POSSUM Report 62: Integration of the POSSUM analysis pipeline for BETA

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Abstract

The POSSUM RM-synthesis pipeline is intended to produce a catalogue of polarisation properties for all compact sources found in the EMU Stokes I images. The Level-5 POSSUM Polarisation Catalogue (PPC) will be created within 24 hours of observations on the ASKAP telescope. The POSSUM team will perform a quality assessment on the catalogue and images, after which they will be released to the community as official Level-6 data products. The RM-synthesis pipeline will be implemented within ASKAPSoft (the real time ASKAP data processing software) and the results presented through the CASDA interface. More advanced analysis (such as fitting models to the Stokes Q & U data) will be performed on longer time-scales by the POSSUM team and used to create 'value added' catalogues and images (Level-7 data products). Here we present a prototype Level-5 RM-synthesis pipeline implemented in the *python* language. To facilitate development, the pipeline has been designed to be modular, with individual POSSUM team members focusing on designing and testing specific modules. Their findings are documented in prior POSSUM reports and are summarised here. This report is intended to provide an overview of the pipeline architecture and to collect all of the algorithms, inputs and outputs in a single document.
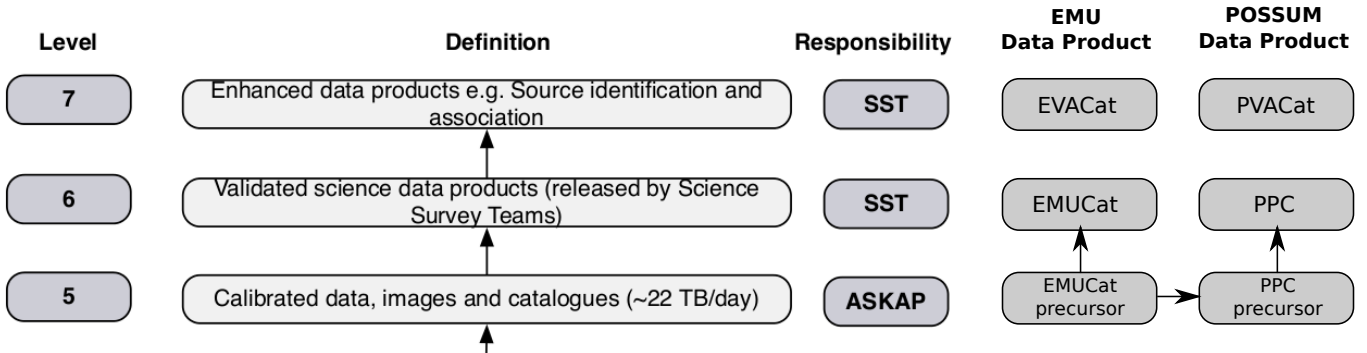
Figure 1: Classification of high-level data products from ASKAP. The Level-5/6 POSSUM Polarisation Catalogue (PPC) presents the polarised properties of the Stokes I sources in EMUCat. Responsibility for creating EMUCat and the PPC is shared between ASKAP and the Survey Science Teams (SSTs). The Level-7 'value added' catalogues are solely the responsibility of the SSTs. Unlike the PPC, the PVACat will not be derived from its equivalent EMU value added catalogue, EVACat. However, PVACat will be extensively cross-linked with EVACat and other external datasets.

1   Introduction

Commissioning of the Boolardy Engineering Test Array (BETA) is well underway in the last quarter of 2014. The first impressive six-antenna Stokes I images have been produced using the Mk I phased array feeds (PAFs). The sole purpose of BETA is as an engineering test-bed on which to learn how to calibrate and operate an array of PAFs. The first polarisation science from ASKAP will be produced by the Mk II PAFs, which will be progressively installed on the antennas during 2014 and 2015, supplanting the older Mk I receivers. It is anticipated that 12 Mk II PAFs will be commissioned by mid 2015 at which point early science operations (including the POSSUM-12 survey) will commence. To comply with this schedule the POSSUM team has developed a prototype POSSUM RM-synthesis pipeline with the goal of producing a catalogue of polarised source properties.

Data produced by ASKAP is classified into 'levels' in increasing order of complexity, as shown in Figure 1. This document explains the creation of the Level-5/6 POSSUM polarisation catalogue (PPC), which is best described as *the simplest catalogue which may be created automatically and in real-time.* The PPC contains an entry for all bright, compact (unresolved or marginally resolved) detections in the Level-6 Stokes I catalogue produced by EMU: EMUCat. We make the distinction here between an EMUCat *source* and *component*: EMUCat sources may contain multiple associated Gaussian components. Grouping components, cross-matching multi-wavelength data and physically interpreting source structure will be tackled in the Level-7 EMU and POSSUM Value Added Catalogues (EVACat and PVACat, respectively) at a later time.

1.1   Integration Plan

The POSSUM pipeline has been designed as a series of modules, each of which performs a self-contained task. Most of the algorithms have been developed by POSSUM team members and documented in previous POSSUM reports. Here we collate that information and present a prototype end-to-end pipeline implemented using the *python* scripting language. *Python* has the advantage of easily wrapping around code written in other languages, while also providing native scientific data processing libraries (numpy, scipy), visualisation tools (matplotlib) and interfaces to relational databases (sqlite3, MySQL). The pipeline is easily plumbed into a web-based interface, facilitating detailed testing by POSSUM team members around the world. The prototype web interface is currently implemented using the lightweight *bottle* web-framework, which includes a local web-server distributed with the pipeline. We hope that the pipeline archetecture will be useful for investigating future algorithms (e.g., fitting polarisation models to Stokes Q and U data) and processing surveys similar to POSSUM (e.g., GALFACTS and ATLAS).
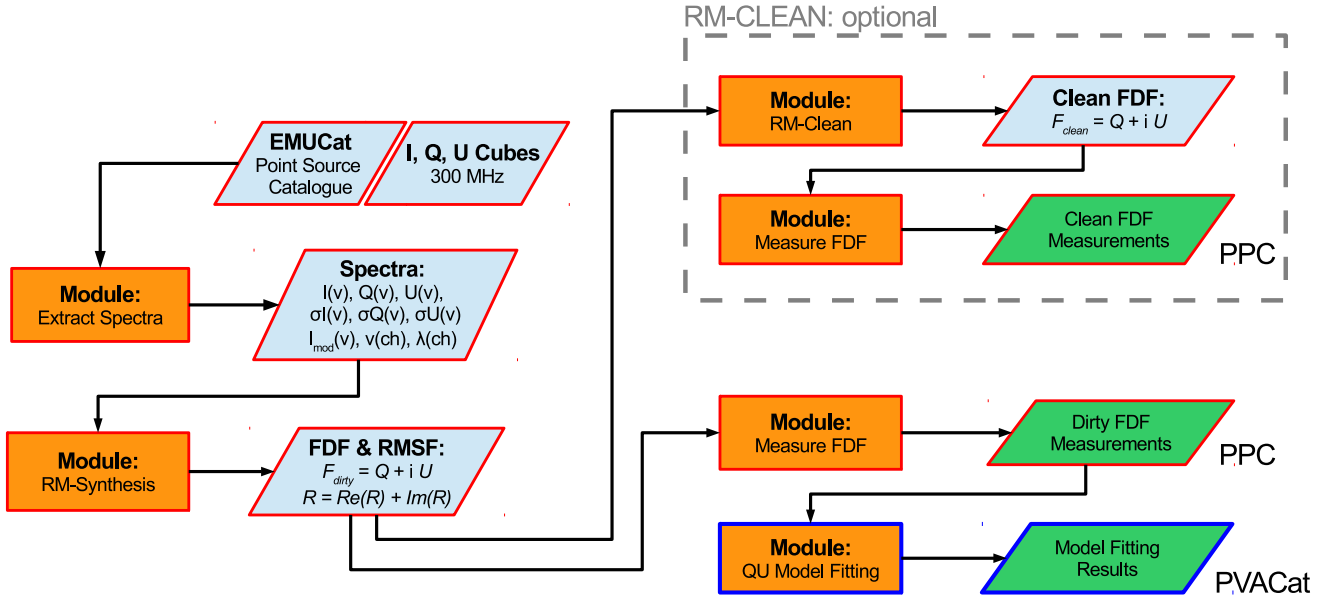
Figure 2: Flow-chart for the POSSUM pipeline. Boxes outlined in red will be implemented within ASKAPSoft, while those outlined in blue will be implemented by the POSSUM team. RM-synthesis is performed on 1-D spectra extracted at the positions of the compact Stokes I sources in EMUCat. The PPC is created from measurements performed on the 'dirty' Faraday Dispersion Functions (FDF). An optional RM-clean step may also be done on FDFs containing polarised emission. The peak RM and polarised intensity in the PPC are used to initialise the advanced algorithms employed to create the PVACat.

