Application of the Regularized Optimization for Hyper-Spectral Analysis (ROHSA) Tool to Faraday Tomography Cubes

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Introduction

Magnetic fields are an unseen yet important contributor to the dynamics processes in our Galaxy like star formation. Although direct measurement of Galactic magnetic fields remains unfeasible, we are able to indirectly probe magnetic field structure through a variety of messengers. The modification of the polarization angle of polarized light as it passes through a magneto-ionic medium is known as the Faraday effect and is one of those messengers. Adopting the formalism of Brentjens and de Bruyn [1] I express the Faraday Depth as the integral along the line of sight:

$$\phi(\boldsymbol{r}) = 0.81 \int_{\text{there}}^{\text{here}} n_e \boldsymbol{B} \cdot \, \mathrm{d}\boldsymbol{r} \text{ rad m}^{-2} \qquad [1]$$

The polarization of light is modified by $\Delta\chi = \lambda^2\varphi$. The Stokes parameters are modelled according to the following integral:

$$P(\lambda^2) = \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} \, \mathrm{d}\phi \qquad [2]$$

The above relation resembles a Fourier transform and indeed can be inverted to solve for the Faraday Depth[1]. The resulting Faraday Depth cubes can be hard to interpret and component separation in Faraday space remains a challenge. The spectral line community developed a tool kit that shares a mathematical similarity to our own problem. Both data sets are cubes with two spatial dimension and a physical dimension:

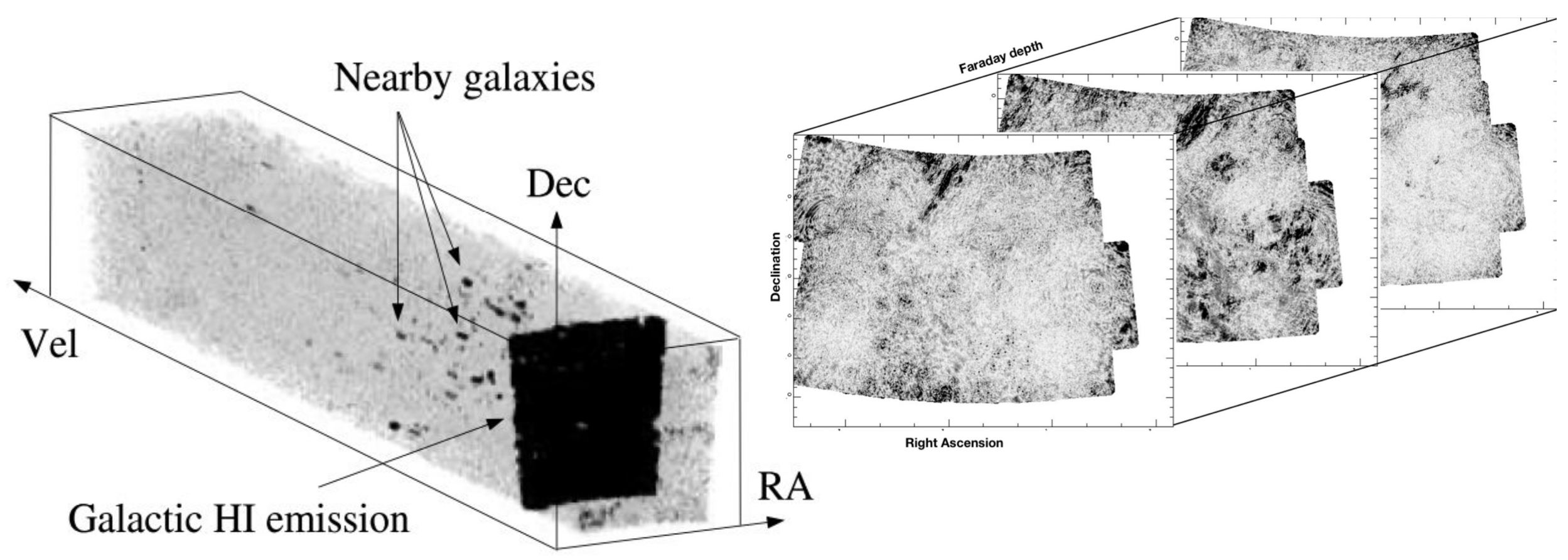

Figure 1: On the left is a cartoon of a 21cm PPV data cube (M. J. Meyer et al. 2004). On the right is cartoon of an RM cube PPF (Cameron Van Eck).

