Note on the description of polarization data
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Abstract

This is a draft note to provide information on how polarized data are usually described and how this could be characterised for VO use. The emphasis is on data likely to be published to the VO, using radio conventions.

1 Status of this document

This is an IVOA Note expressing suggestions from and opinions of the authors. It is intended to share best practices, possible approaches, or other perspectives on interoperability with the Virtual Observatory. It should not be referenced or otherwise interpreted as a standard specification. A list of *current IVOA recommendations and other technical documents can be found at `http://www.ivoa.net/Documents/`.*

Acknowledgements

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Contents

2 Introduction

At the time of writing, VO models and protocols such as STC, SIAP do not explicitly describe polarization data. The extension of SIAP to v2, catering for multi-dimensional data, is in progress. One of the only examples of 3D data currently publically available is the NVSS IQU imge data cubes, where the three Stokes parameters make up 3 planes of the third axis of the cube, the only differences being in the nature of the flux density measured in each plane. VO standards and tools need to encompass polarization by providing metadata labels, recognising and translating native labels (e.g. in FITS) and supporting tools which perform common operations (e.g. display the 3 NVSS planes and combine them to form fractional polarized intensity).

At least initially, we can assume that users wanting to re-extract products or perform accurate, quantitative measurements will use specialised tools (locally or remotely). It is the responsibility of the user or tool provider to interpret the data, apply the algorithms required and make intelligent assumptions where required, including about accuracy. However, the data have to be described well enough for the user to find them and decide what is useful, so the data model should contain basic details relating to accuracy, etc.

This Note is not tied to any one IVOA standard, since some aspects will be included in SIAPv2, some in Provenance, in STC, and so on. The principle intention here is to summarise the required concepts and early attempts at representation and to suggest use cases to drive future developments.

3 Polarization terminology

3.1 Astronomer jargon

Table 1 lists the usual terms used to describe polarization and their relationships. Figure 1 illustrates the ways in which receivers collect either circular or linear polarization. In many instruments the signals can be combined to produce all types of polarization. Astronomical sources can show linear or circular polarization or both (elliptical polarization), or none. Table 1 lists the commonest expressions used to describe polarization. In general, science-ready data published to the VO should be described in terms of Stokes parameters or (fractional) polarized intensities and the polarization angle, or as left- or right-circular polarization. Interconversions such as deriving the polarization angle $\chi = \arctan 2(U, Q)$ can be performed on images by any suitable software. Other uses of feed parameters (RR, LL, RL, LR,

XX, YY, XY, YX) usually belong in the observatory domain since they often require specialised software (or even local conventions) and handling of visibility data. They are included for completeness.

The commonest derived quantity is the Rotation Measure, defined as the variation in polarization angle with observing wavelength, units radians m^{-2}. (For interest, this is due to the fact that the linear polarization angle is rotated when electromagnetic radiation propagates through a plasma and the rotation is greater at longer wavelengths, a phenomenon known as Faraday rotation. This can be produced by the emitting source itself, by terrestrial ionosphere and/or by the intervening interstellar medium.)

In the rest of the Note we concentrate on published polarization measurements, as distinct from observing parameters, although any inclusion of the latter in standards for Provenance etc. should be consistent with the usage for observables.

