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3 mm GMVA Observations of Total and Polarized Emission from Blazar and Radio Galaxy Core Regions

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Abstract: We present total and linearly polarized 3 mm Global mm-VLBI Array (GMVA; mm-VLBI: Very Long Baseline Interferometry observations at millimetre wavelengths) images of a sample of blazars and radio galaxies from the VLBA-BU-BLAZAR 7 mm monitoring program designed to probe the innermost regions of active galactic nuclei (AGN) jets and locate the sites of gamma-ray emission observed by the Fermi-LAT. The lower opacity at 3 mm and improved angular resolution—on the order of 50 microarcseconds—allow us to distinguish features in the jet not visible in the 7 mm VLBA data. We also compare two different methods used for the calibration of instrumental polarisation and we analyze the resulting images for some of the sources in the sample.

Keywords: galaxies: active; galaxies: jets; techniques: high angular resolution

1. Introduction

Combining long baselines and short observing wavelength, Very Long Baseline Interferometry observations at millimetre wavelengths (mm-VLBI) provide very high spatial resolution images. Moreover, the reduced opacity at 3 mm allows us to investigate regions that are optically thick at longer wavelengths, such as the jet formation regions in the vicinity of supermassive black holes. How jets are formed, accelerated, and collimated in such regions is still under debate, and high-resolution polarized images are the key to investigating the energy budget and magnetic field structure that, according to theoretical models (e.g., [1]), should play a major role in these processes.

The Global mm-VLBI Array (GMVA), observing at 3 mm (86 GHz), is currently the main source of high-resolution total and polarized intensity images of active galactic nuclei (AGN) at short millimeter wavelengths. The other way to reach very high resolutions—but at lower frequencies—is to observe with the space VLBI technique, which has provided the highest angular resolution (∼21 µas) achieved to-date [2]. In the near future, VLBI imaging at 1.3 mm will provide an even higher resolution than that which is currently possible with the GMVA.

The GMVA consists of 14 antennas located in Europe, corresponding to Effelsberg (EF), Onsala (ON), Pico Veleta (PV), Plateau de Bure (PdB), Metsähovi (MH) and Yebes (YS), and in the

United States, including the Green Bank Telescope (GBT) and the eight VLBA stations equipped with 3 mm receivers (BR, NL, PT, LA, FD, KP, OV, MK). Korean stations (KT, KU and KY) have also recently joined some GMVA sessions.

Here we present some 86 GHz GMVA images in both total and linearly polarized intensity of a sample of bright and gamma-ray loud blazars taken on 21 May 2016 within a program (PI: A. Marscher) in support of the VLBA-BU-BLAZAR [1] monitoring project; where the latter consists of monthly observations of 37 blazars and radio galaxies with the VLBA at 7 mm (43 GHz). The GMVA program was started in 2008, consists of one or two observations per year of roughly half of the AGN in the VLBA-BU-BLAZAR sample, and is aimed at relating the gamma-ray emission observed in these objects to physical conditions and structure in the mm-wave core region. Information about the program as well as some preliminary results can be found at http://www.bu.edu/blazars/vlbi3mm/, as well as in [3,4].

2. GMVA Observation and Data Reduction

The antennas participating in our observations during the GMVA session of May 2016 were the VLBA stations plus Effelsberg, Onsala, Yebes, Metsähovi, and the KVN array, although it was not possible to recover fringes from Metsähovi. All antennas recorded the data at a rate of 2 Gbps (512 MHz bandwidth) in dual-polarization mode (i.e., right and left circular polarization, RCP and LCP, respectively), apart from Yebes that only observed in LCP; the data were divided into eight 32 MHz sub-bands (IFs) per polarization during the correlation process.

The observed sources, for which the calibration and imaging of both total and linearly polarized intensity have been performed, are: 3C 111, 3C 120, 0716+714, OJ 287, 0954+658, 3C 273, 1510-089, 1633+382, 3C 345, BL Lac, CTA 102, and 3C 454.3.

