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Alliance

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/`.*

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Members of the IVOA Data Model Working Group, including representatives of the US NVO, the Euro-VO and AstroGrid have contributed to the present draft. Use cases and definitions were kindly provided by Paddy Leahy (Manchester) and Robert Laing (ESO).

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.

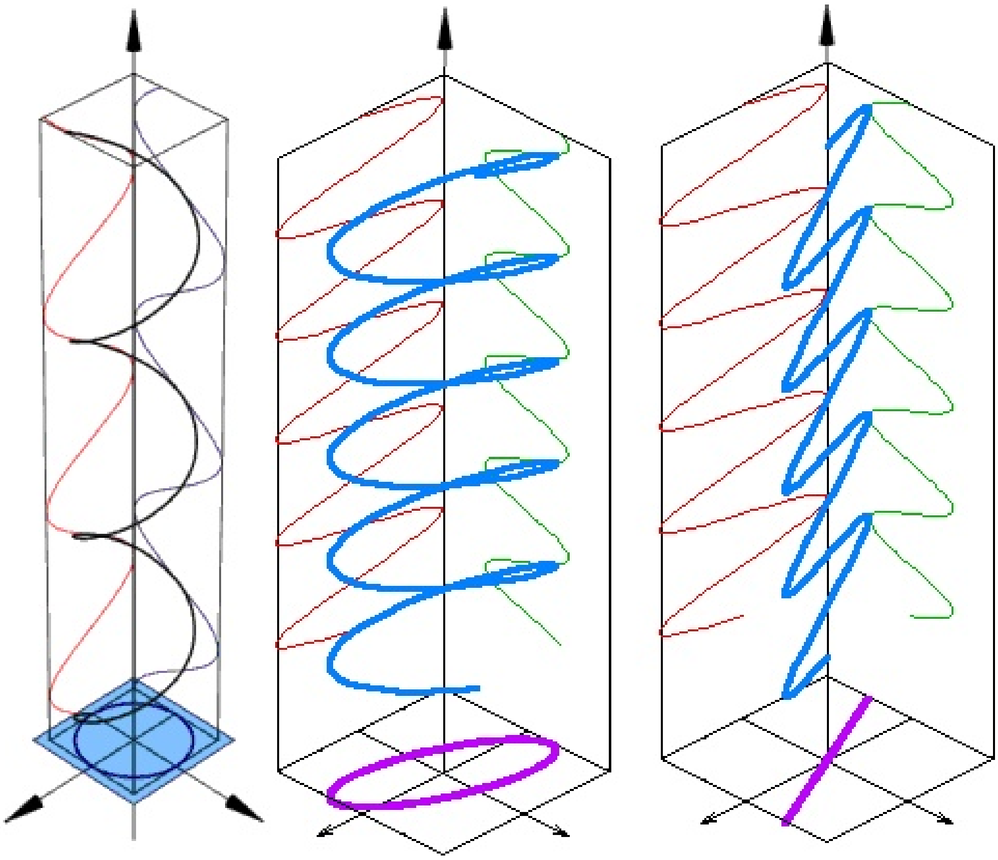

Figure 1: *Cartoons illustrating circular polarization (left) and linear (right), with elliptical polarization in between. Reproduced from Wikipaedia with thanks.*

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. The polarization angle has angular units, normally measured from North towards East. 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;

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	L, R circular polarization
	and LR, RL	(linear) cross hands
	ϕ_{RL-LR}	$RL-LR$ phase difference
Linear feeds	X, Y or XX, YY	Linear polarization,
	and XY, YX	(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.*

strictly speaking, this is elliptical but it is often used in the context of sources where circular polarization is assumed to be negligible.

Raw data in the feed parameters may be in these units or as complex visibilities but hopefully the VO can ignor this for now.

Other products may be formed from polarization data such as the rotation measure RM in units of angle per wavelength^2 (usually rad m$^-2$), or spectral index α, defined via $S(\nu) \propto \nu^{\alpha}$ or $S(\nu) \propto \nu^{-\alpha}$. Hopefully the relevant units will always be provided.