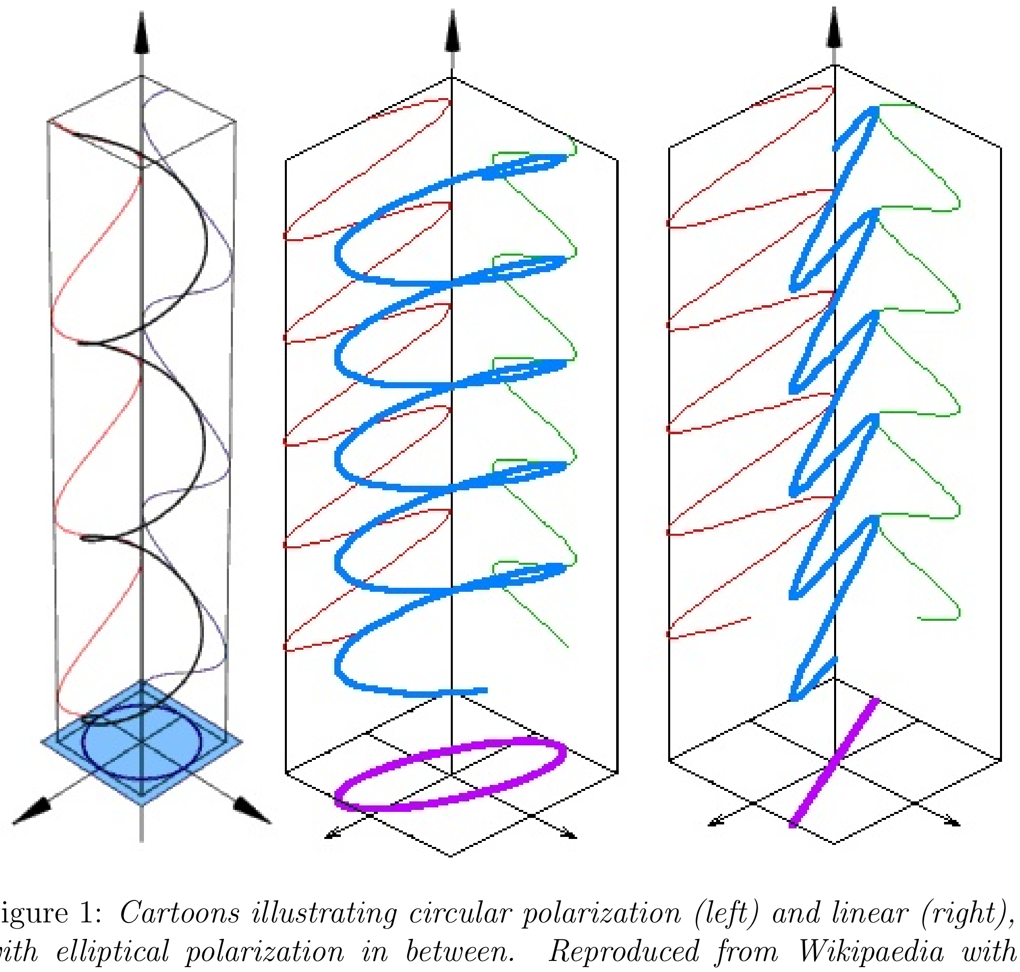

Figure 1: *Cartoons illustrating circular polarization (left) and linear (right), with elliptical polarization in between. Reproduced from Wikipaedia with thanks.*

TERM	COMMON SYMBOL	DESCRIPTION
Stokes parameters	I	Total intensity $(LL + RR)/2$
	Q	Linear polarization $P\cos(2\chi)$ or $(RL + LR)/2$
	U	Linear polarization $P\sin(2\chi)$ or $(RL - LR)/2i$
	V	Circular polarization $(RR - LL)/2$
Circular polarization	LHC, RHC or LCP, RCP or LL, RR, or L, R	Left and Right circular polarization
Linear polarization angle	χ or PA or POLA	$0.5 \arctan 2(U, Q)$ or $0.5\phi_{RL-LR}$
Linearly polarized intensity	P or POLI	$\sqrt{Q^2 + U^2}$
Elliptically polarized intensity	M	$\sqrt{Q^2 + U^2 + V^2}$
Circularly polarized intensity	$\|V\|$	Absolute value of V
Fractional Q	q	Q/I
Fractional U	u	U/I
Fractional V	v	V/I
Fractional linear polarization	p	$\sqrt{Q^2 + U^2}/I$
Fractional elliptical polarization	m	$\sqrt{Q^2 + U^2 + V^2}/I$
Fractional circular polarization	v (strictly, $\|v\|$)	$\|V\|/I$
Circular feeds	L, R or LL, RR and LR, RL ϕ_{RL-LR}	L, R circular polarization (linear) cross hands $RL - LR$ phase difference
Linear feeds	X, Y or XX, YY and XY, YX	Linear polarization, (circular) cross hands

Table 1: *Terms used to describe polarized data. The fractional symbols are less standard and potentially ambigious. Different observatories use different conventions for the labelling of linear feed products and hence for deriving Stokes parameters.*

3.2 Data quality

As with any observable, systematic and relative uncertainties and other indicators should be given (but may not be available). If the data are a cube, then the uncertainties in the observable may be given only once, assumed to apply to all polarization planes. Or, there may be separate values for each plane.