Data were fringe-fitted and calibrated using the common procedure for high-frequency VLBI data reduction in the Astronomical Image Processing System (`AIPS`) (e.g., [5]), with the main difference of using the manual phase-calibration approach instead of the so-called phase-cal injection tones for the correction of delays and phases of the subbands as described in [6]. The phase calibration is the trickiest part, and we found that remaining delays or phase-offset between IFs can easily reduce the coherence of the signal. Phase instabilities mainly come from instrumental and atmospheric effects; at 86 GHz, the troposphere has a very short expected coherence time ($\sim$10–20 s). In addition and mainly due to the changing weather conditions, the accuracy of the amplitude calibration is more limited at mm- than at cm-wavelength.

After the calibration of the right–left phase difference in `AIPS`, we have to correct for the instrumental polarization and calibrate the absolute orientation of the polarization electric vector position angles (EVPAs). The calibration of EVPAs requires the comparison between integrated GMVA EVPA measurements and single-dish EVPA values at the same observing frequency and at nearby epochs. Hence, for the calibration of polarization vectors we used the information contained in 3 mm polarimetric measurements from the POLAMI program [2], with uncertainties in the EVPAs $\leq 5^{\circ}$ [8]. For the calibration of instrumental polarization instead, we tested two different approaches and finally used the most reliable one as we describe in Section 3.

Comparison of Total Flux Densities

In order to check the reliability of the results obtained and in particular of the amplitude calibration, we compare the obtained total flux densities of each source with single dish data of nearby epochs collected from the POLAMI program at the IRAM 30m Telescope (in Granada, Spain), at 3mm, and from the Sub-millimeter Array (SMA) [3], at 1mm. The fluxes from the three programs are reported in

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1 http://www.bu.edu/blazars/VLBAproject.html
2 see [7] and http://polami.iaa.es
3 http://sma1.sma.hawaii.edu/callist/callist.html

Table 1, where we notice that the flux density values are in fairly close agreement between each other only for sources like 0716+714, 0954+658, 1510-089, and 1633+382, that are core-dominated blazars [9]. For the other more extended sources, discrepancies between the GMVA and single dish values are present. These are in part expected because of the weaker extended jets contributing more in single dish data, but we cannot discard a lowering of the flux in GMVA data with low signal-to-noise ratio. That could be the case for weak sources like BL Lac, which in this observation was barely detected.

Table 1. This table reports the names of sources and total flux densities in mJy obtained for Global mm-VLBI Array (GMVA) data on 21 May 2016 and single dish data from the POLAMI (3 mm) and Sub-millimeter Array (SMA) (1 mm) programs. The POLAMI observing epochs are 14 May (first row) and 14 June 2016 (second row), while the SMA epochs are variable but all separated by ∼15 days from the GMVA epoch, apart from 3C 273, 3C 454.3, and 0716+714, where the separation is less than 5 days. For GMVA data we estimate errors to be roughly 10% of the flux, as reported in [3].

Name	GMVA	POLAMI	SMA
3C 111	599 ± 60	1523 ± 84 1293 ± 57	991 ± 53
3C 120	726 ± 30	2627 ± 104 2137 ± 97	1970 ± 102
3C 273	7563 ± 760	–	10,815 ± 541
3C 345	1582 ± 160	2300 ± 94 2994±115	1689 ± 91
3C 454.3	4178 ± 400	9814 ± 1509 12,070 ± 462	10,100 ± 160
0716+714	2455 ± 250	2076 ± 85 2506 ± 102	2132 ± 107
0954+658	572 ± 60	–	786 ± 40
1510-089	2418 ± 240	–	2664 ± 139
1633+382	1027 ± 100	1362 ± 59 1977 ± 79	–
BL Lac	630 ± 60	1952 ± 75 1683 ± 60	–
CTA 102	2736 ± 280	4815 ± 182 4723 ± 180	4429 ± 222
OJ 287	1767 ± 170	–	2932 ± 159

3. Linear Polarization at 86 GHz: Instrumental Polarization Calibration

The instrumental polarization—or "*D*-terms"—were determined using the method of [10]. The *D*-terms are expected to depend only on the receiver characteristics of each telescope and to change slowly with time. Hence, all the sources observed must possess the same *D*-terms, although the accuracy of the measurements depend mostly on the actual parallactic angle coverage, and in part also on the complexity of the polarized source substructure. Considering this, one possible approach for the calibration of the instrumental polarization is to apply to each source a set of *D*-terms that come from the average of the values obtained for all sources after removing outliers (e.g., [11]). In Figure 1 we report the *D*-term amplitudes and phases of the RCP and LCP feed for all the sources in the sample. The average *D*-terms obtained are represented by black diamonds.

