the interferometer elements, to increase the baseline lengths and hence the achievable angular resolution at a given observing frequency, with respect to what is available from the Earth-based networks. The first dedicated SVLBI satellite, the Japanese HALCA was launched in 1997 (Hirabayashi et al., 1998). ASTRO-G is a planned Japanese second-generation SVLBI mission (Tsuboi, 2009) currently foreseen to be launched in 2016. The satellite will carry out observations at 8.4, 22 and 43 GHz, on interferometric baselines several times longer than the Earth diameter. ASTRO-G will provide higher angular resolution (down to 38 µas) and better sensitivity than any SVLBI experiment before. The high sensitivity is mostly achieved by long integrations well in excess of the atmospheric coherence time at the ground-based antennas of the network. This is made possible by the phase-referencing technique which involves rapid switching between the scientifically interesting weak target and a nearby strong calibrator. However, the chance for finding a suitable phase-

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1http://rorf.usno.navy.mil/RRFID_KQ
reference calibrator source, which is sufficiently close to the target severely decreases at higher frequencies ([Asaki et al., 2007]. For enhancing the scientific gain of the mission, it is crucial to find as many compact radio AGN at high frequencies as possible.

It is very important for several reasons to increase the number of radio sources mapped at mm-wavelengths. From an astrophysical point of view, these highest-resolution imaging data are essential to test the physical models of the inner jets, in the region of jet launching near the central supermassive black holes. By combining ground-based 86 GHz VLBI images with 43 GHz SVLBI data obtained with baselines larger by a factor of ∼2, and thus at similar angular resolution, it is possible to create detailed spectral index images. For high-frequency SVLBI, there is also a need to increase the sky density of bright sources that are compact at ∼10 μas scales. These could serve as phase-reference sources for observing nearby fainter targets.

In this paper, we describe our method to identify new potential mm-VLBI and SVLBI target sources from the WMAP point source catalogue, and give the list of the brightest 37 sources selected (Sect. 2). We also give perspectives on finding more sources in the near future (Sect. 3).

2. New mm-VLBI targets from the WMAP point source catalogue

Which AGN are suitable as new candidates for observing with mm-VLBI? To answer this question, we compared the WMAP point source list ([Chen & Wright, 2009]) with the existing VLBI catalogues at high frequencies. After the identifications, we created sub-samples from the already known mm-VLBI sources and from those which do not appear in earlier VLBI lists. We also made a cross-indentification with the most extensive 86 GHz VLBI catalogue to date ([Lee et al., 2008]).

A power-law is usually a good approximation of the continuum radio spectra in the cm and mm wavelength range. The flux density (S) is the function of the observing frequency (ν) as $S \sim \nu^\alpha$, where $\alpha$ is the spectral index. Using the 41, 61 and 94 GHz WMAP flux densities, we calculated the radio spectral index for each source. Note that the point source flux densities are extracted from the 5-year WMAP temperture maps ([Chen & Wright, 2009]) and do not represent a specific epoch. Any possible flux density variability over the 5-year interval is avaraged out this way. The spectral indices cannot be considered as simultaneous. The radio spectra of compact sources are usually flat (i.e. $\alpha \geq -0.5$) as a result of the superposition of several
small synchrotron self-absorbed components with different spectral turnover frequencies. For direct comparison in the VLBI band, we also estimated the source flux densities at 86 GHz, using the spectral index and the flux density measured in the nearest WMAP band (94 GHz). Then we compared the spectral index and flux density distribution of the whole WMAP sample (Chen & Wright, 2009) and our sub-samples. It turned out that on average the WMAP catalogue contains fainter sources with slightly flatter spectra than the earlier VLBI catalogues. The spectral index histograms of the WMAP and the Lee et al. (2008) samples are shown as an example in Fig. 1.