Images or other products of radio interferometry are usually (more or less) completely calibrated, since most corrections have to be applied in the visibility domain. Usually they are in physical units, or in normalised or relative flux units or ratios. Other polarized data published to the VO should be similarly science-ready. However, this may not always be the case, or observing logs describing raw or partly calibrated data may be published.

If the data are fully calibrated, systematic and relative errors for each (or all) polarization product may be given, or the relative errors could be given as error maps, in the same way as for total intensity. It would be desirable to have a pointer to the calibration history and origin of the various errors, and for observing logs or incompletely calibrated data this is very important. The main issues specific to polarized data are:

- Leakage between feeds: has this been corrected? what is the residual, systematic error (usually a fraction of the total intensity)?
- Has the polarization angle been corrected? What is the systematic uncertainty?
- Has compensation been applied for the parallactic angle rotation of the feeds on alt-az telescopes?
- What is the signal-to-noise ratio at which dynamic range limitations become important?
- Some polarization properties can have valid negative values of the observable (e.g. Q, U, V, PA). Hence, their 'believable' values may cover two ranges (e.g. $-1.0 < V < -0.001$ and $0.001 < V < 1$) and propagation of errors in combining quantities needs to take this into account.

3.3 Units

Jy beam^{-1} is the commonest unit for interferometric imaging (whether or not there is an explicit polarization). This means that there needs to be an efficient link between the flux density and the beam size (Resolution, in Characterisation). This is essential for detailed data retrieval queries.

The alternatives are to use Jy arcsec^{-2} or some equivalent fundamental angular unit, or to omit the angular part altogether and use Jy. Data providers might be prepared to use either for the coarsest levels of description, for data discovery. However, the former will confuse users who have a little knowledge – e.g. the limiting flux density of the NVSS is 0.0015 Jy beam^{-1} or 0.0027 Jy arcsec^{-1} – close enough for the difference not to be obvious but different enough to wreck the intention of a query. The latter is sloppy, but possibly more intuitive for coarse-grained selection, since if you want to get results from a range of data collections at different resolutions, the beam size is not the only constraint.

3.3.1 Flux densities

The units of the Stokes parameters I, Q, U and V, of total polarization (linear, elliptical or circular) and of separate circular polarizations (LCP, RCP) are some form of flux density. This can be:

- Jy (or SI-prefixed multiples). This is the normal unit for visibility (Fourier) amplitudes. In the case of spectra and of tables of extracted data, it is, by implication, "per channel" and "per object", respectively.
- Jy beam^{-1} (or SI-prefixed multiples). This is the commonest unit in radio interferometric imaging.
- Jy arcsec^{-2} (or Sr^{-1} or SI-prefixed multiples).
- Jy beam^{-1} Hz (or km s^{-1} or SI-prefixed multiples). This is the most specific unit for spectra extracted from interferometric cubes; beam^{-1} may be omitted or replaced by other units of solid angle.
- W m^{-2} or W m^{-2} Hz^{-1} (or SI-prefixed multiples, or the equivalent in cgs). This would mostly be encountered in processed images intended for comparison with other data or in tabulated data.

Raw visibility data in the feed parameters may also be expressed as complex visibilities (usually amplitude, phase, weight) but hopefully the VO can ignor this for now.

3.3.2 Polarization Angle

The polarization angle is normally measured from North towards East in either of:

- Degrees
- Radians (rarely)

3.3.3 Relative Polarization

The fractional polarizations are dimensionless but can be fractions or percentages. Note that the term *fractional polarization* or *degree of polarization* may be used without further qualification; this usually means fractional or percentage total polarization; strictly speaking, this is elliptical but it is often used in the context of sources where circular polarization is assumed to be negligible.

3.3.4 Derived quantities

More sophisticated derived quantities tend to have fewer alternatives, e.g. Rotation Measure is invariably (as far as we know) expressed in rad m^{-2}. This section will be expanded once we progress to including these in SIAv2, for example.