2 The POSSUM pipeline in detail

The Level-5/6 POSSUM pipeline uses the RM-synthesis algorithm to build a catalogue of rotation measures from ASKAP data. RM-synthesis produces a complex Faraday dispersion function $\mathcal{F}(\phi)$, which is a function of Faraday depth ϕ. The instrumental response is convolved with the signal in an analagous way to aperture synthesis imaging and may be deconvolved using algorithms such as RM-clean. However recent investigations have concluded that the RM-clean algorithm fails to seperate even moderately close RM-components. Deconvolution is an optional step in the prototype pipeline and we prefer to measure the RM from the peak of the 'dirty' dispersion function. The outputs of RM-synthesis are very useful to set the intial parameters of more advanced analysis techniques. Algorithms for fitting physical models directly to the Stokes Q and U data are being investigated for inclusion in a future version of the prototype pipeline (producing Level-7 data products). These will be the subject of separate reports.

Figure 1 shows an updated version of the pipeline flow chart from POSSUM reports 5, 7 and 8. The pipeline starts by extracting 1-D spectra and local noise measurements at the positions of the Stokes I Gaussian components in EMUCat. RM-synthesis (and optionally RM-clean) are performed on the extracted spectra and the properties of the Faraday dispersion function (FDF) are measured. Along with the Stokes I, Q, U and V data-cubes, this catalogue of polarisation properties constitute the Level-5 data products. The Level-5 data must be verified by the POSSUM team before being released to the public as Level-6 data products. In the following subsections we describe each of the modules in turn, documenting the calculations, inputs and outputs.

2.1 Input data and catalogues

The EMU and POSSUM imaging pipelines are completely separate entities. The EMU imaging pipeline will create single-plane multi-frequency synthesis (MFS) images of Stokes *I, Q, U* & *V*, spectral index (α) and curvature (β). The POSSUM imaging pipeline will produce Stokes *I, Q, U* & *V data-cubes* with $N_\nu = 300 \times 1$ MHz channels along the spectral axis. The following image data and catalogues are required inputs to the POSSUM pipeline (also see Table 1):

- Fully calibrated Stokes *I, Q, U* & *V* cubes.

- A catalogue of Gaussian components within 'islands' of emission detected in the Stokes *I* images - EMUCat. Islands which are extended compared to a synthesised beam may contain multiple components and a flag set in the catalogue indicating membership of a cluster.

- The peak right ascension (R.A.) and declination (Dec.) of each component and their associated uncertainties, σ(R.A.) and σ(Dec.).

- The fitted Gaussian full-width at half-maximum (FWHM) major (θ_M) and minor (θ_m) axes, and corresponding uncertainties, $\sigma(\theta_M)$ and $\sigma(\theta_m)$.

- A flag denoting if the Gaussian is part of cluster of components.

The format of EMUCat has not been finalised so in the prototype POSSUM pipeline we adopt the ASCII file produced by the *Aegean*[1] sourcefinder (Hancock et al., 2012). While none of the EMU image data are necessary to run the POSSUM pipeline, they will be a useful source of postage-stamp images for the end user.

Assumptions about the input data

Data entering the prototype POSSUM pipeline is assumed to have the following characteristics:

- The Stokes *I, Q* & *U* radio image data are distributed as FITS files.

- Each channel-map is contained in a single file with 4 data-axes [nX, nY, nFreq=1, 1]. The 3rd axis records the frequency while CRTYPE header card of the 4th axis is used to specify the Stokes parameter.

- The data have been fully calibrated and corrected for instrumental polarisation effects.

- The data have been corrected for the reponse of the primary beam and the edges of the mosaic have been blanked beyond the half-power radius at the highest observed frequency.

- Blanking is implemented by writing IEEE NaNs to the binary data or by using a BLANK header card (magic number).

- All frequency planes have been convolved to a common synthesised beam size.

- Pixels are square and the FWHM beam size is sampled by at least 5 pixels (see POSSUM report 14).

- The frequency (in Hz) of each image plane is specified in a separate ASCII file with N_ν entries (one per channel, on new lines).

- The spatial world coordinate system is of a type known by WCSLIB[2].

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[1]https://sites.google.com/site/mrpaulhancock/data-and-code/aegean
[2]http://www.atnf.csiro.au/people/mcalabre/WCS/

- The data-cubes are calibrated in $\mathrm{Jy\,beam^{-1}}$ and contain the header cards BMAJ, BMIN and BPA specifying the beam size.

- The position, angular size and amplitude of the fitted Gaussians presented in EMUCat has been verified as correct.

- For full ASKAP the EMU and POSSUM surveys will be commensal and the frequency range will cover a single 300 MHz observing band over the frequency range 1130 - 1430 MHz. During the early-science period the POSSUM-12 survey will cover the 700-1800 MHz band in four overlapping 300 MHz chunks. Data for all four chunks must be available before running the POSSUM pipeline on a field.

Table 1: Inputs & outputs for spectrum extraction module.

