Polarisation observations with ALMA

Probing the theoretical possibilities and practical limitations

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1 introduction

Polarization has come up a number of times in ASAC meetings. Both ESO staff and ASAC members appear to feel that a more thorough discussion is in order. ESO has invited me as an expert in polarimetry theory to introduce the subject in the upcoming ASAC meeting in Florence.

The subject is rather complex and surrounded by misunderstandings and prejudices. I hope to clear the way by this introduction. For those who are interested, the accompanying recent theoretical paper summarises a new theory of polarization interferometry and some of its consequences; it includes references to the basic papers. The thrust of that paper is toward phased-dipole arrays, but the theory summarised in it applies to arrays of any type.

2 Hardware facts

2.1 Quasi-linear versus matrix formulations

Polarization-pure linear feeds are relatively easy to manufacture. Indeed, mechanical symmetry necessarily implies electrical symmetry and hence purely linear polarization.

An equivalent mechanical structure for circular polarization does not exist. Practical circular feeds are usually constructed in the form of a linear feed preceded or followed by a linear/circular converter (a dielectric slab in the feed horn or a hybrid behind the transducers). Such converters require a $\pi/2$ phase shift. Over a range of frequencies this can be realised only approximately and with great difficuly, and the result depends critically on manufacturing tolerances. I think one must accept the engineers' assessment that ALMA can only have linear feeds. I doubt that this is a serious setback (see below).

2.2 Primary-beam position-dependent polarization

Let us assume an instrument perfectly calibrated for a point source at a particular position in the primary beam. We will then find that it is still in error for neighbouring positions. Some of the possible causes are

- Reflector curvature: Generally mentioned first but in fact unimportant (-50 dB or lower).
- Non-circular X and Y primary beams due to non-circular feed illumination of the primary reflector: A very major cause.
- The feed supports: The incident radiation is likely to set up longitudinal currents that cause polarized scattering/blocking effects. Thinking of the feed as merely a shadow-caster is too simple, but may be more adequate when the parts are many wavelenths across.
- Asymmetries in the feed design, due e.g. to mirrors or excentric placement of feeds. The VLA's notorious 'beam squint' is of this type.

I think it is fair to say that primary-beam polarization is generally poorly understood. Good models do not, to my knowledge, exist. Measurements are difficult and *very* time-consuming and tedious. For existing instruments they have been made only piecemeal if at all.

Short of planning for a lengthy measurement campaign, the best strategy is to avoid squinting optics as much as possible and maximise the symmetry between opposite polarizations.

3 Polarimetry theory

3.1 Quasi-linear versus matrix formulations

One should be aware that the theory of interferometric polarimetry that our community has used so far is actually only a first-order approximation. To obtain it, one must 1. *assume* weak polarization and small feed errors, and 2. *restrict the scope* to simple feed configurations.

Recently, a new matrix-based formalism has been proposed that makes the general case tractable, so the above limitations are no longer necessary. A compact exposition is given in the accompanying paper. For the time being, we may discuss the matter in terms of the old quasi-linear approximation, as long as we keep in mind that some of the stumbling blocks in the latter are artificial rather than fundamental.

3.2 Calibration procedure

The two confugurations generally known are those of homogeneous arrays of circular and of commonly oriented linear feeds. The theory for both runs parallel except for a cyclic permutation of Stokes Q, U and V. I discuss it in terms of Stokes comnponents for the circular case, showing the corresponding components for the linear case in square brackets.

Using a *known* reference source for calibration, one has the problem of transferring the calibration to a target-source observation; its success depends on the stability of the instrument and its environment. The eventual goal must be to self-calibrate as much as possible.

Self-calibration is done in several steps:

1. Self-calibrate the subsets of R and L [X and Y] receptor channels separately. This provides us maps of $I + V$ and $I - V$ [$I + Q$ and $I - Q$] and channel gains except for an unknown phase offset in each. (It is this *scalar* selfcal step that restricts the scope of the method to homogeneous systems.)
2. Determine the interferometer leakage terms $I \to QU$ [$I \to UV$] from the cross visibilities RL and LR [XY and YX], then make a least-squares fit of feed errors to these leakages. This fit introduces unknown orientation and ellipticity offsets (analogous to the unknown phase in the selfcal fit).

   At this point, we have three parameters still to be determined: the zero points of the feed orientation and ellipticity scales and the difference between the phase zeros of the R and L [X and Y] receptor subsets. These constitute three mutually orthogonal degrees of freedom that correspond to an unknown 3D rotation of the Stokes (Q, U, V) vector. (In the matrix theory, the same result is obtained in a single matrix self-alignment step.)
3. The feed offsets are removed through the assumption that the feeds conform on the average to their nominal specifications (or some other prior assumption). This fixes the rotations on the Q and U [U and V] axes.
4. The phase difference must be determined separately. This requires a natural or artificial source whose Q/U [U/V] is known.

3.3 Second-order effects

Cases have been encountered where the linearisation conditions are violated. Such cases may become more common at higher frequencies. Also reverse leakage ($QUV \to I$) causes phantom residuals in the selfcal fit. In the quasi-linear approach, they must be dealt with by iteration. In the matrix approach the problem evaporates.

3.4 Inhomogeneous systems

The possibility of an array having linear feeds in two p.a. differing by 45 deg was demonstrated with the WSRT as early as 1973, but had to be abandoned ten years later because it was not amenable to selfcal. Matrix theory removes this incompatibility, making arrays with a mixture of feeds a serious option for the future. Whether this future should start with ALMA is a question that we may or may not consider.

4 Some practical matters

4.1 Phase-difference calibration

The phase-difference calibration step is generally considered the most problematic one.

For the circular case, the ratio Q/U represents the p.a. of linear polarization, which must therefore be known for any celestial source to be used as reference.

For the linear case, the simple assumption that $V = 0$ is sufficient; the great advantage is that this assumption can often be made on astrophysical or statistical grounds and therefore applied to an unknown source.

In either case, injection of a pilot signal is in principle also a sound method, but attended by many practical difficulties: Tone vs noise, standing waves in the injection circuitry, multipath effects, ...

4.2 Homogenoeus versus inhomogeneous feeds

The theoretical case for an inhomgeneous feeds system is interesting and a practical application has been shown to work. It solves one major problem, that of phase-difference calibration, but there may be other equally good solutions. Its $\times 2$ inefficiency in observing unpolarized sources is a disadvantage serious enough to kill it, — unless it can be worked around.

A possible way out would be to electronically combine the X' and Y' signals (where the prime stands for 45-deg rotation) to form $X' + Y' = X$ and $X' - Y' = Y$ as inputs for the correlator. This is simple to do and there is no S/N penalty, but it introduces new calibration problems which must be assessed.

4.3 Linear versus circular feeds

I wonder why circular feeds are thought to be superior. I would rather avoid stirring up the old linear/circular controversy, but I feel compelled to challenge Cotton's MMA Note 208. This Note, which seems to have been the main source of input for discussions in ASAC, is clearly biased by its author's absence of experience with other than circular feeds. Its conclusions are construed upon a bad misrepresentation of the linear case.

I think the case deserves to be reexamined. Some ingredients for a fair comparison are to be found in this note. There may be other aspects that I have negelected.

4.4 Bottom line

At higher frequencies and resolutions, both polarization in synchrotron sources and manufacturing errors in feed systems tends to rise, so ALMA is likely to face new challenges. Its design should therefore be as defensive and forward-looking as is practical.