In the second approach tested, we imaged each source using the *D*-term obtained from its own data. Both methods have been tested previously in similar GMVA observations in [6], where the authors claim that no differences were observed between the two methods.

We tested both methods on OJ 287, which presents the best parallactic angle coverage (between 100° and 120° for most of the antennas) and has a simple and compact polarized structure, and in two other less favourable sources: 1510-089 and CTA 102.

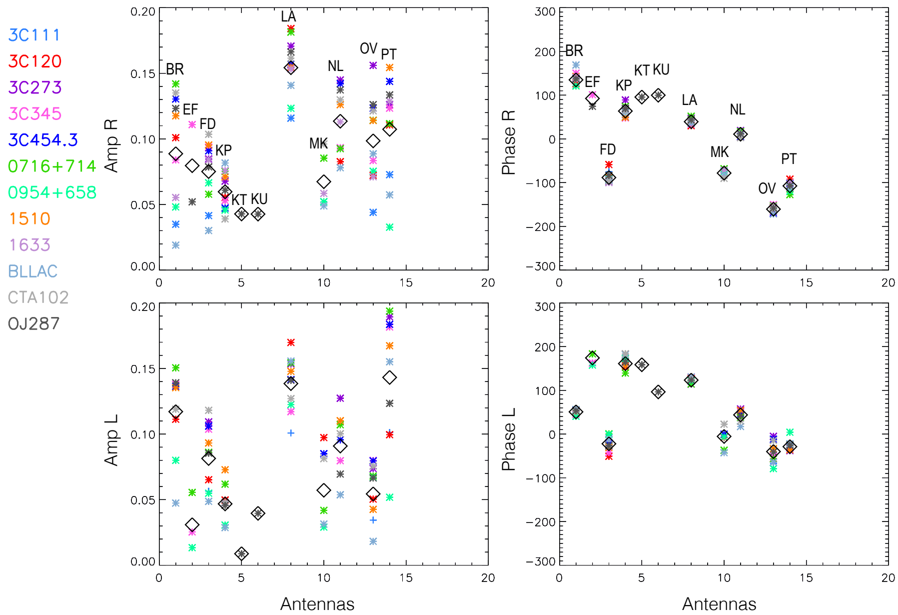

Figure 1. The right and left amplitudes and phases of the *D*-terms for all the sources in different colours. The codes of antennas (see text) are also reported inside the two upper plots. Black diamonds mark the average *D*-term values obtained for each antenna, considering the values of the remaining sources after removing outliers (not displayed in the figure).

4. Results

From the comparison of the linearly polarized images obtained applying the two methods for the calibration of the instrumental polarization, we observe that, in general, the images obtained present some differences. In particular, we found that only in the case of OJ 287 (best case) is the morphology of the polarized flux similar in both images, as can be seen in Figure 2. On the other hand, for the other two sources (1510-089 and CTA 102), the morphology of the polarized flux changes substantially between the two images, and the peak of the linearly polarized flux shifted to a different position when we applied their own *D*-terms (Figure 2, upper panels). Moreover, we notice that for all three sources, the polarized flux decreased when we applied their own *D*-terms.

Since many sources from the sample have a parallactic angle coverage comparable to those of 1510-089 and CTA 102 (less than 100° for most of the antennas), and certainly worse than that of OJ 287, plus some sources also have more complex polarized substructures, we decided to calibrate the instrumental polarization using the average *D*-terms. This approach has the significant advantage of obtaining the final *D*-term values to apply by taking into account a large number of source measurements and not only one. This is of particular importance for a mm-VLBI dataset, where the choice of a calibrator for the polarization is not trivial and also depends on the quality of data.

