Rotation Measure Synthesis Exercises
LOFAR Data School Oct 2010

The goal of these exercises is to gain familiarity with the technique of Rotation Measure (RM) Synthesis. A number of simulated spectro-polarimetric data sets will be Fourier transformed to Faraday depth space with a RM Synthesis code. This can be done for various frequency ranges and coverage, and the results will show some of the possibilities and limitations of the method.

1 The software

1.1 The RM Synthesis module

The RM Synthesis code is kindly provided by Michiel Brentjens. Its inputs are

- complex polarization cube as a function of frequency, in the form of a separate Stokes Q(ν) and Stokes U(ν) cube;
- a list of the frequency channels.

and it outputs

- a polarized intensity P(ϕ) cube as a function of Faraday depth ϕ;
- Stokes Q(ϕ) and U(ϕ) cubes;
- a text file containing the RMSF.

The code is used by typing:

```
> rmsynthesis
```

This call, without any parameters, will display information about its usage and the input and output parameters.

1.2 Visualizing the data cube with kvis

The data visualization package kvis can be used to look at your data set. Feel free to use any 3 data visualization program that you know. For those who want to use kvis but have never done so, here is a quick primer of the most useful functionalities.

Typing `kvis dataset` will open two windows: a data window and a browser window.

The browser window shows you the name of the data set that you have loaded. The button "Histogram" will pop up a new window which shows a histogram of data values. Click left (right) mouse button on the histogram to set the left (right) boundary of the grey scales you want.

The data window has a menu on top.
Intensity lets you select a color coding.
Zoom is straightforward. Click on "zoom policy" and uncheck "integer X zoom" and "Integer Y zoom" to maximize the map.
Overlay: select "Axis labels" and check "Enable" to see axis labels.
Export lets you save the maps.
View pops up a window to see the 3D character of your data. In the View window, select "Profile Mode:

Line" to pop up a window with a cut along the axis selected in "Profile Axis:". Place your cursor on a pixel in the map to see the cut. You can also click "Movie" to get a new window with controls for a movie through your 3D data cube.

For more information about kvis, see the karma/kvis documentation at:
http://www.atnf.csiro.au/computing/software/karma/user-manual/index.html

2 Menu of Data Sets

2.1 The table setting

In the directories that will be assigned to you, you will find a number of subdirectories, each with a set of simulated data sets. These data sets are meant to simulate synchrotron sources and Faraday screens that might occur in the interstellar medium, but of course greatly simplified.

Each data set contains a physical situation which is then "observed" with a certain frequency coverage. This results in Stokes Q and U cubes as a function of frequency, which are then inputs in the RM Synthesis module.

For every data set, a number of frequency ranges (or a subset of these) are available:

name	number of bands	channel width	minimum frequency
nf100A	100	1 MHz	110 MHz
nf100B	100	1 MHz	1000 MHz
nf100C	100	1 MHz	400 MHz
nf50A	50	2 MHz	110 MHz
nf50B	50	1 MHz	160 MHz

Text files with these frequency ranges, to input in the RM Synthesis module, are given in a subdirectory `/Frequencies/`.

2.2 Appetizer: Faraday thin sources

2.2.1 Spicy point source served with a Faraday screen remoulade

Extragalactic sources that are linearly polarized can be used as background probes of the intervening magnetized interstellar plasma. Extragalactic sources do show some intrinsic Faraday rotation generated in the source itself, which adds up to the Galactic RM - we neglect that component here. For a fairly high-latitude extragalactic source, typical values of $n_e = 0.05$ cm^{-3}, $B_{\|} = 1$ μG and $dl = 600$ pc, the RM of the foreground screen is of the order of 30 rad m^{-2}.

The test data sets simulating this situation are called `?_EGS_screen.*.fits` (with ? = Q, U) and they can be found in the subdirectory called `EGS_screen`. The maps consist of two gaussian background sources with each a different Faraday rotation screen in front of them.

Run the rmsynthesis code on these data sets with the appropriate frequency ranges. Then try to answer the following questions:

1. What are the rotation measures of these two sources?

2. How does the RMSF's change with frequency coverage and how does this affect your data?

3. Does this agree with what you would expect based on the equations below?

4. At which frequency can EGS with moderate RMs best be observed? Which telescope?

5. Inspect the 'unprocessed' Q and U maps that are in the directories, which are a function of frequency (and not Faraday depth). Do you understand why they look how they look?

2.3 Main course: Faraday thick sources

2.3.1 Burn slab charbroiled to perfection

In this situation, an interstellar cloud (a square one in this example) has a finite thickness in which it both emits synchrotron emission and undergoes Faraday emission ("Faraday thick" situation). This is a so-called Burn slab, named after the author who first discussed this behavior in 1966.

These data sets are in the subdirectory `/Burnslab`. There are files with names like `*Burnslab.20.2*` and `*Burnslab.5.2*`. The first number gives the number of pixels that the slab is thick, the second number gives the Faraday depth per pixel. I.e. the two data sets have Burn slabs that have a thickness of 20 pixels and 5 pixels, respectively, and both slabs have a Faraday depth of 2 rad m^{-2} per pixel.

Run rmsynthesis for the various frequency ranges and try to explain the results, and the differences between the results for different slabs and frequency coverages. E.g. at low frequencies (frequency range nf100A), the signal in Burnslab.20.2 has a much lower intensity than at higher frequencies (nf100B) - why?

2.3.2 Deluxe H II region smothered with a uniform magnetic field sauce

This situation describes a spherical blob in the center of the data cube. All pixels in the cube emit synchrotron emission, but only the ones within the sphere have a non-zero rotation measure. This could mimic an HII region, in which the electron density is much higher than the surroundings, so that most Faraday rotation would occur inside the HII region, while most synchrotron emission happens outside the source. Note that in this situation both the electron density and magnetic field (strength and direction) are constant within the sphere.

You can find these data in the subdirectory `/Sphere`.

2.3.3 Uniform-field infused supernova remnant pie

The last data set is a variation to the spherical situation: the only difference is that this source is a shell of Faraday rotation instead of a fully-filled sphere. The test data is in directory `/Shell`.

2.4 Dessert: Abell 2255

Here is a real data set, which you can inspect. Hopefully you will have seen the influence of frequency coverage on various Faraday depth components. Can you think of which of the issues are at play here?

This data is taken with the Westerbork Synthesis Radio Telescope in the direction of the galaxy cluster Abell 2255, in the frequency range from 310 to 380 MHz in 128 frequency channels. More details about this data set can be found in R. F. Pizzo, A. G. de Bruyn, G. Bernardi, M. A. Brentjens, 2010, arXiv:1008.3530, "Deep multi-frequency rotation measure tomography of the galaxy cluster A2255".

2.5 Addendum

Keep in mind the important parameters:

$$\delta\phi \approx \frac{2\sqrt{3}}{\Delta\lambda^2} \tag{1}$$

$$\Delta\phi_{max} \approx \frac{\pi}{\lambda^2_{min}} \tag{2}$$

$$|\phi_{max}| \approx \frac{\sqrt{3}}{\delta\lambda^2} \tag{3}$$

where $\delta\phi$ is the resolution in Faraday depth, $\Delta\phi_{max}$ is the maximum scale of a Faraday depth component that is observable, and $|\phi_{max}|$ is the maximum Faraday depth value that can be detected. Note that $\Delta\lambda^2 = \lambda_1^2 - \lambda_2^2$!