Ref.	Symbol	Type	Description
Inputs to module:			
EMU	emuID	ascii	ID of source in EMUCat catalogue.
EMU	compID	ascii	IAU ID of Gaussian fit (which can be a sub-component of a source) in EMU catalogue.
EMU	clusterFlg	integer	Flag indicating whether component is part of a cluster of Gaussian fits.
EMU	(R.A., Dec).	double(2)	Peak Right Asencion and Declination of the EMU component [deg].
Imager	ν	double(N_ν)	Vector of frequencies for each channel.
Imager	$\underline{\mathbf{I}}$, $\underline{\mathbf{Q}}$, $\underline{\mathbf{U}}$	double(N_x, N_y, N_ν, 1)	Cubes of Stokes I, Q & U data as a function of frequency and position [Jy beam^{-1}].
EMU	$\underline{\mathbf{I}}_{\mathrm{mom0}}$	double(N_x, N_y, 1)	Stokes I integrated intensity postage stamp image of each source (optional).
POSSUM	M_{box}	integer	Side of the square box over which to extract the spectrum [pixels]. Must be an odd number (default 5).
Outputs of module:			
§2.2	uniqueName	acsii	Unique name of the component used as a catalogue key. Can be the same as compID.
§2.2	I, Q, U	double(N_ν)	Stokes I, Q and U spectra extracted from a M × M pixel region centered on (RA., Dec.) [Jy beam^{-1}].
§2.2	I_{med}, Q_{med}, U_{med}	double	Band-median values of Stokes I, Q & U [Jy beam^{-1}].
§2.2	$f_{\mathrm{M \times M}}$	double	Normalisation constant to correct the summed spectrum onto the Jy beam^{-1} scale.
§2.2	σ_I, σ_Q, σ_U	double(N_ν)	RMS noise spectra in I, Q and U, measured using the MADFM statistic from an aperture centered on the peak (R.A., Dec.). $A_{\mathrm{ap}} > 50\, A_{\mathrm{bm}}$ [Jy beam^{-1}].
§2.2	σ_{QU}	double(N_ν)	Average RMS noise spectrum from $\sigma_{\mathrm{QU}} = \sum_1^{N_\nu} (\sigma_{\mathrm{Q,i}} + \sigma_{\mathrm{U,i}})/2$.
§2.2	$\sigma_{\mathrm{I,m}}$, $\sigma_{\mathrm{Q,m}}$, $\sigma_{\mathrm{U,m}}$	double	Band-median values of σ_I, σ_Q and σ_U.
§2.2	ν	double(N_ν)	Vector of frequency values for each channel.
§2.2	λ^2	double(N_ν)	Vector of wavelength-squared values for each channel.
§2.2	C_I	double(5)	Coefficients for a nth order polynomial fit to the Stokes I spectrum, where $n \leq 5$.
§2.2	I_{mod}	double(N_ν)	Model Stokes I spectrum from the polynomial fit.
§2.2	edgeFlg	double(N_ν)	**True** if the source lies near the edge of a the field.

2.2 Module: Spectrum Extraction

This module extracts 1-D intensity and noise spectra from the Stokes parameter cubes, and creates a model Stokes I spectrum. Table 1 lists the inputs and outputs, which are described in Section 2.1 and below.

Noise Spectra

To make an accurate correction for the polarisation bias (which is similar in magnitude to the RMS noise - see Wardle & Kronberg 1974) a statistical estimate of the noise in each channel map is required. A noise estimate acurate to 10 percent will result in a ~ 1 percent accuracy in polarized intensity for a 10σ source. POSSUM reports 2 and 21 set the requirement that the measurement be made using a robust statistic over an area greater than 50 synthesised beam areas (A_{bm}). ASKAP data cubes are expected to be dominated by noise and the *median absolute deviation from the median* (MADFM) statistic is robust to the presence of bright pixels from sources within the measurement aperture. MADFM is used by DUCHAMP and for a dataset $X = x_1, x_2 \ldots x_i \ldots x_n$ is given by

$$\sigma = K \, \mathrm{median} \left(|x_i - \mathrm{median}(X)| \right), \tag{1}$$

i.e., the median of the deviations from the median value. In Equation 1, K is a constant scale factor which depends on the distribution of the data. For normally distributed data $K \approx 1.48$.

The noise spectra in the Stokes I, Q and U data are created by measuring the MADFM in each frequency plane using a square aperture centred on the source position. As an alternative an annulus with the same area could be used, omitting the target source, however, MADFM should be robust enough to deliver the same result. The average of the Q and U noise spectra may be used to weight the data during RM-synthesis: the 'variance' weighting option. As an alternative, the noise could be measured from the Stokes V cubes, which are unlikely to contain significant emission. However, this is yet to be investigated in detail (also see Hales et al. (2012) for a discussion of RM-synthesis and noise in polarised datasets).

Source Spectrum

The positional accuracy of unresolved sources detected in the EMU Stokes I images will be significantly better than one spatial pixel. If the peak of a source is offset from a pixel center, extracting a spectrum from the nearest pixel introduces a systematic error leading to an underestimation of the flux density (assuming a similarly unresolved source in all Stokes Q and U images). Spatially oversampling the synthesised beam will decrease this error, but to achieve an acccuracy of a few percent it is necessary to interpolate between image pixels. In addition, for some sources, the peak of the Stokes Q and U may be spatially offset from the Stokes I position. To mitigate these issues, POSSUM report 14 has proposed summing the spectra from a $M \times M$ box centred on the nearest pixel and normalising the result by a multiplicative constant. The normalisation factor $f_{M \times M}$ depends on the number of pixels across a beam FWHM and is given by

$$f_{M \times M} = \left(\sum_{l=-M}^{M} \sum_{l=-M}^{M} \exp \left[-\frac{4 \, ln(2) \, (l^2 + m^2)}{\theta_{\mathrm{bm, pix}}^2} \right] \right)^{-1}, \tag{2}$$

where $\theta_{\mathrm{bm, pix}}$ is the FWHM of the beam in pixels. The normalised sum measurement will yield the correct peak spectrum for an unresolved source and for a slightly resolved source will relieve small offsets in the spatial peak position between Stokes parameters. Report 14 recomends that the POSSUM pipeline implements a 5×5 pixel box. Based on examination of NVSS and FIRST data the authors expect 10 to 20 percent of POSSUM sources will be resolved. They show that, as a rule, polarised intensity images do not have the same morphology as their total intensity counterparts because of polarisation structure on arcsecond scales. For slightly extended EMU sources the 5×5 sum will be sufficient to extract a reasonable spectrum from the Stokes Q and U data. The benefit derived from the normalised sum measurement decreases with source size, so report 14 also reccomends that only sources subtending less than four synthesised *beams areas* be accepted into the POSSUM pipeline.

We note that the normalisation is not strictly necessary if performing RM-synthesis using the fractional $q = Q/I_{\mathrm{mod}}$ and $u = U/I_{\mathrm{mod}}$ spectra. For quality-control purposes it is desirable to extract and store raw spectra in units of Janskys.

