Space VLBI Polarization Observations

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Abstract. Space VLBI polarization (VLBP) observations can potentially provide a wealth of clues about the radio jets in Active Galactic Nuclei and the environment through which they propagate. Technical difficulties associated with such observations are reviewed. Possible tactics for calibration of space VLBP data are presented, and pre-launch ground preparations—underway, planned, and hoped-for—are discussed.

1. Can We Really Expect to Detect Polarization in Space VLBI Experiments?

It is natural to ask whether there exist sources which have compact components which are highly enough polarized that we would expect to be able to detect them on space-earth baselines using the *Radio Astron* or VSOP antennas. Fortunately, this question can be addressed straightforwardly using the results of some ten years of ground-based VLBP observations. Table 1 gives a list of 11 compact extragalactic radio sources which have been found to have components with >25 mJy (roughly the expected detection limit for *Radio Astron* on baselines to large ground antennas) of polarized flux which are essentially unresolved on ground-ground baselines. As can be seen, of the total of 15 entries in Table 1, all but two are actually greater than 45 mJy (roughly the expected detection limit for VSOP on baselines to large ground antennas). Roughly half of the bright (>1 Jy) BL Lacertae objects observed so far have contained components with polarized flux sufficient for inclusion in Table 1.

Table 1.

Source	Correlated polarized flux on long earth baselines (mJy)	Source	Correlated polarized flux on long earth baselines (mJy)
0235+164	115	1803+784	58
0300+470	53	1823+568	37
0735+178	55	2007+777	80
OJ287	100, 180	BL Lac	115, 138
0954+658	45, 120	3C279	190, 150
3C345	170		

References: ROBERTS *et al.*, 1987; GABUZDA *et al.*, 1989a, 1989b, 1992.

With continued ground VLBP observations, we can expect to uncover of order 20–30 good candidate sources for space VLBP observations by the launch times of VSOP and *Radio Astron* in the middle 1990's.

2. Calibration for Space VLBI Polarization Experiments

Suppose we have a VLBI experiment in which all antennas record simultaneously both the right- and left-circularly-polarized (RCP and LCP) signal incident from a compact radio source. Information about the distribution of the total intensity and circularly polarized emission (which is usually considered to be negligible for synchrotron radiation) may be derived from the $R \otimes R$ and $L \otimes L$ ("parallel-hand") correlations. Information about the distribution of linearly polarized emission may be derived from the $R \otimes L$ and $L \otimes R$ ("cross-hand") correlations. If the RCP and LCP signals recorded at each antenna are expressed as follows:

$$v_L = G_L\left[E_L e^{+i\phi_p} + D_L E_R e^{-i\phi_p}\right]$$

$$v_R = G_R\left[E_R e^{-i\phi_p} + D_R E_L e^{+i\phi_p}\right]$$

where D_L and D_R are instrumental polarizations and ϕ_p is the parallactic angle, then the $L \otimes L$ and $R \otimes L$ correlations between two antennas may be written:

$$L_1 \otimes L_2 = G_{L1} G_{L2}^* E_{L1} E_{L2}^* e^{+i\left(\phi_{p1} - \phi_{p2}\right)}$$

$$R_1 \otimes L_2 = G_{R1} G_{L2}^* \left[E_{R1} E_{L2}^* e^{-i\left(\phi_{p1} + \phi_{p2}\right)} + D_{L2}^* E_{R1} E_{R2}^* e^{-i\left(\phi_{p1} - \phi_{p2}\right)} + D_{R1} E_{L1} E_{L2}^* e^{+i\left(\phi_{p1} - \phi_{p2}\right)} \right]$$

where * indicates complex conjugation and the numerical subscripts refer to antennas 1 and 2. The time average involved in the correlation is implicit in these expressions, and second order and higher terms in the D's, source polarization terms ($E_R E_L$* or $E_L E_R$*), or any combination have been neglected. The complex antenna gains G may be determined through the hybrid mapping process, and the parallactic angles ϕ_p are known. In the expression for the $R \otimes L$ correlation, $E_{R1} E_{L2}$* represents the source term we desire; the other terms are instrumental polarization terms, which are typically comparable to or larger than the source term, and must be determined and removed before any information about the source polarization can be obtained.

For ground VLBP experiments, calibration has usually been done using ratios of corresponding cross- and parallel-hand correlations for a source whose polarization is zero (see also ROBERTS *et al.*, 1994; COTTON, 1994):

$$\frac{R_1 \otimes L_2}{L_1 \otimes L_2} = \frac{G_{R1}}{G_{L1}}\left[\frac{E_{R1}E_{L2}^*}{E_{L1}E_{L2}^*}e^{-2i\phi_{p1}} + D_{L2}^* e^{-2i(\phi_{p1}-\phi_{p2})} + D_{R1}\right]$$
$$\sim D_{L2}^* e^{-2i(\phi_{p1}-\phi_{p2})} + D_{R1}.$$

As can be seen, one D rotates as twice the difference in ϕ_p between the two antennas, while the other is fixed. Thus, estimates for both D's may be obtained by obtaining data for the given baseline over a wide range of parallactic angles and fitting for the two D's (Method "A"); this may be done for each baseline and cross-hand correlation in a given experiment. This method typically renders good estimates for many, but not all of the D terms. Alternatively, if one D in this expression is known, the other may simply be solved for (Method "B"). Therefore, in practice what is usually done is to obtain as many good estimates as possible from method A, then use these values to obtain estimates for the remaining D's using method B. In principle, method B only requires 1 or 2 good calibration observations to render accurate estimates for the D's in question.

