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1 Introduction

This document describes the Pipeline data processing required for observations with the SCUBA-2 polarimeter. This document covers polarimeter extensions to both the quick look (QL) system[7] and summit pipeline processing.[8] The observing modes and submm polarimetry in general are discussed elsewhere[11,10,6] but can be summarised as:

Step and Integrate

In this mode, DREAM images are taken either with the waveplate at a fixed angle or with the waveplate rotating slowly (e.g. 12.25 degrees every second). The reconstructed DREAM images are then tagged with the appropriate mean waveplate angle and processed to generate the polarization information. Slow spinning mode improves observing efficiency at the expense of angular smearing.

Fast Spinning

In this mode, the polarimeter spins fast (e.g. 12.5 Hz) whilst the acquisition reads out STARE images at 200 Hz, each of which will be tagged with the waveplate angle. The SMU will move to different jiggle positions every few seconds in order to fill in the 450-μm array.

2 Algorithms

This section describes the different techniques that will be used to calculate the polarization parameters of a POL-2 observation. In general the aim of these algorithms is to accurately calculate the I, Q and U Stokes parameters. Once these parameters are calculated, signal-to-noise can be increased by combining I, Q and U images before calculating the polarization angle and percentage. The degree of polarization and the position angle of that polarization are related to the Stokes parameters as follows:

$$Q = Ip\cos 2\theta \tag{1}$$

$$U = Ip\sin 2\theta \tag{2}$$

or alternatively,

$$p = \frac{\sqrt{Q^2 + U^2}}{I} \tag{3}$$

$$\theta = \frac{1}{2}\arctan\left(\frac{U}{Q}\right) \tag{4}$$

Additionally, dimensionless variants of Q and U as a fraction of the total intensity I are defined as

$$q = \frac{Q}{I} \tag{5}$$

$$u = \frac{U}{I} \tag{6}$$

Equations 3 and 4 can then be rewritten in terms of these *reduced* Stokes parameters as:

$$p = \sqrt{q^2 + u^2} \tag{7}$$

$$\theta = \frac{1}{2} \arctan\left(\frac{u}{q}\right) \tag{8}$$

2.1 Direct arithmetic

If the images taken at different waveplate angles are observed close enough in time such that sky rotation is negligible (from the pixel resampling viewpoint as well as from the waveplate viewpoint), q and u can be calculated using simple arithmetic techniques:

$$q = \frac{I_0 - I_{45}}{I_0 + I_{45}} \tag{9}$$

$$u = \frac{I_{22.5} - I_{67.5}}{I_{22.5} + I_{67.5}} \tag{10}$$

where I_N indicates the intensity image for a waveplate angle of N degrees. This cycle repeats every 90 degrees such that 4 sets of q and u can be obtained for a single rotation of the waveplate. Once sufficient q and u images have been obtained they can be combined to increase the signal-to-noise. This may include despiking the stack of images to remove outliers (standard CCD mosaicking tools can be used for this, e.g. CCDPACK makemos[3]).

Note that even though in principal q and u can be obtained from a single pixel without reference to other bolometers, in actuality other bolometers are required to calculate the background sky signal for each of the individual STARE images since the denominator in the above equations will include a residual sky signal from each image. In fast spin mode 4 images could be taken at 50 Hz, and in this case the sky background would most likely be constant.[14] For step-and-integrate mode the sky will have changed between images, therefore the numerator will also be contaminated by residual sky signal.

2.2 Sine fitting

SCUBA uses the algorithm implemented in POLPACK.[13,1] In this technique signals from arbitrary waveplate angles are fitted to determine the Stokes parameters. This technique has the advantage over the direct arithmetic method in that there is no requirement for the images to be exactly 22.5 degrees apart. This was important for SCUBA where each image would take more than 30 seconds to complete and by the end of a waveplate cycle sky rotation could be significant.

Like the previous method, accurate sky subtraction is required for the images to be fitted in order to remove platforming from differing sky offsets. This is particularly important if the images at nearby waveplate angles are coadded prior to fitting which may tend to smear out the underlying signal.

2.3 Fourier components

In general, the signal from a single bolometer will be sensitive to a large variation in background sky signal combined with a very small modulation due to the rotation of the waveplate. Since the frequency of this modulation is known, for fast spinning mode the time series of each bolometer can be analyzed independently to extract the Fourier components at that frequency.[11] This approach has the key advantage that modulations at frequencies other than the polarization frequency, in particular the sky signal, are filtered out.

In summary, for the set of N measurements $v(t)$ the real and imaginary components corresponding to the modulation with period T is calculated using

$$A = \frac{1}{N} \sum v(t) \cos\left(\frac{2\pi t}{T}\right) \tag{11}$$

$$B = \frac{1}{N} \sum v(t) \sin\left(\frac{2\pi t}{T}\right) \tag{12}$$

such that

$$Q = 2A \tag{13}$$

and

$$U = 2B \tag{14}$$

and p and θ are then determined as in eqn. 3 and 4. As for the direct method, an accurate I image is still required to calculate the percentage polarization but the polarization angle can be accurately determined.