Model Stokes I Spectrum

The RM-synthesis algorithm assumes that spectral-index effects have been subtracted from the input spectra. An easy method of doing this is to divide the Stokes Q and U spectra by the Stokes I. However, this has the undesirable effect of introducing non-Gaussian noise, so a model fit to the Stokes I spectrum should be used instead. In prototype POSSUM RM-synthesis pipeline a polynomial of up to order 5 is used, depending on how complex the spectrum is likely to be. A third order fit should be sufficient for the 300 MHz bandpass, but we may need to investigate the utility of higher-order fits for the 1100 MHz bandpass of POSSUM-12.

The EMU imaging pipeline will produce images of higher order Taylor terms characterising the spectral index and curvature of the Stokes I spectrum. These may also be used to generate a model, however, this procedure has not yet been tested on real data.

Other measurements on the spectra

At this stage in the pipeline suitable Stokes I, Q, U and V spectra have been extracted from all compact components in EMUCat. RMS noise spectra have also been measured from a large aperture centred on the source. The following measurements are made on the raw spectra and stored in the catalogue database:

- The band-median intensity values I_{med}, Q_{med}, U_{med} and V_{med}.

- The band-median sensitivity $\sigma_{\mathrm{I,m}}$, $\sigma_{\mathrm{Q,m}}$, $\sigma_{\mathrm{U,m}}$, $\sigma_{\mathrm{V,m}}$.

- A vector of frequencies and wavelength-squared values mapped to each channel number.

- A unique name based on the spatial position of the Gaussian component. This is used as the root of filenames in which data are stored on disk.

Vector outputs (e.g., spectra) are written to ASCII files on disk using the same filename root (e.g., $<uniqueName>$ _specQ.dat_), while simple measured values are stored in the database. The EMU data and catalogue supplies the following data and database entries

- A postage stamp Stokes I FITS image of each component.

- The unique EMUCat component ID to be written to the database.

- The EMUCat flag indicating membership of a cluster. This could be an integer indicating the number of Gaussians fit to the island.

- Coordinate, size and position-angle information along with absolute errors in each parameter.

2.3 Module: RM-Synthesis

The RM-synthesis algorithm used in the pipeline is described in POSSUM reports 1 and 17. The original IDL implementation by Tim Robishaw was ported to the *python* language by Cormac Purcell and a number of small enhancements made. Inputs and outputs to the RM-synthesis module are documented in Table 4 and the module described in detail below.

RM-synthesis description

RM-synthesis operates on the complex polarised spectrum expressed as a function of the wavelength-squared $P(\lambda^2) = Q(\lambda^2) + i\,U(\lambda^2)$. The user chooses the Faraday depths ϕ_j at which to sample the Faraday dispersion function (FDF), defined by Burn (1966) as

$$\mathcal{F}(\phi_j) = K \sum_{i=1}^{N} w_i\,P_i\,e^{-2\,i\,\phi_j\,(\lambda_i^2 - \lambda_0^2)}, \tag{3}$$

where the sum is taken over all channels and w_i is the weighting at the ith channel. K is a normalisation constant defined as

$$K = \left(\sum_{i=1}^{N} w_i \right)^{-1} \tag{4}$$

and λ_0^2 is the reference wavelength-squared, which for POSSUM is taken to be the weighted mean of the observed λ^2 channels

$$\lambda_0^2 = K \sum_{i=1}^{N} w_i\,\lambda_i^2. \tag{5}$$

By default the weights assigned to each λ_i^2 channel are given by $w_i = 1/\sigma_{QU,i}^2$, where $\sigma_{QU,i}$ is the corresponding amplitude of the mean RMS noise measured from the Stokes Q and U cubes in that channel (see Section 2.2).

The output of RM-synthesis, refered to as the 'dirty' FDF, is the true complex FDF convolved with a sampling function, dubbed the rotation measure spread function (RMSF). The RMSF is analogous to the synthesised beam in aperture-synthesis imaging and has a main-lobe and side-lobes structures. For sources with sufficient signal-to-noise the RMSF may be deconvolved from the dirty FDF, for example, using the simple Hogbom CLEAN algorithm described by Heald (2009). This step is optional and will not likely be used in the production POSSUM RM-synthesis pipeline.

Calculating the RM Spread Function

The complex rotation measure spread function may be calculated from the λ^2 sampling of the observations and the weight $w(\lambda^2)$ applied to each λ^2 channel via

$$\mathcal{R}(\phi_j) = K \sum_{i=1}^{N} w_i\,e^{-2\,i\,\phi_j\,(\lambda_i^2 - \lambda_0^2)}. \tag{6}$$

The form of the RMSF in polarised intensity is that of a sinc function, with a main-lobe which can be characterised by Gaussian profile. During the deconvolution process the final clean-component model is convolved with a model Gaussian main lobe. For the case of uniform weighting the FWHM of the main lobe has been evaluated by Brentjens & de Bruyn (2005) to be $\sim 2\sqrt{3}/(\lambda_{max}^2 - \lambda_{min}^2)$ via a 2nd-order expansion. Schnitzeler et al. (2009) evaluated the FWHM as 3.8 after a 4th order expansion. When weighting by the $1/\sigma_{Q,U}^2$ (the default choice for the POSSUM pipeline) the FWHM of the main lobe will likely be broader than this ideal and must be measured manually. To do this we mask off the sidelobe structure (by examining the 1st derivative of the RMSF to locate the first 'flat' away from the peak) and perform a minimum-χ^2 Gaussian fit to the main lobe. The parameters of the fit are stored in the database.

Table 2: Inputs & outputs for the RM-synthesis module.

Ref.	Symbol	Type	Description
Inputs to module:			
§2.2	I, Q, U	double(N_ν)	I, Q and U spectra [Jy beam^{-1}].
§2.2	I_{mod}	double(N_ν)	Model Stokes I spectrum [Jy beam^{-1}].
§2.2	σ_{QU}	double(N_ν)	For each channel an estimate of the RMS noise [Jy beam^{-1}].
§2.2	w	double(N_ν)	Vector of weights assigned to each channel when performing RM-synthesis. Two possible schemes are *uniform* (equal weighting) or *variance* (w $\propto \sigma_{QU}^{-2}$).
§2.2	λ^2	double(N_ν)	Vector of wavelength-squared values [m^2].
POSSUM	N_ϕ	integer	Number of channels in the Faraday depth sampling vector.
POSSUM	$\delta\phi$	double	Spacing between the Faraday depth channels [rad m^{-2}].
POSSUM	ϕ_0	double	Centre RM of the Faraday depth vector, [rad m^{-2}]. Defaults to zero.
Outputs of module:			
§2.3	ϕ	double(N_ϕ)	Faraday depth vector [rad m^{-2}]
§2.3	$\mathcal{F}(\phi)$	double(N_ϕ, 2)	Complex 'dirty' Faraday dispersion function $\mathcal{F}(\phi) = \mathcal{Q}(\phi) + i\mathcal{U}(\phi)$ derived from the Stokes Q(ν) and U(ν) spectra [Jy beam^{-1} rmsf^{-1}].
§2.3	ϕ_2	double($2\,N_\phi$)	Double-size Faraday depth vector for use with the RM-clean algorithm [rad m^{-2}].
§2.3	$\mathcal{R}(\phi_2)$	double($2\,N_\phi$, 2)	Double-size complex Rotation Measure Spread Function generated using λ^2, ϕ_2 and w(ν).
§2.3	$\Delta\phi_\mathcal{R}$	double	FWHM width of the RMSF determined by a Gaussian fit to the main lobe.
§2.3	λ_0^2	double	Reference λ^2 used when performing RM synthesis [m^2]. Determined from the weighted average of the λ^2 vector.
§2.3	ν_0	double	Equivalent frequency to λ_0^2 [Hz].

