ALMA Instrumental Polarization
Summary of Current Status

1 Introduction

Measuring the polarization properties of astronomical sources is an important aspect of ALMA's scientific programme. A large fraction of astronomical millimetre-wave sources produce partially polarized emission – in most cases the polarization is linear but in some cases there is a circular component as well. Polarization is generally caused by scattering processes in the sources and/or the effects of magnetic fields, so measurements of the orientation and amount of polarization provide information on the emission mechanisms, the source geometry and the alignment and strength of the magnetic fields, which are thought to play a critical role in processes like star formation.

Typically the fractional polarization (the sum of the values of the Stokes parameters[1] Q, U and V divided by the total intensity I) is quite low – perhaps only 1 or 2% – but we need to be able to measure this rather accurately in order to get the astronomical information out. For example a 10% error in the values of each of the parameters Q and U would lead to errors of up to 4 degrees in the orientation of the linear polarization. For this reason the requirement is that, after calibration, observations of an un-polarized source should show residual polarization of no greater than 0.1%. This is the one of the more challenging ALMA Scientific Requirements (number 320 – see ALMA-90.00.00.00-001-A- SPE)[2]. In my view it ranks immediately after angular resolution, sensitivity and image quality in importance.

ALMA uses linearly polarized feeds and we can call their <u>voltage</u> outputs X and Y. This means that the interferometric measurement of the Stokes parameters U and V using say antennas "a" and "b" is made by forming the "cross-handed" products $X_a . Y_b^*$ and $X_b . Y_a^*$. (The other parameters I and Q come from the direct products $X_a . X_b^*$ and $Y_a . Y_b^*$.) From this it can be seen that the presence of cross-polar components in the signals from the front-ends and the antennas (i.e. the presence of some of the Y-polarization from the source in the X output and vica versa) will produce large spurious polarization in the results. In particular, if the polarization purity of each front-end is only –20dB, this means that the output <u>voltage</u> X_a actually contains 10% of the Y polarisation from the input signal, and vica versa). The spurious response could then be at a level as high as –10dB. That is to say, observation of an un-polarized source could produce values of up to 10% for the value of U/I. (The actual value of the spurious polarized flux and the question of how much ends up in U or in V depends on the relative phases of the leakages into the various channels that are involved.)

---

[1] Recall that if X and Y are the electric field strengths at 0 and 90 degrees, the total flux $I = X.X^* + Y.Y^*$, the linear polarization in the 0 degree direction, $Q = X.X^* - Y.Y^*$, the linear polarization in the 45 degree direction, $U = X.Y^* + Y.X^*$ and the circular polarization $V = jX.Y^* - jY.X^*$.

[2] Note that the actual wording of this specification is "The error in polarized flux for a source where the circularly and linearly polarized fluxes are zero shall be no more than 0.1% of the total intensity on axis after calibration" with the footnote that "Meeting the polarization requirements is particularly important in band 7 and could require a quarter-wave plate". I am not clear why the limitation to the performance "on-axis" was included. In the System Specifications this requirement is expanded to include the idea that the Instrumental Polarization shall be set at -20dB with the further factor of 10 to be achieved by calibration. Both the on-axis and off-axis cases are included there although a (tbc) has been added for the off-axis case. I assume that this indicates uncertainly as to whether or not this can be achieved.

The consequence of this is that with just 20dB polarization purity in the front ends, but no other significant contributions from other parts of the system, our calibration procedures will need to be good enough to reduce the spurious response by a factor of ~100 in order to reach the requirement of 0.1% after calibration. This is going to be very difficult to achieve. Clearly it requires that the instrumental effects have to be stable to better than 1% over the "polarization calibration cycle". The time for this is presently set at 1 month in the system specifications, which seems ambitious. It is however clear that the absolute minimum is that it must remain stable as the telescopes track a source and as they move to suitable calibration sources which may be quite far away in the sky because they have to have special properties – either no polarization or an accurately known amount.

It should be noted that other arrays designed to make polarization measurements have adopted far more stringent requirements for the un-corrected instrumental polarisation – for example, I believe that for the VLA the specification for the cross-polar leakage of the front-ends is –40dB. I suspect that in drawing up the Front-End specification an incorrect interpretation has been made of the System Specification (number 224 in ALMA-80.04.00.00-005-B-SPE) which refers to an overall instrumental cross-pol of < –20dB. As demonstrated above, it is the voltage response of each element of the array that matters, so the requirement on the front-end should have been set at –40dB to achieve this. In fact it should really have been even lower that that in order to allow for some contributions from other parts of the system. It appears that this point was missed.