3.4 FITS metadata and its limitations

The FITS header fragment below shows the use of the FITS coding shown in Table 2. The image is multidimensional, with 288 pixels on each of the positional axes (Right Ascension and Declination), but only one frequency coordinate. It has 4 entries on the Stokes axis, and can be treated as a datacube. The third dimension is actually `NAXIS4`, the STOKES axis, containing 4 planes, with a `CRVAL4` of 1 and increments `CDELT4` of 1, starting from `CRPIX4` at plane 1. Hence, the Stokes values present are (1, 2, 3, 4), representing I, Q, U, V. Figure 2 shows the corresponding images.

```
SIMPLE  =                    T /Standard FITS
BITPIX  =                  -32 /Floating point (32 bit)
NAXIS   =                    4
NAXIS1  =                  288
NAXIS2  =                  288
NAXIS3  =                    1
NAXIS4  =                    4
CTYPE1  = 'RA---SIN'
CRVAL1  =   1.389184979518E+01
CDELT1  =  -1.111111111111E-03
CRPIX1  =   1.450000000000E+02
CUNIT1  = 'deg     '
CTYPE2  = 'DEC--SIN'
CRVAL2  =   4.762418423798E+00
CDELT2  =   1.111111111111E-03
CRPIX2  =   1.450000000000E+02
CUNIT2  = 'deg     '
CTYPE3  = 'FREQ    '
CRVAL3  =   4.860100000000E+09
CDELT3  =   1.500000000000E+08
CRPIX3  =   1.000000000000E+00
CUNIT3  = 'HZ      '
CTYPE4  = 'STOKES  '
CRVAL4  =   1.000000000000E+00
CDELT4  =   1.000000000000E+00
CRPIX4  =   1.000000000000E+00
CUNIT4  = '        '
```

The VO could (should?) provide tools to extract polarization metadata from FITS headers where possible, but this can only be accomplished reliably for polarization parameters (correctly) described by the values in Table 2.