Inputs and outputs to the RM-synthesis module

The RM-synthesis module takes as inputs the fractional $q(\lambda^2) = Q(\lambda^2)/I(\lambda^2)_{\mathrm{mod}}$ and $u(\lambda^2) = U(\lambda^2)/I(\lambda^2)_{\mathrm{mod}}$ spectra, a vector of λ^2 values, a vector of weights $w(\lambda^2)$ and a linearly sampled vector of Faraday depths ϕ (constructed from N_ϕ, $\delta\phi$ and ϕ_0). The fractional polarisation spectra are used instead of straight Stokes $Q(\nu)$ and $U(\nu)$ so as to divide out any spectral-index in the source. A noiseless model fit $I(\nu)_{\mathrm{mod}}$ to the raw Stokes I spectrum is required so as to preserve the noise statistics in the fractional polarised spectra.

The miniumum desirable ϕ search range is set by the expected RM of the Galaxy of $\pm 600\,\mathrm{rad\,m^{-2}}$ (Van Eck et al., 2011), however, the observations set hard limits as follows. The maximum detectable RM (ϕ_{max}) of background sources or Faraday screens is set by the minimum channel width $\delta\lambda_{\mathrm{min}}$ sampled by the observations. According to Brentjens & de Bruyn (2005)

$$\phi_{max}\,|_{\mathrm{screen}} = \sqrt{3}/\delta\lambda_{\mathrm{min}}^2. \tag{7}$$

The maximum detectable Faraday depth of mixed emitting and rotating regions is given by

$$\phi_{max}\,|_{\mathrm{mixed}} = \pi/\lambda_{\mathrm{min}}^2, \tag{8}$$

while the range of scales detectable in Faraday depth is $\lambda_{\mathrm{max}}/\lambda_{\mathrm{min}}$. The FWHM of the RMSF main-lobe when all frequency channels are uniformly weighted is given by

$$\Delta\phi_{\mathcal{R}} = 2\sqrt{3}/\Delta\lambda^2, \tag{9}$$

where $\Delta\lambda^2 = \lambda_{\mathrm{max}}^2 - \lambda_{\mathrm{min}}^2$. For RM-clean to correctly identify the peak in the FDF the RMSF main lobe must be well-sampled ($\Delta\phi_{\mathcal{R}}/\delta\phi \geq 5$). POSSUM report 52 evaluated the inputs to RM-synthesis and suggested that the Faraday depth sampling interval $\delta\phi$ for POSSUM be less than $30\,\mathrm{rad\,m^{-2}}$. However, to recover the correct fractional polarisation $p_{peak} = \sqrt{q_{peak}^2 + u_{peak}^2}$ without derotating from λ_0 to $\lambda = 0\,\mathrm{m}$ requires $\delta\phi \leq 5\mathrm{rad\,m^{-2}}$.

The RM-synthesis module returns the following as outputs (see Table 4): the complex 'dirty' FDF (with amplitude expressed as units of polarisation fraction), the value of reference wavelength λ_0^2 and equivalent frequency ν_0, the complex RMSF and its Faraday depth sampling vector ϕ_2. To allow CLEANing across the full range of the FDF ϕ_2 must span twice the input ϕ-range (extended by half again either side of ϕ_0). For convenience, the module also returns the fitted FWHM of the main lobe of $|\mathcal{R}|$.

Recovering the dirty FDF in Jy

At this stage all compact EMUCat components have a complex dirty FDF expressed as a polarisation fraction. To recover the FDF in units of absolute polarised intensity (i.e., Janskys), the real $\mathcal{Q}(\phi)$ and imaginary $\mathcal{U}(\phi)$ parts of $\mathcal{F}(\phi)$ must be multiplied by the Stokes I amplitude at the frequency ν_0 corresponding to λ_0^2. This is calculated directly from the model fit to the Stokes I spectrum. $\mathcal{Q}(\phi)$, $\mathcal{U}(\phi)$ and ϕ are then stored to disk in ASCII text files alongside the complex RMSF $\mathcal{R}(\phi_2)$. The following parameters are stored in the database at the time the FDF is generated:

- The number of channels in the FDF N_ϕ.

- The channel spacing $\delta\phi$ in $\mathrm{rad\,m^{-2}}$.

- The RM in the centre channel ϕ_0 in $\mathrm{rad\,m^{-2}}$.

- The reference wavelength λ_0^2 and equivalent frequency ν_0.

The dirty FDF created by the RM-syntheis module is now passed to the FDF measurement module.

2.4 Optional Module: RM Deconvolution

Note: If deconvolution is performed on the dirty FDF, the parameters measured from the clean FDF are written to the database, but not used in further analysis. The measurements performed on the dirty FDF are used to inform more advanced algorithms downstream.

The simplest method of deconvolving the RMFS from the dirty FDF is to use the CLEAN algorithm developed by Högbom (1974) for use with aperture synthesis imaging. Heald (2009) first demonstrated that the CLEAN algorithm could be applied to Faraday dispersions functions and presented the full recipe in Appendix A of that paper. The algorithm used in the POSSUM pipeline is broadly similar, with a number of small changes, notably weighting each λ^2 channel by $1/\sigma_{QU}^2$ and doubling the extent of the RMSF so as to remove sidelobe structure across the full extent of the FDF. The algorithm has been described in POSSUM report 17 by Tim Robishaw, however, for completeness we sumarise it here.

1. Find the location of the peak channel in the polarised intensity dirty FDF ($\mathcal{P}(\phi) = \sqrt{\mathcal{Q}(\phi)^2 + \mathcal{U}(\phi)^2}$).

2. If the amplitude of the peak in $\mathcal{P}(\phi)$ is greater than a user-defined cutoff, a shifted and scaled version of the complex RMSF is subtracted from the complex dirty FDF. The real and imaginary parts of the RMFS are scaled by a gain factor $g = 0.1$ in the POSSUM pipeline.

3. The complex values of $g\,\mathcal{F}(\phi)$ are accumulated to a clean-component spectrum.

4. Steps 1-3 are repeated until the peak of $\mathcal{P}(\phi)$ is below the cutoff, or a specified number of iterations have been performed.