One obvious approach to polarization calibration for space VLBI data is to use methods A and B on all ground-ground baselines to determine all instrumental polarization D terms for all ground radio telescopes, just as would be done for a "normal" ground VLBP run. Then, once the ground D's are known, method B can be used on baselines between the spacecraft antenna and ground telescopes to obtain estimates for the spacecraft antenna D. Each space-ground baseline will give an independent estimate for the spacecraft D. This approach does not require a large number of spacecraft calibration observations taken over a range of parallactic angles, but rather simply 1 or 2 calibration observations, say, at the beginning and end of the set of observations on the target sources.

Another interesting possibility is to make observations of the polarization calibrator source with the space-ground VLB array while rotating the spacecraft antenna about its pointing axis. This effectively provides data over a large range of spacecraft orientation angles (the spacecraft equivalent to the parallactic angle) in a relatively small amount of time. The feasibility of this scheme will depend on the range of orientation angles that are accessible given other spacecraft constraints, as well as the time over which these calibration observations could be made.

Thus far we have been talking in terms of antennas which can simultaneously record both RCP and LCP, as will be the case for *Radio Astron*. We should point out that although the VSOP antenna will only record one circular polarization, this does not imply that VSOP will not be able to do space VLBP observations. The only effect of this limitation is that the uv coverage obtained on space-ground baselines will not be symmetrical. The reason for this is that the relationship between measured cross-hand (u, v) points and the conjugate points at $(-u, -v)$ is:

$$R_1 \otimes L_2(-u,-v) = \left[L_1 \otimes R_2(u,v)\right]^*. \qquad (1)$$

Thus, the cross-hand *uv* coverage is symmetric only when both $R \otimes L$ and $L \otimes R$ correlations are always present, and this will not be the case if one or more antennas only records one circular polarization. In this case, fewer visibility points will be available for construction of the polarization map, but useful polarization information is still obtained. In fact, the earliest ground VLBP experiments used four antennas, only two of which recorded both RCP and LCP, and these data have yielded a number of interesting scientific results (WARDLE *et al.*, 1986; ROBERTS *et al.*, 1987; GABUZDA *et al.*, 1989b).

3. Current and Future Preparations for Space VLBP Observations

Work currently being done as preparation for the possibility of making space VLBP observations falls into several categories:

• *The development of calibration techniques, such as those described above*

In addition, we are attempting to identify possible complications over ground based VLBP—increased likelihood of time dependence for the spacecraft instrumental polarization term, e.g.—so that techniques can be developed to effectively do the polarization calibration despite these complications.

• *The identification of candidate sources*

Gabuzda and Cawthorne have recently completed $\lambda = 6$ cm ground VLBP observations of a complete sample of northern BL Lacertae objects (KÜHR and SCHMIDT, 1990). We expect results from these observations to roughly double the number of space VLBP candidates. In addition, ground VLBP observations are being pushed toward higher frequency, which will provide a means of searching for the most compact polarized VLBI components.

• *Polarization structure simulations for Radio Astron*

We have been adapting the Calgary User Assistance Software and the Brandeis VLBI Package to handle space VLBP data, and then using these programs to create simulated *Radio Astron* space VLBP data and to image these data. Such studies are very useful for investigating the extent to which various sources of error corrupt the fidelity of the total intensity and polarization images produced.

Work still to be done includes:

• *Further imaging simulation studies for both Radio Astron and VSOP*

Such studies will enable us to investigate the effects of residual instrumental polarization, asymmetric *uv* coverage, amplitude calibration errors, etc. on the fidelity of the I and P images produced.

• *Calibration simulation studies*

We will simulate space VLBP data including the contribution of instrumental polarization terms, and then attempt to do the polarization calibration for these data. We intend to do this via blind tests, to minimize the bias of the person attempting the calibration. These studies will be very helpful in testing various calibration strategies and identifying which are most effective.

• *Continued ground observations, especially at higher frequency*

• *Determination of instrumental polarizations for additional ground stations*

A number of antennas which may be used in space VLBI observations have never been used in ground VLBP experiments (Algonquin, Arecibo, most Southern hemisphere antennas, e.g.). To maximize the effectiveness of space VLBP experiments, it is necessary to determine the polarization performance of these antennas before they are used in space VLBP experiments.

- *Ground testing to estimate the Radio Astron and VSOP instrumental polarizations*

Both laboratory testing and testing through actual ground interferometric observations are useful for these estimations. Testing should be done as soon as possible, so that results can be used to argue for reduced spacecraft D terms if needed.

4. Conclusions

It is clear that ground-based VLBP observations are yielding a wealth of information about the compact radio structure of Active Galactic Nuclei. Such observations have been underway for some 10 years, and our experience with these ground observations is of great help in investigating the exciting possibility of making space VLBP observations. We are able to identify ~11 good candidate sources for such observations, and expect that further ground VLBP observations will reveal a total of ~20–30 by the time *Radio Astron* and VSOP are observing. We believe we have a good understanding of how to do the polarization calibration for space VLBP observations, and will be doing simulations to test possible strategies. Ongoing polarization imaging simulations will also be very useful in giving us a better idea what we can expect from space VLBP data. We have no doubt that these preparations will prove worthwhile; even if the number of data provided by space VLBP observations are limited, they will likely offer very valuable insights into the sub-miliarcsecond radio emission in AGN.

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