Some of the final linearly polarized (in colors) and total intensity (in contours) GMVA images are shown in Figure 3, where the absolute calibration of EVPAs has also been applied. The rms reached in all the total intensity images was ∼1–3 mJy/beam and in polarized images was ∼4–7 mJy/beam. The median value of the beam considering all images was ∼0.2 × 0.06 mas.

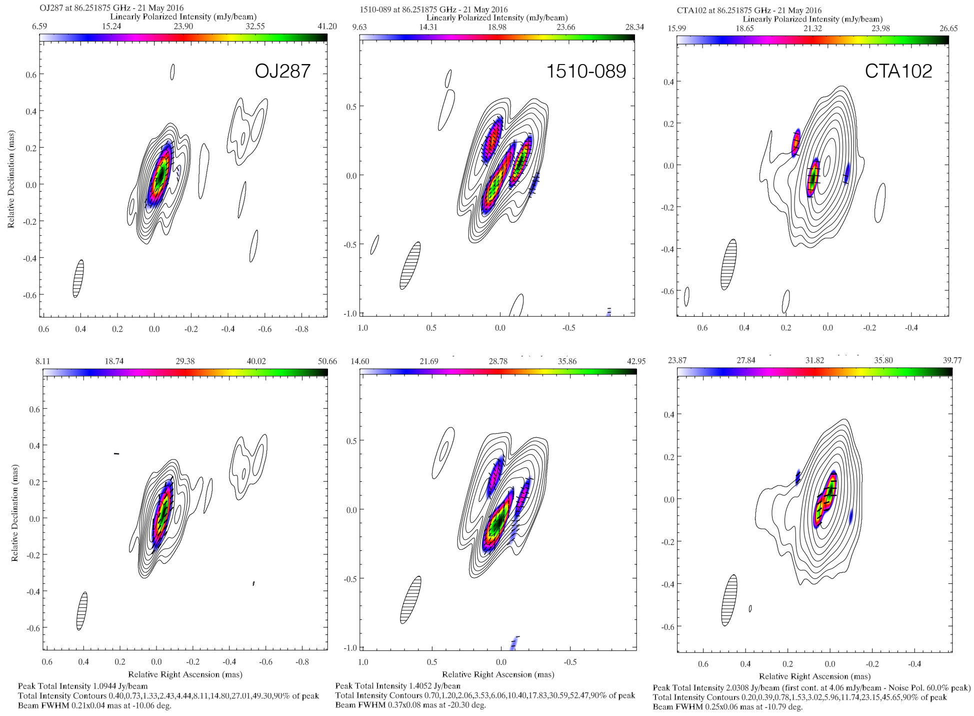

Figure 2. This figure shows 3 mm GMVA images in total (contours) and linearly polarized (colours) intensity of OJ 287, 1510-089, and CTA 102 taken on 21 May 2016. Black sticks represent the electric vector position angles. The upper panels are the resulting images after applying to the sources their own *D*-terms, while in the lower panel we applied the average *D*-terms to all the sources.