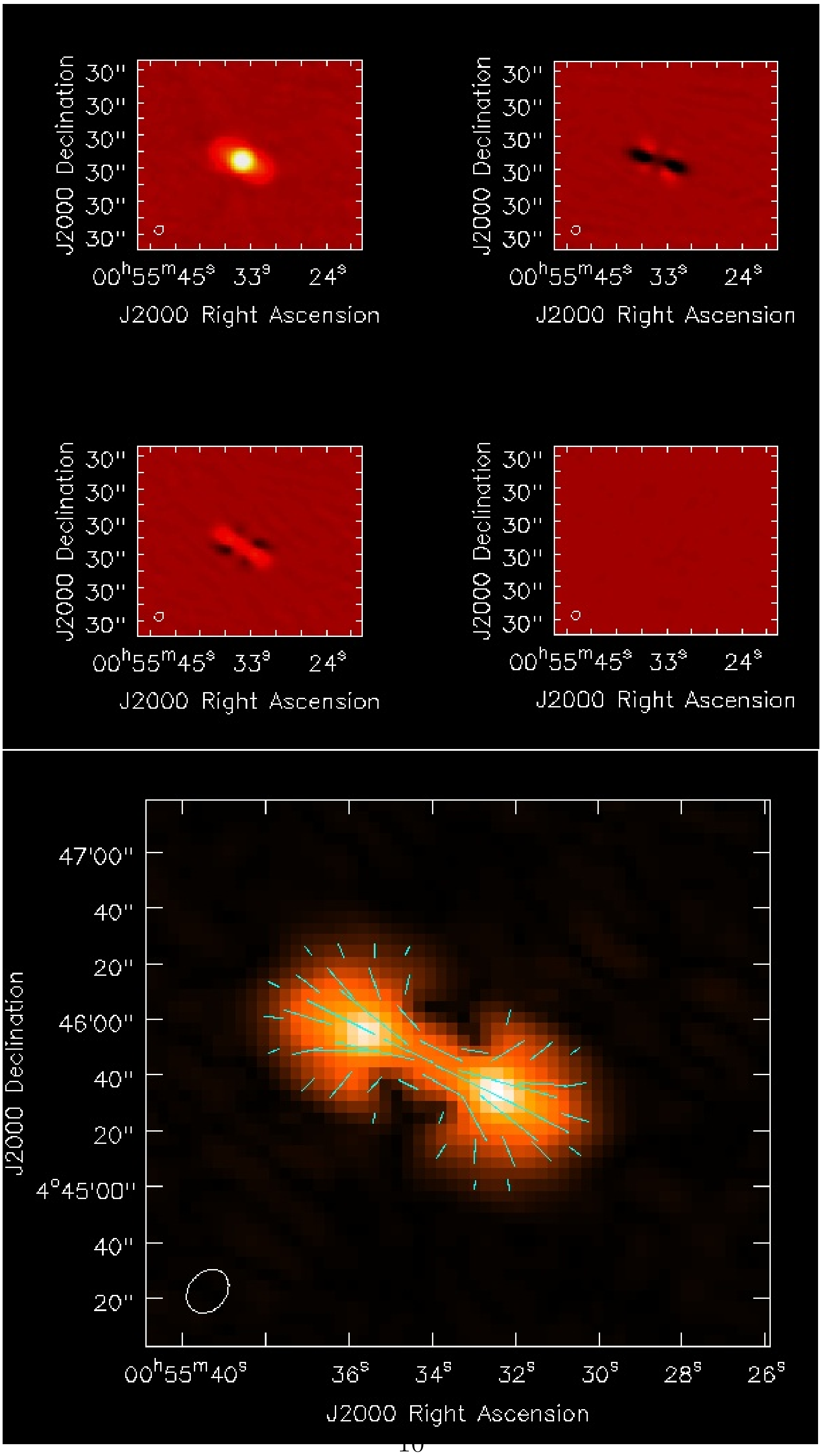

Figure 2: *VLA images of Jupiter at 1.4 GHz. From left to right: Top row, Stokes I (total intensity), Stokes Q. Middle row, Stokes U, V (no signal in V). Bottom, Polarized intensity, with polarization vectors overlaid.*

I	Q	U	V	RR	LL	RL	LR	XX	YY	XY	YX	POLI	POLA	UNDEF
1	2	3	4	-1	-2	-3	-4	-5	-6	-7	-8	5	7	- - -

Table 2: *FITS codes and their meanings for the polarization axis. Strictly speaking, only I, Q, U and V are Stokes parameters, but the FITS Stokes axis covers all terms for polarization parameterization. Note that most parameters can be present in any of Fourier (visibility) data, images, spectra, time series or tabular data.*

Even then, the FITS header of a cube with multiple polarization planes can only contain at most one set of values for the data maximum and minimum, the noise rms and the mean value of the observable.

FITS does not fully convey all the necessary information, for example there is no code for rotation measure and the FITS axes cannot convey that such an image was made from e.g. a 50-MHz polarization angle image centred on 1420 MHz, a 100-MHz image centred on 4000 MHz and a 150-MHz image centred on 8000 MHz. This information should be available in the history file but the data provider should be responsible for extracting the necessary metadata (including units).

This issue is relevant also for other advanced products such as the spectral index α, defined via $S(\nu) \propto \nu^{\alpha}$ or $S(\nu) \propto \nu^{-\alpha}$, or optical depth or moment images derived from data cubes.

4 Polarization as an observable

4.1 ucds

Measures of polarization are essentially observables (or models/simulations of observables), based on flux density measurements or estimates. The FITS values (Table 2) could form the basis for ucds, e.g.

```
phot.flux.density;phys.polarization.stokes.I
phot.flux.density;phys.polarization.stokes.Q
phot.flux.density;phys.polarization.stokes.U
phot.flux.density;phys.polarization.stokes.V

phot.flux.density;phys.polarization.circular.RR
phot.flux.density;phys.polarization.circular.LL

phot.flux.density;phys.polarization.linear.POLI
phot.flux.density;phys.polarization.linear.POLA
```

At present, the ucd `phys.polarization` refers to polarization degree or percentage. This is potentially ambiguous – as are the symbols in common use – so it might be better to use constructs such as:

```
phot.flux.density;phys.polarization.stokes.V.fraction
phot.flux.density;phys.polarization.circular
phot.flux.density;phys.polarization.circular.percent

phot.flux.density;phys.polarization.linear.fraction
phot.flux.density;phys.polarization.linear.percent
```

corresponding to v, $|V|$, $100 \times |V|/I$, p, $100 \times p$.

