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HIGH ACCURACY ($\ll$ 1%) POLARISATION MEASUREMENTS WITH THE WSRT

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ABSTRACT The procedure for polarisation measurements with radio synthesis telescopes is fraught with uncertaincies and shaky assumptions. Therefore, their accuracy will be limited to a few percent at best. It is investigated here whether it will be possible to improve this accuracy by a factor 10-100 with the WSRT, which has excellent polarisation characteristics, very small closure errors, and redundant spacings. The latter can be used to calibrate the instrument in a way which is less dependent upon assumptions about the polarisation of the calibrator source. They also cause more reliable convergence of the SELFCAL model, by reducing the number of free parameters. Although the investigation is not yet finished, the tentative conclusion is that it may be possible, with crossed dipoles, to derive completely model-independent values for Q/I, U/I and V/I.

INTRODUCTION

The accuracy of polarisation measurements with radio synthesis telescopes is limited to about a percent. For linear polarisation observations this is usually sufficient, but circular polarisation requires an accuracy that is 10-100 times better. The same accuracy would be desirable for monitoring the short-term polarisation variability that has recently been discovered in certain galaxies.

The Westerbork Synthesis Radio Telescope (WSRT) may be the most suitable instrument to achieve increased polarisation accuracy, for the following reasons: 1. The telescopes have very little instrumental polarisation because the feeds are axi-symmetric. 2. The sky does not rotate with respect to the telescopes, because of the equatorial mounts. 3. Model-independent internal calibration is possible with the help of redundant baselines. 4. The closure errors are very small (typically 0.01%).

Unfortunately, this conference has come too early for the presentation of wonderful results, but some progress has been made: it turns out to be possible to eliminate the socalled "offset- difference" problems by using redundant spacing calibration. But the solution is degraded by the interaction of the 4

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different types of dipole errors (phase, gain, dipole angle and ellipticity) with each other. This is a serious problem, which may or may not be fundamental.

BACKGROUND

Some formulas

Each of the 14 WSRT telescopes has two perpendicular dipoles, X and Y, which can be rotated as a unit. Usually the units in different telescopes are parallel (++), but it is also possible to rotate the dipole unit over an arbitrary angle. If the unit of a telescope are rotated over 45 degr, we talk of "crossed" (+×) dipoles. The correlation product M_{12} between two dipoles with posi- tion angles ϕ_1 and ϕ_2 can be written as (see Weiler, 1973):

$$\begin{aligned} M_{12} = 0.5\, G_{12}\, (& I\, [cos(\phi_1 - \phi_2) - A_{12}\, sin(\phi_1 - \phi_2)] \\ & + Q\, [cos(\phi_1 + \phi_2) - B_{12}\, sin(\phi_1 + \phi_2)] \\ & + U\, [sin(\phi_1 + \phi_2) + B_{12}\, cos(\phi_1 + \phi_2)] \\ & - i\, V\, [sin(\phi_1 - \phi_2) + A_{12}\, sin(\phi_1 - \phi_2)]\,) \end{aligned} \quad (1)$$

in which the G , A and B factors contain the four different kind of dipole errors: phase(p), gain($q = \log(g)$), dipole angle error (δ) and ellipticity(θ):

$$A_{12} = (\delta_1 - \delta_2) - i\,(\theta_1 + \theta_2) \quad (2)$$

$$B_{12} = (\delta_1 + \delta_2) - i\,(\theta_1 - \theta_2) \quad (3)$$

$$G_{12} = (1 + q_1 + q_2) - i\,(p_1 - p_2) \quad (4)$$

Note that the real (q, δ) and imaginary (p, θ) dipole errors appear in the equations with opposite sign (at least in the A-factors, which dominate because of their association with I), so that they can be distinguished from each other in principle. The Stokes parameters (I,Q,U,V) are calculated with the help of the 4 possible combinations between the X and Y dipoles of two telescopes. For parallel dipoles (++), the equations reduce to a particularly simple form:

$$M_{xx} = 0.5\, G_{xx}\, (I - Q) \quad (5)$$

$$M_{yy} = 0.5\, G_{yy}\, (I + Q) \quad (6)$$

$$M_{xy} = 0.5\, G_{xy}\, (-U - iV - A_{xy}\, I) \quad (7)$$

$$M_{yx} = 0.5\, G_{yx}\, (-U - iV - A_{yx}\, I) \quad (8)$$

Of course the formulas for left (L) and right (R) circularly polarised dipoles, like the VLA has, look very similar (see Thompson et al, 1986) and lead to simular conclusions.