It is against this background that we are faced with the prospect that the production front-ends may not meet even the –20dB requirement and that we may have to accept –16dB or –17dB.

The next sections describe the various contributions to the instrumental cross-pol and the information that I have about the expected levels.

2 Instrumental Polarization due to the Antenna Geometry

In general this will be relatively small. Although the ALMA system does use feeds which are somewhat off-axis, the angles are small – a few degrees at most – and so the resulting cross-polarization should not be significant, at least for small sources at the centre of the beam. When we consider the polarization as a function of position across the primary beam, which is important for observations of more extended sources, then the properties of the antennas may start to have an influence, especially at the higher frequencies where the distortions of the surface become significant. The details of this can be extracted from the analysis that TICRA has done, although these contributions have not been separated out in their report at present and we should ask them to do that. As far as I can see from the results that they do show, the struts that support the secondary mirror do not play a significant role in the instrumental polarization.

3 Instrumental Polarization due to the Front-End

Most of the elements in the Front-End optics – cryostat windows, IR filters, off-axis mirrors, lenses and polarizing grids – can in principle contribute to the cross-pol.

The windows and filters will only contribute significantly if the materials they are made of are anisotropic. It is well known that this is true for Goretex (which means that the cabin "membrane" is another possible source of cross-pol so long as we continue to use Goretex for that). Measurements on the moulded flouro-polymer IR filters used in band 7 showed that they are producing cross-pol at levels of up to about –25dB. This is perhaps due to the flow of the material as it is moulded. This area – windows and filters – is clearly one where there are significant contributions at present and where we should be able to do better.

For most of the other components we should be able to predict and control the cross-pol rather well. The corrugated feed-horns that we are using generally have peaks in their cross-pol patterns –30dB or more below the co-polar peak. The grooved lens used in band 3 was investigated in detail and again a value of around –30dB peak was found from both theory and measurement. Well-made polarizing grids should have nearly ideal properties – that is they reflect one linear polarisation and transmit the other – with spurious response well below –30dB. This is however not true if the grid is placed in a highly divergent beam and if the grid is at an inclined angle to the direction of propagation then the orientation of the gridwith respect to the polarization must take account of the projection effects. Curved off-axis mirrors will produce cross-pol but the amount depends on the angle of incidence, the size of the beam and the power of the mirror. Where two mirrors are used the geometry can be arranged such that the cross-pol largely cancels out.

All these predictable effects were taking into account in the modelling carried out by TICRA. Here is a summary of the values they calculated for the complete front-end:

Band	Freq (GHz)	Eta_pol	Purity
3	100	0.9993	-31.5
4	144	0.9983	-27.7
6	243	0.9996	-34.0
7	324	0.9932	-21.7
9	661	0.9878	-19.1

Table 1. Predicted values for the “integrated” cross_pol for the ALMA front-ends.

Here TICRA have reported the “polarization efficiency” calculated in terms of the integrated power in the co-polar and total fields across the aperture of an idealized telescope. I have converted this to the cross-pol purity just using $10\log_{10}(1 - \text{eta\_pol})$. This is essentially what one would observe with an ideal telescope for a source on-axis. Measuring the receiver cross-pol with, for example, and cold load and polarizing grid is close to being equivalent, but there will be some effect from the divergence of the beam in that measurement.

Note that TICRA did not have enough details of the optics to model the other bands. A calculation was also made for band 3 at 115GHz and this showed higher cross-pol due to a problem with the feed.

It is apparent that only Band 9 is expected to miss the –20dB requirement as a result of these “designed-in” factors. In that case the high cross-pol is a result of the use of a polarizing grid between the two off-axis mirrors which means that the cancellation cannot take effect. Band 7 uses a similar layout but the geometry is such that the –20dB figure is not breached. (In fact IRAM’s own calculation gives a value of ~–24dB for the peak cross-pol.) Band 6 is predicted to have good performance since the two off-axis mirrors are in a compensated arrangement. Bands 3 and 4 have only one off-axis mirror (in their warm optics) and so they cannot be compensated but the power is quite low so that the predicted cross-pol levels are still quite good.

The measured cross-pol reported by all the cartridge manufacturers are apparently higher than these predicted figures, although in the case of Band 4 the excess seems to be quite small. This almost certainly means other elements are contributing to the front-end cross-pol. As already pointed out, IR filters and perhaps windows may be making contributions at present but there is no intrinsic reason why these cannot be made small. Reflections of signals from the windows or filters back into the horn may also be involved, but again it should be possible to control these.

