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Skynet's Suite of Processing Algorithms for Single-dish Radio Telescopes

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Abstract. Skynet is an international network of over two dozen optical robotic telescopes operated out of the University of North Carolina at Chapel Hill. Having recently acquired privileges to the 20-meter radio telescope located at Green Bank Observatory, our team of programmers have worked to develop Radio Cartographer, a new software package that cleans and maps radio data. Here, we outline its major processing procedures and highlight the heavy influence and use of robust Chavuenet rejection (RCR) as a procedure to statistically identify and remove various forms of radio contaminants. Implementing RCR into Radio Cartographer allows us to consistently extract both accurate and precise flux values from distributions comprised of as high as 85 percent contaminated data. Combining this procedure with weighted modeling and other processing tools, we produce both cleaned and photometrically viable radio images for professional use.

1. Introduction

Skynet is a collection of over two dozen telescopes distributed around the globe aimed at providing constant, public, and real-time robotic access to professional telescopes (Reichart 2006). Since its conception in 2005, nearly 10 million observations have been taken with Skynet's telescopes with motives ranging from professional scientific inquiry to education. Only recently, in 2014, did Skynet receive its first radio telescope–the 20-meter radio telescope at Green Bank Observatory–to be incorporated into the network, and ever since, our team of programmers and astronomers has worked to develop a comprehensive set of procedures for both robotic acquisition and automatic processing of radio data. Our completed solution is Radio Cartographer, and its capabilities are outlined in §2. We conclude in §3, where we discuss in further detail RCR, our newly developed outlier rejection procedure that is frequently used within Radio Cartographer to separate contamination from physical data.

2. Radio Cartographer

Radio Cartographer is Skynet's attempt to produce the most complete and comprehensive set of processing procedures for radio data sets collected from single-dish radio telescopes (Martin et al. 2019). Its most general features are outlined below.

Figure 1. Radio Cartographer Software Progression

2.1. Background Subtraction

Background subtraction is our procedure to statistically remove instances of undesired elevation dependence, en-route drift, atmospheric variation, and long-duration radio frequency interference (RFI) contamination. The procedure operates by dividing the survey observation into individual scans, calculating the associated scatter for each scan, and then fitting many local baselines to data within each scan's angular distance-flux subspace. For each baseline, we then iteratively reject the most deviant point and refit the baseline model until the scatter of the baseline falls within the expected scatter of the scan itself. After all local baseline models have been fit, we then calculate the average of the local models at each data point using RCR to then provide a global background model for each datum which we subtract from the raw flux to produce a data set cleaned of background contamination. Radio Cartographer also uses this same functionality for optional spectral cleaning. If the radio telescope offers a spectral mode, background subtraction can remove response function bias of the receiver and flux dependence from continuum radio emitters if desired.

2.2. Radio Frequency Interference Rejection

Radio Cartographer also is capable of removing instances of short-duration RFI following a procedure similar to that of background subtraction. This procedure involves fitting a two-dimensional squared cosine model on each datum and iteratively rejecting deviant points from that model until the refitted cosine falls within the expected scatter of the survey. Once the cosine fitting routine is complete, each datum contains a distribution of model values from which RCR can extract the non-contaminated average flux.

2.3. Surface Modeling

With cleaned data, Radio Cartographer proceeds to interpolate the sparse gird of points into a FITS image using weighted modeling. Specifically, at each pixel, we fit a ten-parameter polynomial to the surrounding radio data, and retain only the interpolated value at the center of the fit. This ensures accurate fitting while maintaining the resolution capabilities of the telescope. This procedure serves as an alternative to the commonly used weighted averaging which can blur data upwards of 40 percent.

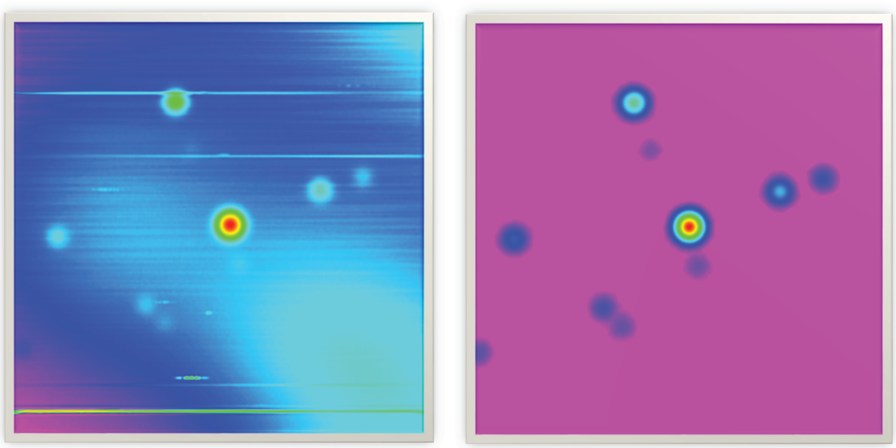

Figure 2. Left: Radio Cartographer's interpolation of simulated raw data. There are clear instances of short duration RFI, long duration RFI, background structure, and elevation dependence. Right: Radio Cartographer's post-processing interpolation of the simulated data.

2.4. Large Scale Structure

Radio Cartographer's primary data product comes in the form of a small-scale structure FITS image, but it also offers the additional capability of extracting and mapping large-scale structure data. To do this, we retain the background contamination that was removed from the small-scale structure data, equilibrate the data to the same background level (to accommodate for instances of long duration RFI or receiver drop outs), and then perform a RFI rejection routine using the 10-parameter polynomial fit to accommodate the unknown geometry of the background structure. We then use weighted modeling to interpolate the data.

2.5. Appending

Finally, Radio Cartographer offers the ability to append radio data sets for additional processing power. Once each observation is individually background subtracted, we combine the data for additional statistical confidence in RFI subtraction. This allows us to resolve fainter structure with greater accuracy as well as process wide surveys taken over many observations.

2.6. Photometry

Combining the small-scale structure and weight maps, Radio Cartographer also offers the option to automatically perform photometry on the brightest sources in the image, utilizing the strength of RCR for added significance.

3. Robust Chauvenet Rejection

Robust Chauvenet rejection is a novel outlier rejection technique that evolves Chauvenet's criterion by sequentially applying different measures of central tendency and empirically determining the rejective sigma value (Maples et al. 2018). Chauvenet criterion is the assertion that an numerical outlier is characterized if $NP(> |z|) < 0.5$ where N is the number of points and $P(> |z|)$ is the cumulative probability of being more than z standard deviations from the mean, assuming a Gaussian distribution (Chauvenet 1863). This rejection procedure succeeds for distributions with low-to-mild contamination, but fails when applied to more seriously biased data sets. The reason for this is because both the mean and standard deviation are not robust measures of the true distribution, as they are heavily biased by the outliers they are attempting to reject. RCR identified this flaw and addresses it with two techniques. First is the use of less precise but more accurate tendency measures like the median and mode to calculate mu. The second is the empirical measurement sigma using a regressional fit to the inverse error function of the data set. With these more statistically robust measures, one can apply Chauvenet's criteria to eliminate the most discrepant outliers, and then repeat this rejection with updated and more precise tendency measures like the mean to perform another round of iterative rejection which repeats until converging on the correct mu and sigma. We have found that RCR is capable of extracting both an accurate and precise mu and sigma value from data sets with contamination as high as 85 percent. Source code can be found at `http://www.skynet.unc.edu/rcr`.

References

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