The Regularized Optimization for Hyper-Spectral Analysis (ROHSA) tool was developed by the Hyperstars collaboration at Paris-Saclay University to extract diffuse structures in hyper-spectral cubes. ROHSA attempts to decompose the spectral structure into a coherent Gaussian basis based on a multi-resolution process. ROHSA performs regression analysis in parameter space using a non-linear least squares criterion[2]. For an appropriate choice of wavelength band and in the case of Faraday thin sources the Gaussian waveform makes for an excellent approximation of the signal. I explore the application of the ROHSA tool to rotation measure data and will refer to the modified version as ROHSA-RM hereafter. Reliable recovery of Faraday Depth components is pivotal to spatial reconstruction of the parallel magnetic field along the line of sight.

Experimental Methods

Stokes QU Simulator

Synthesized Stokes Q and U cubes with fractal Brownian motion amplitude and Faraday Depth profiles.

RM Synthesis

The QU cubes were fed to RMsynth which attempt to invert equation 2 for F(φ), or the FDF.

RM Clean

The FDF cube is fed to RM Clean to attempt to extinguish the noise along each line of sight.

ROHSA-RM

The clean FDF cube is fed to ROHSA-RM which attempt to fit Gaussian with fixed width to spectra in each LOS.

Results

I produced plots of the amplitude and Faraday Depths maps. Residual maps of the input and output ROHSA-RM maps were calculated and plotted. Power spectra of the input, output, and residual maps were calculated and plotted. Spectra plots of the loudest and quietest pixels were plotted with the gaussians whose parameters are informed by the ROHSA-RM fit. The plots are presented next:

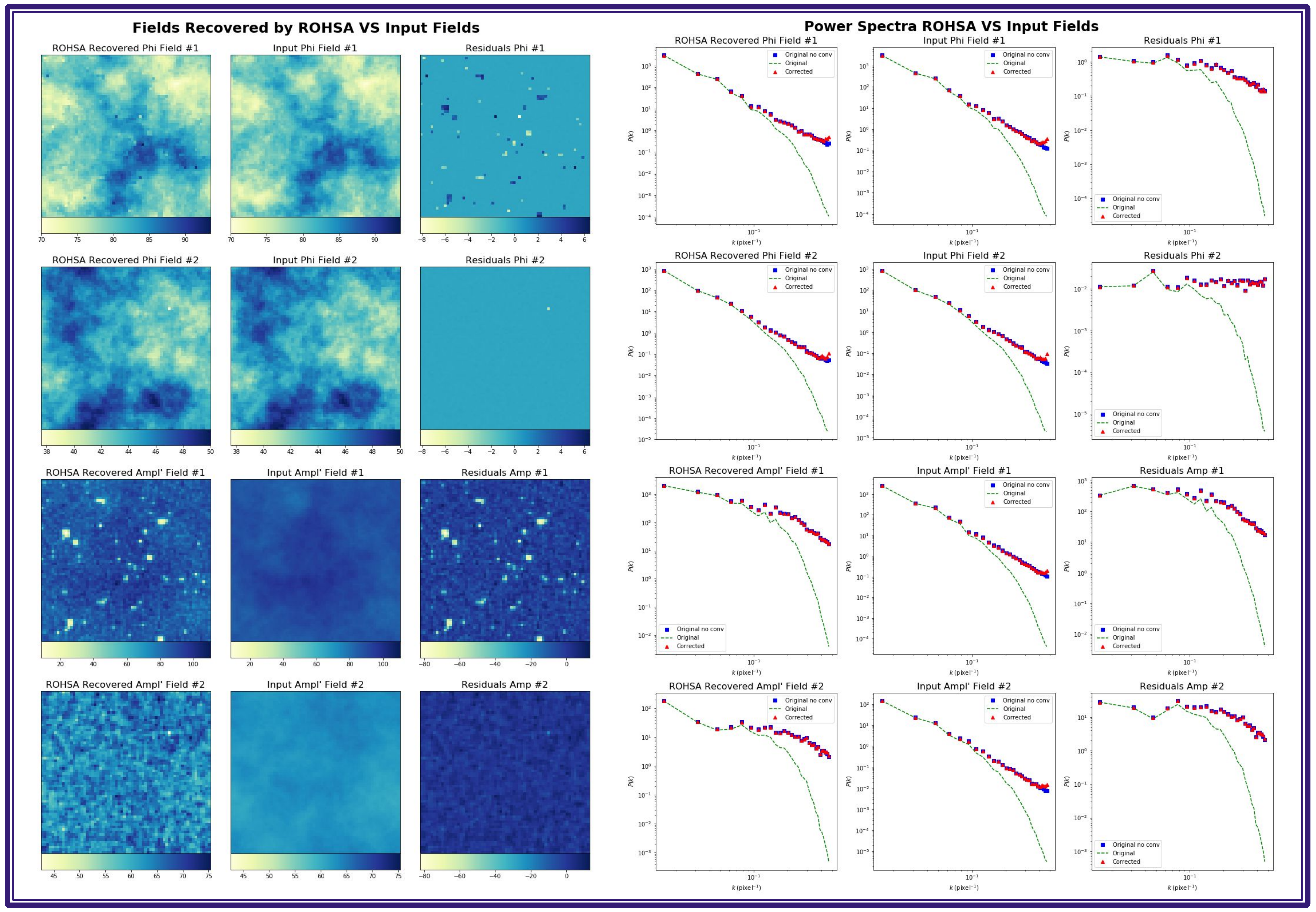

Figure 2: The left panel: depicts the output ROHSA-RM Faraday Depth and amplitude fields (left column), the input fields (middle column), and residuals between the two columns (right column). The residual of both FD components appears to be strikingly uniform. There are "islands" of relatively large residuals in the first FD field. The source of this anomaly is unclear but could possibly be accounted for by statistical variance of noise in the FD cube. The reconstructed amplitude maps both exhibit a peculiar morphology. The first reconstructed amplitude field appears to show the same "islands" as the corresponding FD field. These may be correlated however further inquiry is required. The second reconstructed amplitude field appears to be characterize a fairly uniform but noisy field. The residuals of both amplitude field components have not remarkable structure with the exception of the aforementioned "islands" in the first field. The right panel: depicts the power spectra of the fields in the left panel in on a log-log scale. The input fields are generated by transforming a user defined power law function from Fourier space to map space. We expect a linear form for the input maps output maps in the case of successful reconstruction. The power spectra of both FD fields show excellent agreement for all spatial frequencies. The power spectra of both recovered amplitude fields reveal that ROHSA-RM boosts the power on scales corresponding to k = 0-0.4. The ROHSA-RM imprints itself on the power spectrum of the recovered amplitude scales suggesting that the amplitude field parameter fit procedure needs be revisited in order to improve the agreement between the model and data.