5. The clean-component spectrum is convolved with the Gaussian model of the RMFS main lobe and the result added to the residual $\mathcal{F}(\phi)$. The final output is referred to as the clean FDF.

Tim Robishaw suggested in report 4 that we determine the clean cutoff from the noise in the Stokes V spectra. **This needs to be investigated**. The following parameters are saved to the database immediately after running CLEAN:

- Maximum mumber of iterations $N_{\mathrm{iter,\,max}}$.

- The clean gain g.

- The clean cutoff expressed as a multiple of $\sigma_{\mathrm{QU,\,med}}$.

- The algorithm for determining clean componnent locations (currently peak channel).

- Number of iterations performed $N_{\mathrm{iter,\,done}}$.

The real and imaginary FDF are saved to an ASCII file with extension *<uniqueName>_cleanFDF.dat*. The real and imaginary clean-component spectra are also be saved to *<uniqueName>_ccFDF.dat*.

2.5 Module: Measure the FDF

Detecting a Polarised Signal

If a polarised signal is present it will manifest as a peak in polarised intensity of the FDF $\mathcal{P}(\phi) = \sqrt{\mathcal{Q}(\phi)^2 + \mathcal{U}(\phi)^2}$. We find the peak channel in $\mathcal{P}(\phi)$ and if the amplitude $\mathbf{P}_{\mathrm{peak}}/\sigma_{QU} \geq \mathrm{SNR}_{\mathrm{detect}}$ then we record a detection in the database. Peaks found in this manner will have quantized values of $\mathbf{P}_{\mathrm{peak}}$ and ϕ_{peak} so we interpolate between the channels values by performing a three-point parabolic fit centred on the peak channel. This procedure avoids quantising the measured values of ϕ_{peak} and results in a more accurate estimate of the polarised intensity.

POSSUM report 11 by Sam George presents the results of Monte Carlo simulations aimed at quantifying the false detection rate at different S/N levels. He recomends adopting an 8σ detection threshold, above

Table 3: Inputs and outputs for the RM-clean module.

Ref.	Symbol	Type	Description
Inputs to module:			
2.3	ϕ	double(N_ϕ)	Faraday depth vector[rad m^{-2}]
2.3	$\mathcal{F}(\phi)$	double(N_ϕ, 2)	Complex 'dirty' Faraday dispersion function $\mathcal{F}(\phi) = \mathcal{Q}(\phi) + i\mathcal{U}(\phi)$ derived from the Stokes Q(ν) and U(ν) spectra [Jy beam^{-1} rmsf^{-1}].
2.2	ϕ_2	double($2\,N_\phi$)	Double-size Faraday depth vector [rad m^{-2}].
2.2	$\mathcal{R}(\phi_2)$	double($2\,N_\phi$, 2)	Double-size complex Rotation Measure Spread Function generated using λ^2, ϕ_2 and w(ν).
2.2	$\Delta\phi_\mathcal{R}$	double	FWHM width of the RMSF determined by a Gaussian fit.
POSSUM	$N_{\text{iter, max}}$	integer	Maximum number of iterations for RMCLEAN
POSSUM	g	double	Loop gain for each iteration of RMCLEAN
POSSUM	c	double	Sigma cut-off for the maximum remaining residual at which RMCLEAN should halt.
POSSUM	σ_{QU}	double	Noise spectrum to determine cutoff (on a per channel basis).
POSSUM	κ	integer	Algorithm for determining clean component locations
Outputs of module:			
2.5	$\mathcal{F}_c(\phi)$	double(N_ϕ, 2)	Restored 'clean' Faraday dispersion function $\mathcal{F}_C(\phi) = \mathcal{Q}_C(\phi) + i\mathcal{U}_C(\phi)$. [Jy beam^{-1} rmsf^{-1}].
2.5	$\mathcal{F}_m(\phi)$	double(N_ϕ, 2)	Complex model component spectrum of Faraday dispersion function [Jy beam^{-1}].
2.5	$\mathcal{F}_r(\phi)$	double(N_ϕ, 2)	Residual complex polarisation spectrum [Jy beam^{-1} rmsf^{-1}].
2.5	$N_{\text{iter, done}}$	integer	Number of iterations performed by RMCLEAN.
2.5	$F_{\text{max}-\text{iter}}$	integer	Flag indicating maximum iterations performed i.e., clean cutoff not reached.

Table 4: Measurements on the Faraday dispersion function.

Ref.	Symbol	Type	Description
Inputs to module:			
§2.3	ϕ	double(N_ϕ, 2)	Faraday depth vector matching $\mathcal{F}$ [rad m^{-2}].
§2.3	$\mathcal{F}(\phi)$	double(N_ϕ, 2)	Complex Faraday dispersion function divided into real $\mathcal{Q} = \Re\mathcal{F}$ and imaginary $\mathcal{U} = \Im\mathcal{F}$ parts.
§2.3	$\Delta\phi_\mathcal{R}$	double	FWHM width of the RMSF.
§2.3	λ_0^2	double	Reference wavelength-squared used when performing RM-synthesis.
POSSUM	$\mathrm{SNR}_{\mathrm{debias}}$	double	Signal-to-noise threshold above which to perform debiasing.
POSSUM	$\mathrm{SNR}_{\mathrm{detect}}$	double	Signal-to-noise threshold for a valid detection.
Outputs of module:			
§2.5	$\mathbf{P}_{\mathrm{peak, ch}}$, $\sigma(\mathbf{P}_{\mathrm{peak, ch}})$	double	Polarised intensity $\mathbf{P} = |\mathcal{P}|$ and uncertainty of the peak in the Faraday dispersion function [Jy].
§2.5	$\mathbf{P}_{\mathrm{peak, ch, eff}}$	double	Effective polarised intensity [Jy]. Debiased using Eqn 10.
§2.5	$\phi_{\mathrm{peak, ch}}$, $\sigma(\phi_{\mathrm{peak}})$	double	Faraday depth and uncertainty measured from the peak channel of the Faraday dispersion function [rad m^{-2}].
§2.5	$\mathbf{P}_{\mathrm{peak, fit}}$, $\sigma(\mathbf{P}_{\mathrm{peak, fit}})$	double	Polarised intensity and uncertainty of the peak found by a 3-point parabolic fit [Jy].
§2.5	$\mathbf{P}_{\mathrm{fit, ch, eff}}$	double	Effective polarised intensity [Jy]. Debiased using Eqn 10.
§2.5	$\phi_{\mathrm{peak, fit}}$, $\sigma(\phi_{\mathrm{peak, fit}})$	double	Faraday depth and uncertainty of the peak found by a 3-point interpolation [rad m^{-2}].
§2.5	$\mathrm{D}_{\mathrm{dirty}}$	boolean	**True** if $\mathbf{P}_{\mathrm{peak, fit}} > \mathrm{SNR}_{\mathrm{detect}}$, **False** otherwise. If $\mathrm{D}_{\mathrm{dirty}} = \mathrm{False}$ then $\mathbf{P}_{\mathrm{peak, fit}}$ represents an upper limit.
§2.5	$\mathrm{E}_{\mathrm{dirty}}$	boolean	**True** if ϕ_{peak} occurs within $\Delta\phi_\mathcal{R}/2$ of the edge of the FDF, false otherwise.
§2.5	ψ_{λ_0}, $\sigma(\psi_{\lambda_0})$	double(2)	Polarisation position angle at λ_0 and its error [degrees].
§2.5	ψ_0, $\sigma(\psi_0)$	double(2)	Polarisation position angle de-rotated to $\lambda = 0$ and its error [degrees].
§2.5	f, σ_f	double	Fractional polarised intensity and its error.
§2.5	SNR, $\sigma(\mathrm{SNR})$	double	Signal-to-noise ratio ($\mathbf{P}_{\mathrm{peak, fit}}/\langle\sigma_{QU}\rangle$) in polarisation and its error.
§2.5	C_1	double	Faraday complexity metric 1: Deviation of $\mathbf{P}(\nu)$ from a constant.
§2.5	C_2	double	Faraday complexity metric 2: Residual structure in $Q(\nu)\,\&\,U(\nu)$ after subtracting a single Faraday thin component at the peak detected in $\mathcal{F}(\phi)$.