Current calibration strategy

In all but exceptional cases, the dipoles will be parallel (++). The usual calibration strategy consists of the following steps:

[1] The dipole gain and phase errors are determined with the help of a "known" calibrator, using equation (5) for the X- dipoles, and (6) for the Y-dipoles. Any inaccuracy in the assumed value for Q will be interpreted as a gain error.
[2] The dipole angle errors and ellipticities are determined, using equations (7) and (8). Note that they will be inaccurate by the value of the "phase-offset difference (POD)" between the X and Y dipoles, which has not been measured in step [1].
[3] The POD is determined with the help of a calibrator with strong U. It is assumed that A_{xy} and A_{yx} are negligible in this stage, and that $V = 0$. If this assumption is incorrect, this will translate into a spurious V in later observations.
[4] Finally, the estimated dipole error values are assumed to be **stable** during the observations, which may take several hours. Instrumental effects like δ and θ will usually be stable to 0.01%, and dipole gains and the POD to 0.1%, but the dipole phases will vary by a few percent at least, due to the atmosphere. At the lower frequencies, there will also be ionospheric Faraday rotation.

Thus, even if the polarisation of the calibrators were known to high accuracy, the dipole errors could be determined with confidence, but the error variability would still be the limiting factor. A possible solution may be the use of SELFCAL, which implies continuous calibration during the observations. But the he introduction of more source parameters (polarisation) into a SELFCAL model may not be helpful for convergence to the correct result.

THE USE OF REDUNDANT BASELINES

Redundancy calibration (see Noordam & De Bruyn, 1982) is a way to estimate the four types of dipole errors **without** the help of a tentative SELFCAL model of the observed object. The method is based on the observation that, if two interferometers have the same baseline length and orientation, and look at the same object with the same beam, bandpass and dipole position angles, their measured outputs should be identical if there are no instrumental errors. If there is sufficient redundancy in the array, it is possible to find a solution for dipole errors of the various telescopes relative to each other. But since it is a comparative method, absolute offsets of gain and ellipticity, and absolute gradients over the array for the phase and the dipole angle have to be determined in some other way, e.g. with the help of a known calibrator or a SELFCAL model.

For parallel dipoles (++), the redundancy solutions for the X- dipoles and the Y-dipoles are independent, which means that they have different unknown absolute offsets (see fig 1a). Since these include the unknown phase offset difference (POD) and the gain offset difference mentioned before, the calibration accuracy will still be limited by our uncertainty about the polarisation characteristics of calibrator sources. But at least the use of redundancy will reduce the variation during the observations of the absolute error values by a factor $\sqrt{14}$, and any SELFCAL models will have less freedom

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to converge to the wrong result, because of the reduced number of free parameters.

Further improvement may be achieved by rotating the dipole-units of some of the telescopes by 45 degr. Although the individual interferometers will no longer be redundant, the Stokes parameters (I,Q,U,V) measured by equal baselines must be equal. It turns out that for "crossed" dipoles (+×) there is a single combined solution for the X- and Y-dipoles, thus eliminating the troublesome offset- differences (see fig 1b).