4.2 Usage

Polarization data may be images, spectra (from single dish or visibility data), Fourier (visibility) data, time series or other representations of the sky, or catalogues of polarization properties. Observatory logs may require terms related to the feed parameters for describing potential polarization products.

Data can have just one polarization parameter[1]. If this is not specified then the default is total intensity (Stokes I). If it is specified, this may be in the form of a Stokes axis with a single value, or it may be found in the image (spectrum etc.) header, or in the column label or header of a table. In all such cases, the rest of the metadata required for the VO is as for any other data. Metadata extraction or visualisation tools simply need to interpret the polarization label and units appropriately.

If data are provided as a collection of different polarizations, this may be in the form of a cube, as in Section 3.4. If more than one polarization is present, then all polarizations must be specified. The number of polarizations present ($NAXIS4$ in the FITS cube header given in Section 3.4) should be given. 'Cubes' may have more than 3 dimensions; for example, the FITS header shown in Section 3.4 might have multiple frequency channels (`NAXIS3` > 1). If there is a multi-valued polarization axis, then all polarization planes should have the same coordinates apart from the plane number and the label of the observable. They should all have the same units (e.g., Polarization Angle cannot be in the same cube as Polarised Intensity). The characterisation of the observable may be different, such as different bounds or errors.

[1]'single polarization' implies that the output of just one telescope feed, e.g. only LL, is present, so we try to avoid this in other contexts.

If the data are in the form of a collection of separate images (etc.) which share some characterstics such as position, frequency, then it should be possible to copy the metadata in common with minimum effort, or modify it as required.

4.3 Metadata Model

Polarization metadata can be modelled using the characterization data model. The various polarization states can be described as different values on a characterization axis. This axis is peculiar in that it always consists of a discrete set of literal values. This is partly analogous to a spectral axis containing several planes, spaced irregularly and of different spectral widths (often the case, for example, when preparing SEDs) which can be expressed as a set of labels of observing bands.

Characterizing the polarization axis is thus accomplished by listing the polarization states present in the dataset. The VOTable serialisation provides a PolarizationAxis.enumeration utype for a FIELD giving the list of "available" polarization states

The different polarization states can have different detection limits, dynamic ranges and so on. If there is more than one polarization present within one data set, this makes it difficult to characterize globally because their different Observable bounds, resolution etc. cannot be associated with specific polarization axis values in the present model implementation. It may be sufficient to set outer bounds at the coarsest level (usually taking the maximum total intensity as the upper bound and its negative as the lower bound).

If more precision is available,characterization is considered complex and each polarization state can be described as a segment of characterization (see XML serialisation example).

5 Examples

5.1 Registry search

At present, VOExplorer finds 151 resources with *polari** in any field. However, some of these are in the instrument description but the data supplied is not polarized. The only useful data seem to be catalogues, found via ucds.

5.2 Data Access Layer implications

The S*AP protocols (see SIAv2 draft) should provide the functionality to allow the discovery of specific or generic polarization states other than total intensity (e.g. Stokes Q or Linear Polarization, respectively). For recognition (discovery)the SIAv2 query response will provide a FIELD with utype PolarizationAxis.enumeration. For selection (access) the POL paremeter of the query interface will allow the filtering of some of the POL states on demand. This should also enable access to services offered by data providers such as the on-demand generation of polarization products such polarization angle from Q and U, and, eventually, Rotation Measure etc., although we do not yet have an obvious vocabulary for quantities without FITS codes.

5.3 Catalogues

This includes tabulated measurements (not observing logs). This should be straightforward, using ucds and TAP/VOQL.

A Appendix A: XML serialisation example

To follow...

B Appendix E: Updates of this document

2009 November 8

Moved sentence on concentration on published data to section 3.1

Added subsection 3.2 on units and moved relevant mentions to there.

Moved old 4.3 (Data Quality) to section 3.3

FITS section is now 3.4. Mentioned limitations on metadata in FITS headers and restricted applicability of potential VO tools.

4.1 Added suggestion that we want initially to only worry about polarization quantities which have FITS codes.

Corrected sloppy wording in 4.2 Usage,

Added new sub-sections Metadata model 4.3

Replaced 5.2 with subsection on DAL implications