For creating a new list of bright and compact quasars that are suitable for subsequent mm-VLBI and SVLBI studies, we adopted the selection method of Lee et al. (2008), using the WMAP point source catalogue (Chen & Wright, 2009) as the initial sample. First we excluded those WMAP sources that have already been investigated with 86 GHz VLBI before. Then we applied 1 Jy as the lower limit of total flux density. According to Chen & Wright (2009), the sources with $S > 1$ Jy are reliable detections in their WMAP list. However, the number of suitable sources could be increased if a less conservative lower flux density limit is used. Following Lee et al. (2008), only the objects above $-40^\circ$ declination were considered since the antennas of the Global Millimeter VLBI Array (GMVA) are in the northern hemisphere. As a result, we obtained a list of 38 radio sources. A comparison with the properties of the Lee et al. (2008) catalogue sources shows that our new objects are in general fainter but their spectra are somewhat flatter, and thus likely sufficiently compact for VLBI detection.

To verify the suitability of our new sources, and to supplement the new catalogue with other basic data, we searched the NASA/IPAC Extragalactic Database (NED)\footnote{http://nedwww.ipac.caltech.edu} for optical identifications. We also compiled broad-band radio spectra and collected VLBI images of the sources made at lower frequencies.

The optical identifications yielded 30 quasars, 5 galaxies and 2 unclassified sources. One of the sources (PMN J0527−1241) turned out to be a planetary nebula. Indeed, this source remained undetected with the Japanese VLBI Exploration of Radio Astrometry (VERA) array at 22 GHz (Petrov et al., 2007), consistently with an upper limit of 0.11 Jy for the correlated flux
Figure 1: Spectral index histograms of the whole WMAP sample (top) and its overlap with the biggest 86-GHz VLBI sample to date [Lee et al., 2008] (bottom). The two distributions are similar, the WMAP-only sources have somewhat flatter radio spectra on average. The median spectral index for the whole WMAP sample is $-0.30$. For the WMAP sources that are known mm-VLBI objects as well, the median spectral index is $-0.37$. The median absolute deviations are 0.48 and 0.37 respectively.
density on the baselines of VERA. This source is therefore Galactic and its radio structure is resolved, so we excluded it from our final list. We give the name, the 86 GHz flux density interpolated from WMAP measurements, the spectral index calculated from WMAP flux densities, the redshift, and the optical identification of 37 extragalactic objects selected as potential new mm-VLBI targets in Table 1.

VLBI images at lower frequencies (2.3 and 8.4 GHz) were collected from the Very Long Baseline Array (VLBA) calibrator list maintained by the U.S. National Radio Astronomy Observatory (NRAO). Maps were found here for all but one of our 37 sources. However, the missing object, PKS J1332+0200 was imaged with the VLBA at 5 GHz (Fomalont et al., 2000). This proves that our remaining 37 objects are indeed compact extragalactic sources.

For compiling the broad-band radio spectra, our primary source of information was a catalogue made with the Russian RATAN-600 radio telescope (Kovalev et al., 1999). It is based on instantaneous flux density measurements at six different frequencies between 1 and 22 GHz. The effect of time variability is excluded due to the simultaneous measurements. The Kovalev et al. (1999) catalogue contains sources with declination between $-30^\circ < \delta < +43^\circ$. We found complete 6-frequency data for 20 of our sources. Another 6 sources were partially covered in the frequency range. For the remaining sources, we again used the NED to search for 1.4 and 4.8 GHz flux densities from the literature. Fig. 2 and Fig. 3 show broad-band spectra for the 26 sources found in Kovalev et al. (1999), with the WMAP flux densities at 41, 61 and 94 GHz included. The majority of our sources have flat radio spectra over nearly two orders of magnitude in frequency. However, a number of sources can be classified as High-Frequency Peakers (HFP) that show convex spectrum peaking at above $\sim 5$ GHz, and therefore negative spectral index in the WMAP bands (e.g. PMN J0457$-2324$, GB6 J0825+0309, PMN J2000$-1476$, PMN J2131$-1207$; Fig. 2). When imaged with VLBI, these sources are expected to be generally less compact than those with flat spectra in the broadest range of frequencies, but more compact than the Gigahertz-Peaked Spectrum (GPS) sources of which the spectrum peaks at lower frequencies (e.g. Vollmer, 2008).

We also looked for supplementary broad-band radio spectral information in the SPECFIND catalogue (Vollmer, 2010) which was compiled from a large

\[^{3}\text{http://www.vlba.nrao.edu/astro/calib/index.shtml}\]
literature database of non-simultaneous flux density measurements. For the available sources, the broad-band spectral index is also listed in Table 1 for comparison. Note that there is indication of a spectral break in some cases, thus the linear spectral fits are not always the best representations of the broad-band spectrum.