For the lower frequencies – up to Band 6 – the ortho-mode transducers are another possible source of cross-pol. By design of course they should be good, although it is obviously harder to machine the small waveguide components to the required accuracy at millimetre wavelengths than it is at, e.g. the VLA frequencies. I assume that the manufacture and testing of the OMT's has been carried out in such a way as to ensure that they are not making a substantial contribution to the cross-pol.

4 Other Contributions to Polarization Errors

In measuring the Stokes parameter Q we rely on taking the difference between the two channels: $X_a . X_b^* - Y_a . Y_b^*$. This means that in order to measure this to the required level of 0.1% we need to be able to calibrate the relative amplitudes of the X and Y polarization channels to better than 1 part in 1000. This is mainly a system stability issue and it is likely that the Front-End instabilities will be an important contribution here. Again the requirement is that the stability is good enough as we track the source for an extended period and move to a calibrator which may be quite far away in the sky. I don't think the present specification covers this problem properly either.

Similarly the separation of the U and V parameters, which are both derived from the cross-hand correlations but with a 90 degree phase shift in the case of the circular term V, is dependent on the relative phases of the channels. The phase stability is of course dependent on many parts of the system including both front-end and backend.

Other contributions to polarization errors might arise in the correlator and from analogue or digital cross-talk between channels. It seems to me that these contributions should be small and probably easier to calibrate-out than those in the front-end.

5 Status of Individual Bands

(This is sketchy at the moment as I need to get more information from the testing that is presently underway.)

5.1 Band 3

The reports at the May 2007 optics review indicated that the measurements of the horn-lens combination are in line with expectations (after taking account of the matching grooves in the lens). Measurements are presently underway at the FEIC of the full system, which includes the external optics. I am not clear what the preliminary measurements show.

5.2 Band 4

The report given at the optics review indicates values of ~–22 to –24dB for the peak cross-pol for the complete system, including the external optics. This presumably means that the integrated value would meet the –20dB requirement with some margin, but this will need to be confirmed by further processing of this data and/or direct measurement.

5.3 Band 6

I have not seen any data but I understand that the tests that have been done show that the requirement is not met and a change request is therefore being considered.

I understand that the IR filters are being examined as a possible source of the excess. As mentioned above, the OMT's are another component that could be involved. I understand that the specifications on these call for –25dB polarization "isolation", which is presumably the same thing as what I am calling "purity". This would already be a significant contribution. I have however seen some test data that appears to show only –20B of isolation.

5.4 Band 7

IRAM measured the pre-production Band 7 cartridges using a grid and a cold load and found values spread between –19.5 and –17.5dB. The fact that there was a substantial spread in the results shows that the cross-pol is not all due to the intrinsic design geometry, for which the predicted value is below –21dB, as discussed above. As also mentioned above, IRAM have also presented measurements showing that the filters are making a significant contribution.

A change request has recently been approved by the Change Control Board (against the strong recommendations from the Science IPT). This puts that requirement in the form "The polarization efficiency of the tertiary optics system shall exceed 98%", which would be equivalent to –17dB for the integrated cross-pol. I note that this wording appears to set no limits on contributions from front-end sources other than those arising in the optics. It is very much to be hoped that this relaxation will not prevent serious work being undertaken to remove the sources of error due to such things are IR filters, which should be relatively easy to cure.

5.5 Band 9

SRON reported measurements of around –18dB for Band 9 at the optics review. Most of this is presumably due to the intrinsic optical design. (The prediction was –19dB.)

A change request asking for the specification for this band to be relaxed to –16dB is still pending. In this case it seems that there is little we can do except agree to some relaxation, since a complete re-design is not realistic at this stage, but it is not clear that the reduction to as poor a figure as –16dB is justified.

6 Conclusions

There is no doubt that performing polarization measurements to the required accuracy will be difficult and we will certainly not achieve this without careful work to make the system as good as is practical and to understand the sources of instrumental polarization. Given that the intrinsic polarization level is in any case higher than we can tolerate, we will only be able to make meaningful astronomical measurements by performing careful calibrations using sources which are known to have no polarization and sources for which the true polarization is known. It is therefore particularly important to identify any sources of polarization errors that could vary as a function of time or elevation.

I feel that insufficient attention has been paid to the polarization requirements in the past and that we need to take them more seriously now.

Richard Hills 17th Dec 2007