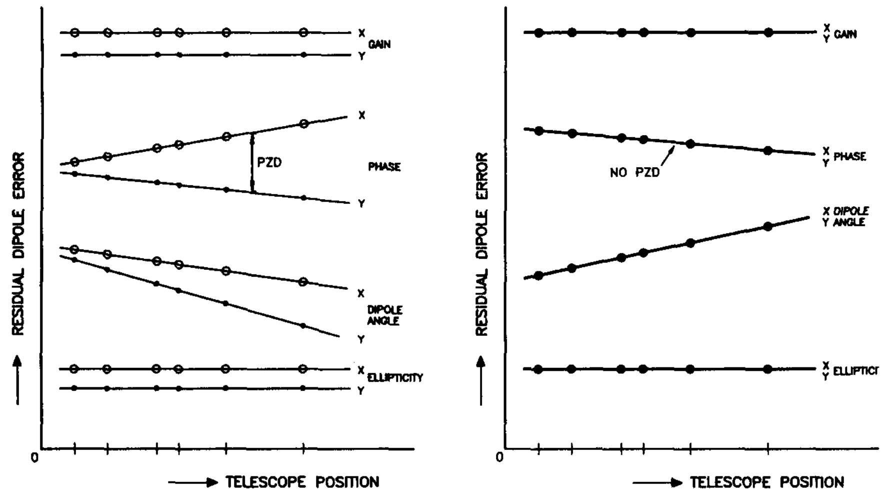

Fig. 1. Illustration of the nature of the absolute errors that cannot be determined with redundancy calibration, for the case of parallel dipoles (left) and crossed dipoles (right). For the latter, a single combined solution exists for both X- and Y-dipoles, eliminating the "offset-difference" problems.

In principle, we are now in a very favourable position: not only is the accurate calibration of the various dipole errors much less dependent on our knowledge of the polarisation of the calibrator source, but also the number of degrees of freedom on the SELFCAL model has been reduced to a minimum. Absolute gain and phase offsets may now be eliminated by dividing by I. The resulting **model-independent** values of Q/I, U/I and V/I will only depend on variations of "mechanical" quantities like absolute ellipticity and dipole angle gradient over the array, which will very likely be stable to better than 0.01%.

Unfortunately, there is a problem. Although the solution with crossed dipoles may be perfectly consistent, it is degraded by interactions between the two real errors (dipole angle and gain), and also between the two imaginary ones (phase and ellipticity). Simulations show, that the estimated errors (of all four types) for the X- and Y-dipoles per telescope are wrong by equal but opposite amounts. Because in the case of the dipole angle errors, it is as if the two perpendicular dipoles per telescope are forced apart, the effect is called the "Samson-effect", after the Biblical hero who forced the pillars apart and caused the temple to come crashing down. At the time of this conference, no "Delilah-strategy" has been found to deal with the Samson-effect, and it may or may not be fundamental. The Samson-effect does not occur for parallel dipoles, which may be seen from the fact that equations (5) and (6) contain only two of the four types of dipole errors.

DISCUSSION

It is clear that the single redundancy solution for all X- and Y-dipoles, is potentially very powerful, and may lead to polarisation measurements with a very high accuracy. But even if the Samson-effect proves fundamental, and crossed dipoles cannot be used, redundant spacing calibration will be an improvement over current practice.

The investigation is not finished. There is an, as yet unexplored, intermediate case, where the dipoles are parellel, but the object has strong linear U polarisation. The resulting signal strength in M_{xy} and M_{yx} gives a better solution than normally with parallel dipoles, but the case is not very general.

Effects like instrumental polarisation for off-axis objects have also not been taken into account yet. Crossed dipoles may introduce undesirable effects here, which partly negate the better calibration of dipole errors. In that case, the most promising application will be variability measurements of the quantities Q/I, U/I and V/I in on-axis compact objects.

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Peter Dewdney: Since the Redundancy Solution for antenna gains in the WSRT must be done for each increment of hour angle, and each such solution may produce an offset of the centroid of emission, what method do you use in the absence of a model (model independent) to tie together the solutions at different hour angles?
J. Noordam: We have to use a model, unfortunately. But thanks to the redundancy constraint, we only have to solve for one independent gain and phase error per HA-cut rather than 14 (the number of telescopes).

Ray Norris: An alternative approach to determine the PZD (and that adopted on the A.T.) is to fire a noise diode at an intermediate position angle and continuously measure the phase difference between the X and Y dipoles. This at least removes the instrumental problem.
Jan Noordam: Yes, but not the atmosphere, and anything that happens in the telescope before injection (e.g. standing waves). Moreover, the injection process itself may introduce errors that are not in the data. Don't forget that we are trying to reach 0.01% accuracy, which is only possible by using the object itself.