We found indications of variability in several cases, because the low- and high-band measurements were made at different epochs. A simple visual inspection of the spectral shapes in Fig. 2 leads to a conservative estimate that at least \( \sim 25\% \) of our sources are variable on the level of \( \sim 50\% \) or more. Particular examples are PMN J0132−1654, PMN J0137−2430, PMN J0808−0751, PMN J1037−2934, PMN J1337−1257, GB6 J1635+3808, GB6 J1753+2847, and PMN J2229−0832. Both the flat-spectrum and the variability are indicative of the compact radio structure.

3. Perspectives

Using the point source catalogue based on the first 5-year observations of WMAP (Chen & Wright, 2009), we constructed a list of 37 bright extragalactic sources that are well suited for observations at 86 GHz with ground-based VLBI, and at 43 GHz with the second-generation ASTRO-G satellite and its co-observing ground radio telescope network. These sources have never been imaged with VLBI at 86 GHz, and would extend the list of known mm-VLBI sources by almost 25%.

Further improvement is expected from using the point source catalogue of the Planck spacecraft. The European CMB space mission was launched in 2009. Throughout its expected lifetime until 2012, it makes sensitive all-sky measurements at nine different frequencies, from 30 to 857 GHz. The Planck point source catalogue (Vielva et al., 2001) is estimated to have a detection limit of \( \sim 0.4 \) Jy at around 100 GHz, and flux density uncertainties of \( \sim 15\% \). Our method described here could easily be extended to lower flux density levels. Thus the Planck list will be an essential new tool to look for even more potential mm-VLBI target sources, based on their measured flux densities and spectra. The most recent Planck Early Release Compact Source Catalog (Ade et al., in press) already shows promising perspectives for studying the spectral energy distributions of extragalactic radio sources. Technical developments and network extensions, including the addition of the Atacama Large Millimeter and Submillimeter Array (ALMA) for ground-based mm-VLBI observations, will largely increase the detection sensitivity
Table 1: The list of the 37 bright WMAP extragalactic point sources selected as potential new mm-VLBI targets