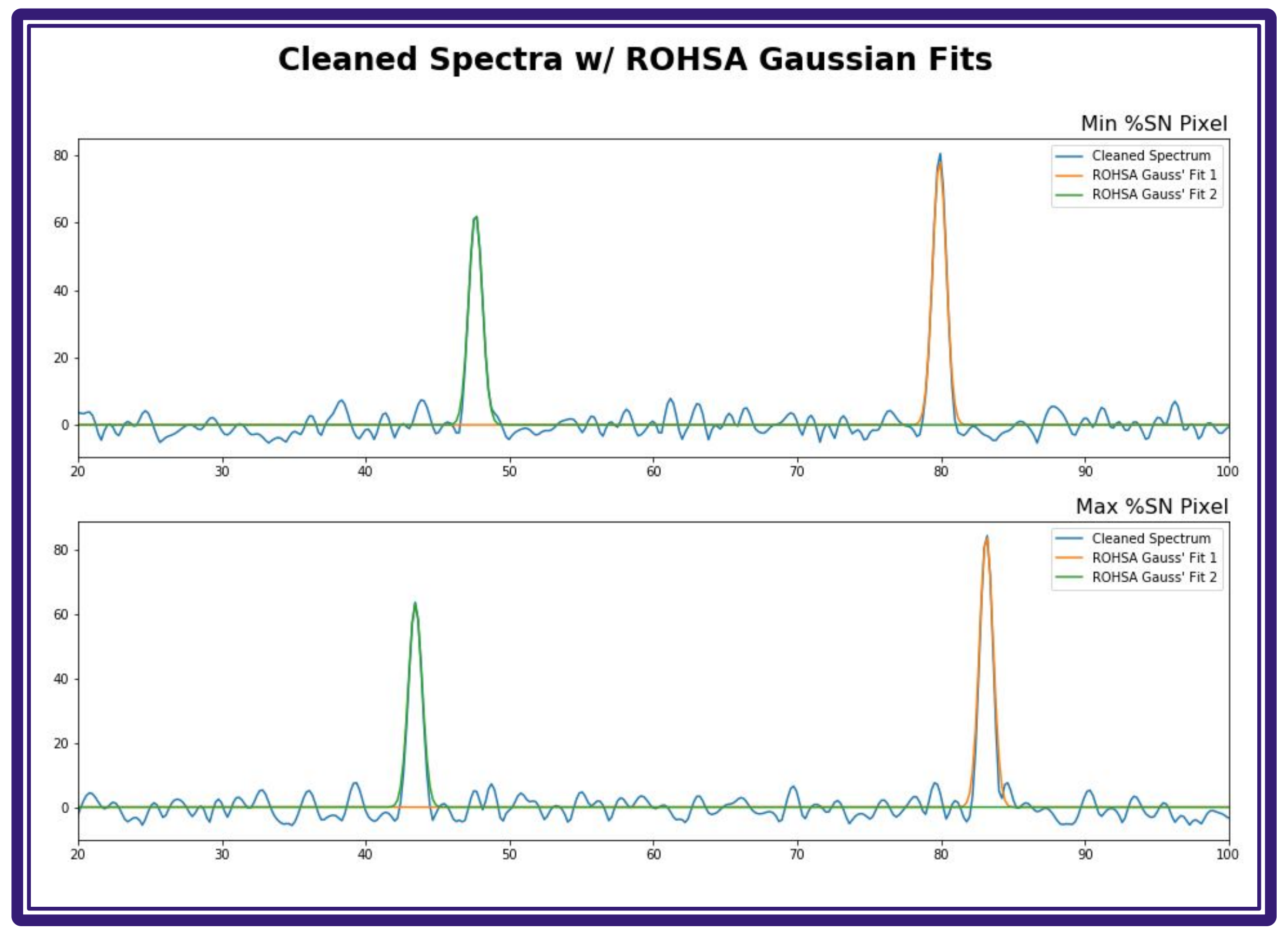

Figure 3: A plot of the spectrum corresponding to the pixel with the minimum signal to noise in the cube in the top panel and maximum signal to noise in the bottom panel. The blue curve is RMcleaned FDF, in orange and green are the ROHSA-RM gaussian fits. By visual inspection, the ROHSA-RM gaussian fits appear to successfully lock onto features in the spectrum and do fairly well at estimating the centroid.

Discussion

The ROHSA-RM tool successfully recovered the centroids of features in Faraday Depth space for the case of two well separated fBm components as seen in figure 2. The residuals of the output and input phi fields are centered about 0 with variation characteristic of noise. The amplitude field residuals for both features show discernible structure. Figure 3 shows that ROHSA-RM performs well on pixels characterized by a low signal-to-noise. Further investigation is necessary to determine the factors affecting the quality of the amplitude parameter fits. A preliminary investigation direction can be the effect of hyperparameters of ROHSA which control the penalty of smoothness imposed on the fit parameters. Another possible direction is the use of an alternate model such as an RMTF template. I performed the same analysis on a two intersecting Faraday Depth planar profiles. The test revealed that ROHSA is unable to properly lock onto and describe the gradient. Both the fBm and gradient profile cases provide valuable insight into the caveats of the tool before application to real world data. I applied the ROHSA-RM tool to LOFAR IC342 data. ROHSA-RM was able to recover mixed features in FD of components identified in literature [3].

References

[1] Brentjens, M. A., and A. G. De Bruyn. "Faraday Rotation Measure Synthesis." Astronomy & Astrophysics, vol. 441, no. 3, 2005, pp. 1217–1228., doi:10.1051/0004-6361:20052990.
[2] Marchal, Antoine, et al. "ROHSA: Regularized Optimization for Hyper-Spectral Analysis." Astronomy & Astrophysics, vol. 626, 2019, doi:10.1051/0004-6361/201935335.
[3] Van Eck, C. L., et al. "Faraday Tomography of the Local Interstellar Medium With LOFAR: Galactic Foregrounds Towards IC 342." Astronomy & Astrophysics, vol. 597, 2017, doi:10.1051/0004-6361/201629707.