which the error distribution of ϕ_{peak} becomes approximately Gaussian and the false detection rate drops below 10^4 (see George et al. 2012). For this reason we only consider peak fits above $\text{SNR} > 8\sigma_{\text{QU}}$ as valid detections.

Parameters of the Peak: $\mathbf{P}_{\text{peak}}$, $\sigma(\mathbf{P}_{\text{peak}})$, ϕ_{peak} and $\sigma(\phi_{\text{peak}})$

Once a detection has been confirmed the amplitude $\mathbf{P}_{\text{peak}} = \max(|\mathcal{P}(\phi)|)$ and $\text{RM} = \phi_{\text{peak}}$ should be measured by interpolating between the channels around the peak. Currently this is done by performing a three-point parabolic fit centred on the peak ϕ channel. This procedure avoids quantising the measured values of ϕ and results in a more accurate estimate of the polarised intensity. The fit should not be performed below a signal-to-noise ratio of four, however, this is well below our detection threshold. POSSUM report 11 recomends correcting the observed polarised intensity for polarisation bias according to

$$\mathbf{P}_{\text{eff}} = \sqrt{\mathbf{P}_{\text{peak}}^2 - 2.3\sigma_{\text{QU}}^2}, \tag{10}$$

but only for sources with $S/N \geq 5$.

In the POSSUM pipeline we perform the equivalent of fitting Gaussians (or parabolas) to the peak of a Faraday dispersion function[3]. Expressions for the uncertainties in Gaussian fitting are given by Condon et al. (1998) and we use these with the pipeline. The uncertainty in RM is given by

$$\sigma(\phi_{\text{peak}}) = \frac{\Delta\phi_{\mathcal{R}}}{2\,(S/N)} = \frac{\Delta\phi_R\,\sigma_{QU}}{2\,\mathbf{P}_{\text{peak}}}, \tag{11}$$

where $S/N = \mathbf{P}_{\text{peak}}/\sigma_{QU}$ is the signal-to-noise ratio of the polarised intensity and $\Delta\phi_{\mathcal{R}}$ is the FWHM of the RMSF main-lobe. The corresponding uncertainty in the polarised intensity is given by

$$\sigma(\mathbf{P}_{\text{peak}})^2 = \frac{2\,\mathbf{P}_{\text{peak}}^2}{\sigma_{QU}^2}. \tag{12}$$

Note that if no signal was detected above a threshold of $\text{SNR}_{\text{detect}}$ then $\mathbf{P}_{\text{peak}}$ is set to $\max(|\mathcal{P}(\phi)|) \times \text{SNR}_{\text{detect}}$ and the flag D_{dirty}=False indicates that this value is an upper limit.

Polarisation Angle at λ_0 and $\lambda = 0$: ψ_{λ_0}, $\sigma(\psi_{\lambda_0})$, ψ_0 and $\sigma(\psi_0)$

The polarisation angle at λ_0 is given by

$$\psi_{\lambda_0} = \frac{1}{2}\tan^{-1}\left(\frac{\mathcal{U}|_{\phi_{\text{peak}}}}{\mathcal{Q}|_{\phi_{\text{peak}}}}\right) \tag{13}$$

and its corresponding uncertainty by

$$\sigma(\psi_{\lambda_0})^2 = \frac{1}{4}\frac{\sigma_{\text{QU}}^2}{\mathbf{P}_{\text{peak}}^2} \quad \dots \quad \text{radians} \tag{14}$$

Once the RM of a source and the observed polarisation angle are known the polarisation angle at $\lambda = 0\,\text{m}$ may be calculated from Brentjens & de Bruyn (2005)

$$\psi_0 = \psi_{\lambda_0^2} - \phi_{\text{peak}}\lambda_0^2. \tag{15}$$

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[3]Prior to the development of RM-synthesis the usual way to measure RMs was to fit a straight line to a plot of ψ versus λ^2. For the case of a single Faraday thin component the uncertainties are comparable to those of RM-synthesis. Assuming a straight-line fit to ψ versus λ^2, Brentjens & de Bruyn (2005) derive the standard uncertainty in the RM as $\sigma(\phi_{\text{peak}}) = \sigma_{QU}\,/\,[4\,(N-2)\,\mathbf{P}_{\text{peak}}^2\,\sigma_{\lambda^2}]$, where N is the number of λ^2 channels, σ_{QU} is the common noise level in the Stokes Q and U spectra and $\sigma_{\lambda^2}^2$ is the variance in the λ^2 distribution given by Equation 17.

This is known as do-rotating the polarisation angle to the intrinsic value. The corresponding uncertainty σ_{ψ_0} in the de-rotated polarisation angle is given by

$$\sigma_{\psi_0} = \frac{1}{4\,(N_\nu - 2)\,\mathbf{P}_{\mathrm{peak}}^2} \left(\frac{N_\nu - 1}{N_\nu} + \frac{\lambda_0^4}{\sigma_{\lambda^2}^2} \right),\tag{16}$$

where N is the number of frequency (or λ^2) channels and $\sigma_{\lambda^2}^2$ is the variance in the λ^2 distribution given by

$$\sigma_{\lambda^2}^2 = \frac{1}{N_\nu - 1} \left[\sum_i \lambda_i^4 - N_\nu^{-1} \left(\sum_i \lambda_i^2 \right)^2 \right].\tag{17}$$

Fractional Polarisation: f and σ_f

RM-synthesis is performed on $(q, u) = (Q/I_{\mathrm{mod}}, U/I_{\mathrm{mod}})$ and the FDF is multiplied by $S_{\lambda_0} = I_{\mathrm{model}}|_{\lambda_0}$ to return the FDF it to units of Jy beam^{-1} rmsf^{-1}. Assuming an unresolved Faraday-thin source, the fractional polarisation is given by $p = \mathbf{P}_{\mathrm{peak}}/I_{\mathrm{model}}|_{\lambda_0}$ and the error by $\sigma(p) = \sqrt{(\sigma(\mathbf{P}_{\mathrm{peak}})^2 + \sigma_{\mathrm{QU}}^2)}$.