3 Instrumental Polarization

The instrumental polarization will be calculated by observing unpolarized standard sources. As for SCUBA[5] and ROVER,[4,12] the instrumental polarization will be specified for each bolometer as a function of elevation and the data will be corrected using the following equation:

$$I_{\text{Actual}} = I_{\text{Measured}} - I_{\text{Mean}} p_{\text{inst}}(e)(1 + \cos(4W - 2\theta(e))) \tag{15}$$

where $p_{\text{inst}}(e)$ is the fractional instrumental polarization at angle $\theta(e)$ and waveplate angle W. In fast spinning mode the mean flux can be calculated directly from the processed image stack (since no resampling will be needed). For step and integrate mode it may be necessary to use the approximation implemented in the SURF[9] remip task:

$$I_{\text{Actual}} \approx I_{\text{Measured}} \times (1 - p_{\text{inst}}(e)(1 + \cos(4W - 2\theta(e)))) \tag{16}$$

where we have made the approximation that $I_{\text{Mean}} \approx I_{\text{Measured}}$ (which is fine for small instrumental polarizations). This allows the IP correction to be performed without access to the full time series.

Unlike SCUBA, the SCUBA-2 bolometers form a regular array so the IP will be specified for each pixel as a 3-D file (using NDF[15] for compatibility with the rest of the architecture) where the first two dimensions correspond to the bolometer array, and the third dimension has slices of

- Instrumental percentage polarization at the horizon
- Gradient in p (i.e. $p = p_{\text{horizon}} + p_{\text{slope}} \times e$)
- Polarization angle of IP at horizon (degrees)
- Gradient in theta (i.e. $\theta = \theta_{\text{horizon}} + \theta_{\text{slope}} \times e$)

Corresponding variance values will also be supported in the NDF `VARIANCE` extension. IP correction will then consist of simple array arithmetic.

4 Variance handling

It is important that variance information is used when determining the significance of individual polarization parameters from the Stokes cube. Variance can be handled a number of ways and depends on the observing mode. POLPACK will make use of variance data when calculating polarization percentage and angle from a Stokes cube.

For fast spinning mode, if the DA system provides variances for the I, Q and U data directly these variances will be used in subsequent processing. If variances are not made available they will be derived when multiple cubes are present.

For step-and-integrate mode variances will be derived either by stacking images at the same waveplate location prior to fitting (which will be susceptible to sky background platforming) or directly by using a stack of IQU cubes.

5 Quick Look Processing

The Quick Look system[7] provides near-real time feedback to the observer during data acquisition. For DREAM and STARE imaging the Data Acquisition (DA) system makes reduced images available every few seconds. These images are then minimally processed and coadded into a running mean for the current observation.

For polarimetry observing the QL system must provide preliminary polarization information to the observer. The I image will be displayed and polarization percentage and angle will be overlaid. As the observation proceeds an IQU cube will be formed and subsequent frames will be coadded to improve the signal-to-noise. This cube will be resampled to RA/Dec coordinates to compensate for image rotation. The QL will provide basic polarization statistics to the observer.

GAIA[2] will be used for image and polarization display (a polarization plugin for GAIA is available although an ORAC-DR interface to it will be required).

For polarimetry observing the DA system has two modes of operation:

1. For step-and-integrate mode the DA system will not have enough data available to it to generate Stokes parameters. In this mode the DA will provide the individual processed images to the QL and these images will be processed either with POLPACK[1] or directly by subtraction (see earlier sections). Both modes will be developed for commissioning.
2. For fast spinning mode the DA system will generate I, Q, and U images from the 200 Hz data (the interface is still TBD). These images will be resampled to RA/Dec and coadded with earlier IQU images.

6 Pipeline Processing

The main summit data reduction pipeline will be a superset of the QL pipeline in that the summit pipeline will generate the IQU cube similarly to the approach used by the QL except for the following improvements:

- The IQU data for the observation can be calculated by stacking all the individual IQU cubes (the QL can only do a running average). This will allow despiking.
- Mosaics and co-adds of all the observations in the same reduction group can be combined to provide increased signal-to-noise and larger area coverage.

Once the final IQU cube is created the final polarization parameters can be calulated and displayed. The image display will be similar to the QL display except that the more control will be available to the user via the ORAC-DR display configuration tool.

This pipeline will be under recipe control (reduction recipes are set in the Observing Tool)[8] to allow the PI to optimize the reduction processing for the specific science goals of their project. A set of recipes is not yet defined but there will be at least the following:

COMPACT_SOURCE Optimize the recipe for an isolated compact source. Polarization information will be binned over the source. This would be the equivalent of SCUBA polarimeter photometry. Additional optimizations for the sky subtraction may be possible in this mode (but only for step-and-integrate since the 200 Hz data are not utilised by the pipeline in STARE mode).

EXTENDED_SOURCE Treat the resulting polarization catalogue as an extended source. This recipe may include adaptive binning of the catalogue such that areas of the map with high signal-to-noise retain resolution whereas areas of the map with lower signal-to-noise will be binned to beam resolution.

In principle recipes could be provided to allow the PI to specify whether they would prefer sine fitting or a direct arithmetic approach when processing images from step-and-integrate mode.

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