| WMAP name     | Other name | $S_{86}$ [Jy] | $\alpha_{WMAP}$ | $\alpha_Y$ | $z$ | ID |
|---------------|------------|---------------|-----------------|------------|-----|----|
| J0012−3952    | PMN J0013−3954 | 1.1±0.4 | 0.53 | ... | ... | U  |
| J0132−1653    | PMN J0132−1654 | 1.1±0.4 | 0.37 | −0.22 | 1.02 | Q  |
| J0137−2428    | PMN J0137−2430 | 1.2±0.4 | −0.52 | −0.40 | 0.83 | Q  |
| J0152+2208    | GB6 J0152+2206 | 1.2±0.4 | 0.10 | −0.12 | 1.32 | Q  |
| J0403−3604    | PMN J0403−3605 | 3.3±0.3 | −0.03 | 0.28  | 1.41 | Q  |
| J0428−3757    | PMN J0428−3756 | 1.4±0.4 | 0.29 | 0.10  | 1.11 | Q  |
| J0453−2806    | PMN J0453−2807 | 1.0±0.4 | 0.00 | −0.12 | 2.55 | Q  |
| J0456−2322    | PMN J0457−2324 | 1.8±0.4 | −0.45 | 0.12  | 1.00 | Q  |
| J0757+0957    | GB6 J0757+0956 | 1.4±0.5 | −0.15 | 0.08  | 0.26 | Q  |
| J0808−0750    | PMN J0808−0751 | 1.1±0.4 | 0.11 | −0.31 | 1.83 | Q  |
| J0825+0311    | GB6 J0825+0309 | 1.2±0.5 | −0.34 | 0.14  | 0.50 | Q  |
| J0840+1312    | GB6 J0840+1312 | 1.1±0.5 | −0.54 | −0.75 | 0.68 | Q  |
| J0914+0248    | GB6 J0914+0245 | 1.1±0.5 | 0.25 | −0.04 | 0.42 | G  |
| J1037−2934    | PMN J1037−2934 | 1.9±0.4 | 0.43 | 0.19  | 0.31 | Q  |
| J1127−1858    | PMN J1127−1857 | 1.2±0.4 | 0.11 | 0.21  | 1.05 | Q  |
| J1219+0549    | 1Jy J1216+06 | 1.3±0.4 | −0.54 | ...   | 0.01 | G  |
| J1222+0414    | GB6 J1222+0413 | 1.0±0.4 | 0.01 | −0.06 | 0.96 | Q  |
| J1246−2547    | PMN J1246−2547 | 1.2±0.4 | −0.45 | 0.04  | 0.63 | Q  |
| J1258−3158    | PMN J1257−3154 | 1.2±0.4 | 0.13 | 0.03  | 1.92 | Q  |
| J1316−3337    | PMN J1316−3339 | 1.4±0.4 | −0.30 | −0.07 | 1.21 | Q  |
| J1332+0200    | GB6 J1332+0200 | 1.2±0.4 | 0.35 | −0.41 | 0.21 | G  |
| J1337−1257    | PMN J1337−1257 | 4.8±0.5 | −0.29 | −0.18 | 0.53 | Q  |
| J1356+1919    | GB6 J1357+1919 | 1.1±0.4 | −0.20 | −0.53 | 0.72 | Q  |
| J1512−0904    | 1Jy 1510−08 | 1.7±0.4 | −0.13 | −0.19 | 0.36 | Q  |
| J1516+0014    | GB6 J1516+0015 | 1.0±0.4 | −0.12 | −0.56 | 0.05 | G  |
| J1517−2421    | PMN J1517−2422 | 1.8±0.5 | −0.18 | 0.05  | 0.04 | G  |
| J1635+3807    | GB6 J1635+3808 | 3.4±0.4 | −0.03 | −0.01 | 1.81 | Q  |
| J1734+3857    | GB6 J1734+3857 | 1.0±0.4 | −0.11 | 0.27  | 0.97 | Q  |
| J1753+2848    | GB6 J1753+2847 | 1.1±0.4 | −0.07 | 0.08  | 1.11 | U  |
| J1849+6705    | GB6 J1849+6705 | 1.5±0.3 | 0.08 | −0.20 | 0.65 | Q  |
| J1923−2105    | PMN J1923−2104 | 2.2±0.5 | −0.10 | ...   | 0.87 | Q  |
| J1958−3845    | PMN J1957−3845 | 1.7±0.5 | −0.76 | 0.20  | 0.63 | Q  |
| J2000−1749    | PMN J2000−1748 | 1.4±0.4 | −0.09 | 0.42  | 0.65 | Q  |
| J2005+7755    | 1Jy 2007+77 | 1.1±0.4 | 0.41 | 0.30  | 0.34 | Q  |
| J2131−1207    | PMN J2131−1207 | 1.4±0.4 | −0.62 | 0.09  | 0.50 | Q  |
| J2229−0833    | PMN J2229−0832 | 1.7±0.5 | −0.26 | 0.14  | 1.55 | Q  |
| J2354+4550    | GB6 J2354+4553 | 9.3±0.4 | 0.32 | −0.25 | 1.99 | Q  |

Notes: Col. 1 – WMAP source name; Col. 2 – Other name; Col. 3 – estimated 86-GHz flux density (Jy); Col. 4 – spectral index calculated from WMAP flux densities [Chen & Wright, 2009]; Col. 5 – spectral index from the [Vollmer, 2010] catalogue; Col. 6 – redshift from NED; Col. 7 – optical identification from NED (Q=quasar, G=galaxy, U=unclassified)
Figure 2: Radio spectrum of the sources, including the 6-frequency data from the Kovalev et al. (1999) catalogue (diamonds), and the WMAP flux densities at 41, 61 and 94 GHz (triangles).
Figure 2: – Continued
Figure 2: – Continued
in the near future. Regular global VLBI imaging at an even higher frequency, 230 GHz, will soon be established (e.g. Krichbaum et al., 2008).

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Figure 3: Radio spectrum of the sources based on the WMAP catalogue (triangles) and the 1.4 and 4.8 GHz data collected from NED (diamonds)
Figure 3: – Continued

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