3.2 FITS

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  = '        '
```

In the rest of the Note we concentrate on published polarization measurements, as distinct from observing parameters, although any inclusion of the

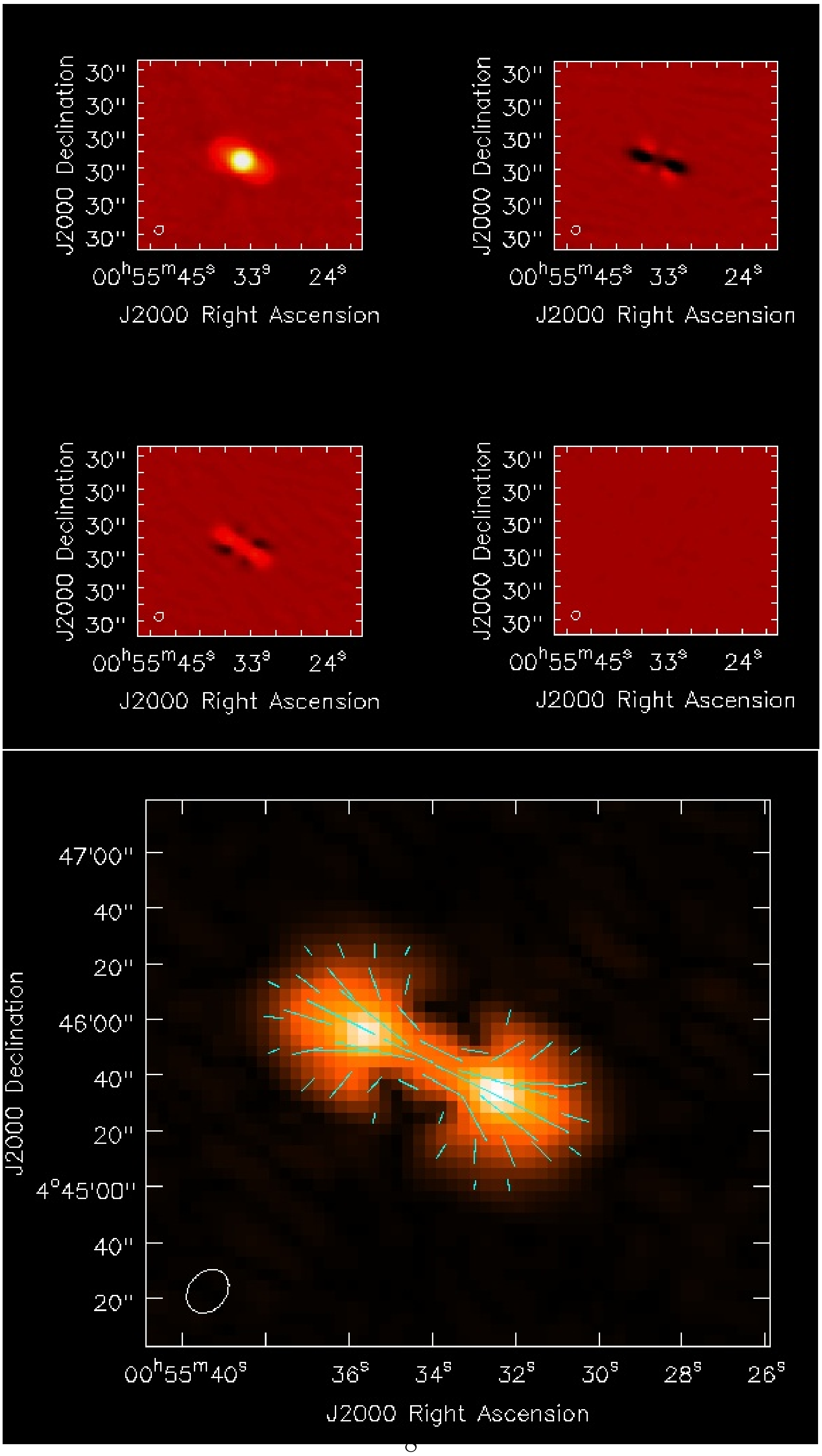

Figure 2: *VLA images of Jupiter at 1.4 GHz. From left to right: Top row, Stokes I (total intensity), Stokes Q. Middle row, Stokes U, V (no signal in V). Bottom, Polarized intensity, with polarization vectors overlaid.*

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.*

latter in standards for Provenance etc. should be consistent with the usage for observables.

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), time series or other representations of the sky, or catalogues of polarization properties. Observatory logs may also be published, which may require terms related to the feed parameters for describing potential polarization products.

Data can be in just one polarization[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 more than one polarization is present, then all polarizations must be specified. The number of polarizations present ($NAXIS4$ for a FITS cube) should be given.

If data are provided as a collection of different polarizations, this may be in the form of a cube, as in Section 3.2 or some other association. If a cube, then all polarization planes should have the same coordinates apart from the plane number and the label of the observable. The characterisation of the observable may be different, such as different bounds or errors.

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.

'Cubes' may have more than 3 dimensions; for example, the FITS header shown in Section 3.2 might have multiple frequency channels (`NAXIS3` > 1).

4.3 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

[1] Since 'single polarization' has a technical meaning for telescope feeds, I try to avoid this in other contexts.

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?

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 Finding and obtaining observed data

This includes images, spectra etc. in the domain of S?AP standards. There are two parts to the process; *recognising* and *selecting* polarized data. Recognition is a matter of making sure that data are registered correctly with *polari* as one or more axes labels, but not solely `.stokes.I`. Initially, we should get services working using other selection criteria (spatial, spectral, temporal) just to return polarized data. We should then investigate whether there is any demand for more sophisticated selection.

5.3 Catalogues

This includes tabulated measurements (not observing logs). This should be straightforward, using ucds and ADQL, once the Registry problem is overcome.

A Appendix A: XML serialisation example

B Appendix E: Updates of this document