Assessing the complexity in the FDF

A simple Faraday screen manifests as a single delta-function in the FDF, with a unique Faraday depth and polarised intensity. The fractional polarisation spectrum $p(\nu)$ of this simple source will be flat and the $q(\nu)$ and $u(\nu)$ spectra describe sine-waves. Such a source is described as 'Faraday simple' (or Faraday thin) and can be assigned a unique RM in the PPC. Any FDF which deviates significantly from this simple case is called 'Faraday complex' and must be analysed with more advanced algorithms. The complexity can be due to additional Faraday-thin components along the line of sight, synchrotron emission internal to the rotating gas, which broadens the signal in the FDF (Faraday thick), or de- and re-polarisation effects. Faraday complexity can be seen as additional structure in $\mathcal{P}(\phi)$ and variation in $p(\nu)$ away from a flat spectrum.

In the Level-5 pipeline we define two measures of Faraday complexity as follows. The first codifies the deviation in fractional polarised intensity from a constant value. We defined C_1 as

$$C_1 = \frac{\sum_j (p_j - \langle p \rangle)^2}{(N_\nu - 1)\,\sigma(p)^2},\tag{18}$$

where p_j is the fractional polarisation in the jth channel. The value of C_1 should be measured from a binned version of the p spectrum to maximise the signal-to-noise ratio. Investigations are underway to determine the ideal averaging interval for POSSUM and POSSUM-12. The second metric measures the residual structure in the complex FDF after a single Faraday thin model component has been subtracted from the peak.

$$C_2 = \frac{\sum_j \left[(q_j - q_{j,\,\mathrm{mod}})^2 + (u_j - u_{j,\,\mathrm{mod}})^2 \right]}{(N_\nu - 1)\,\sigma(p)^2},\tag{19}$$

where q_{mod} and u_{mod} are fractional Stokes Q and U spectra for a single Faraday thin component with the parameters measured from the current FDF. The model spectra to be subtracted are generated from

$$\mathcal{P}(\nu) = p \exp\left[2i\,\psi_0) + \phi_{\mathrm{peak}}\,(c/\nu)^2) \right],\tag{20}$$

where $Q(\lambda^2) = \Re\,\mathcal{P}(\nu)$, $U(\nu) = \Im\,\mathcal{P}(\nu)$ and c is the speed of light in a vacuum.

Flags and other information

The following information is recorded to the database:

- Signal to noise threshold $\mathrm{SNR}_{\mathrm{detect}}$ used in the algorithm.

Table 5: Additional measurements on the clean Faraday dispersion function.

Ref.	Symbol	Type	Description
Inputs to module:			
2.2–2.5	ϕ	double(N_ν)	Faraday depth vector matching $\mathcal{F}_c$ [rad m^{-2}].
2.2–2.5	$\mathcal{F}_c(\phi)$	double(N_ν, 2)	Deconvolved complex Faraday dispersion function.
2.5	$\mathcal{F}_m(\phi)$	double(N_ϕ, 2)	Complex model component spectrum of Faraday dispersion function [Jy beam^{-1}].
2.5	T_c	double	Complexity threshold: if the 2nd moment of $\mathcal{F}_m(\phi)$ is greater than $T_c \times \Delta\phi_\mathcal{R}$ then the spectrum is deemed complex.
Outputs of module:			
PPC	s	integer	Code for complexity of spectrum: 0 = single unresolved RM component; other values reserved for different types of behaviour.
PPC	r_1	integer(5,2)	code for quality of $\phi_{\mathrm{peak,\,fit}}$, $\psi_{\mathrm{peak,\,fit}}$, $\mathbf{P}_{\mathrm{peak,\,fit}}$, f, SNR and their errors; 0 = all values acceptable; other values reserved for potential issues (e.g. insufficient signal-to-noise to determine RM).

- Flag that a detection was made D_{dirty}.

- Signal to noise of the detection SNR.

- The effective peak polarised intensity $\mathbf{P}_{\mathrm{eff}}$ corrected for polarisation bias.

If polarised emission was not detected then the detection flag is set to *False*, indicating that the recorded parameters are limits only. We do *not* record the RM value for an insignificant peak in the FDF spectrum.

Optional: Measurements on the clean FDF

Measurements on the clean FDF are identical to those of the dirty FDF plus the additions recorded in Table 5.

3 Issues identified

The following issues were identified during the construction of the pipeline:

- Instrumental polarisation correction memo needed.

- How do we deal with changing primary beam size? Currently cutoff at FWHM of highest freq.

- Spectrum extraction method needs to be ajusted for elongated beams.

- best method to model the Stokes I spectrum? Polynomial fit? (What order?) Low-pass filter? (What cutoff?)

4 Specifications of the PVACat

Similar to the PPC, the PVACat starts from a catalogue of Stokes I sources provided by EMU - the EMU Value Added Catalogue (EVACat). The PVACat will adopt the following from the EVACat:

- Identification and characterization of multiple POSSUM components associated with a single EMU component.

- Cross-IDs with other multi-wavelength datasets and catalogues, including full Bayesian likelihood analysis of positive matches.

- Redshifts and other distance indicators.

- Source type identification and derived properties.

The PVACat will codify the polarisation properties of each source beyond the simple RM measurements of the PPC. The definition of the PVACat is still under development, but it may include the following:

- Dominant and secondary RMs (if they exist) for each POSSUM component in PPC or added as above.

- A further categorization of Faraday properties of existing PPC entries and/or multiple POSSUM components. This may take the form of models fit directly to the Stokes spectra or to the 3-D data cubes, e.g., turbulent Faraday screens, inclined radio-galaxies.

- Statistics of RM properties for well-defined classes of objects (e.g., by optical ID, redshift)

- Cubes of RM for whole sky [includes diffuse emission, not just around EMU sources, as in PPC], with and without single dish data.

- Lower resolution products for better surface brightness sensitivity. We may want to average P instead of Q,U.

Later versions of the PVACat may also contain entries for sources identified solely in the Stokes $Q\,U\,\&V$ data. The algorithms for performing such source-finding are at a very early stage of development.

A wide range of policy decisions remain, with respect to PVACat. These include:

- How/when will be management structure for PVACat be set up;

- Process for vetting both basic (managed) and enhanced (voluntary) products prior to inclusion.

- Temporary or permanents proprietary nature of enhanced data products and timing (probably staged) of public releases; (EMU's bias is to disseminate everything as quickly as possible.)

- How to reserve projects for students.

- Publication policies;

- Coordination with EMU.

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