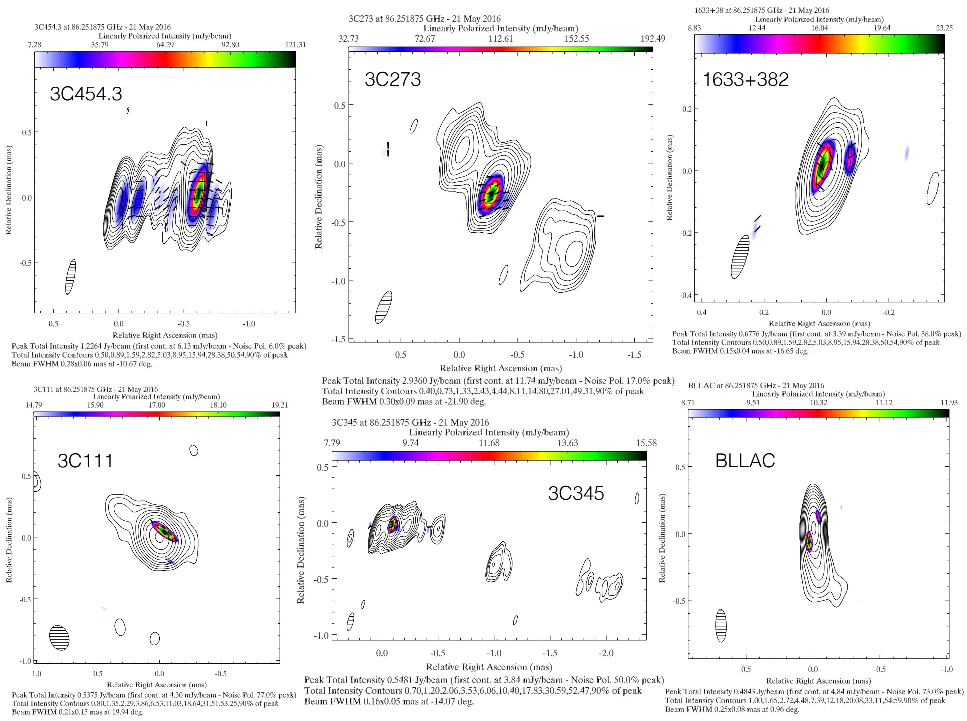

Figure 3. This figure shows 3 mm GMVA images of the quasars 3C 454.3, 3C 273, 1633+382, 3C 345, the radio galaxy 3C 111, and BL Lac. Colours, contours, and black sticks represent the same as in Figure 2.

The high resolution reached with these mm-VLBI observations allows us to distinguish features not visible in 43 GHz VLBA observations (e.g., the polarized features at ∼0.1 mas from the core in 3C 454.3 and 3C 345). These features become apparent when we compare the GMVA data presented here with data from the VLBA-BU-BLAZAR program of a nearby epoch (10 June 2016), available at the program's webpage. A possible complex structure of the 3C 454.3 core was discussed in [12] using super-resolved images at 7 mm. Another quite noticeable result from the GMVA observations is seen in the image of the quasar 1510-089, where at 86 GHz we see an unusual feature on the eastern side of the source, here distinguishable in both total and linearly polarized intensity maps but visible only in the polarized flux in the 43 GHz VLBA data.

Moreover, a comparison between the fractional polarization in GMVA and 43 GHz VLBA data reveals slightly higher values in GMVA data (between 2% and 9%) than in 43 GHz VLBA data (between 1% and 6%), as expected because of lower beam depolarization at shorter wavelength.

5. Conclusions

We have presented the most complete sample so far of 3 mm GMVA polarized images of AGN jets. We showed that 3 mm GMVA observations are a powerful tool to investigate the central regions of distant blazars and radio galaxies, thanks to the reduced opacity at 3 mm and the improved angular resolution that allow us to distinguish features not visible in 43 GHz VLBA observations (e.g., 3C 454.3, 3C345, and 1510-089).

From the comparison of two different methods for the calibration of the instrumental polarization, we tested that the *D*-terms of a source are well-defined only in the case of good coverage of the parallactic angle, as expected. Moreover, we found that a poor parallactic angle coverage can lead to changes in the source polarized structure and intensity.

The use of average *D*-terms instead of the *D*-terms proper of the source itself for the calibration of instrumental polarization turns out to be a more stable method, also producing more reliable polarized intensity images.

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Author Contributions: C.C. performed the calibration and analysis of GMVA data. A.P.M is the P.I. of the GMVA experiment and, together with S.G.J., they provided the 43 GHz VLBA data-set. T.P.K. contributed to the scientific discussion and data calibration. J.L.G. contributed to the D-term analysis. I.A. provided POLAMI data. U.B., J-Y.K. and J.A.H contributed to the observation and data calibration. A.J.Z. contributed to the scientific discussion. C.C. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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