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Quality Assessment Tool for SKA Continuum Imaging Pipelines

Ying-He Celeste Lü *(1), Gabriella Hodosán (2), Feng Wang(3), Simon Daley-Yates(1,4) and Tim Cornwell(1)
(1) Cavendish Astrophysics Group, University of Cambridge, Cambridge, CB3 0HE, UK
(2) RAL Space, STFC Rutherford Appleton Laboratory, Didcot, Oxfordshire, OX11 0QX, UK
(3) Centre For Astrophysics, Guangzhou University, Guangzhou, Guangdong, China, 510006
(4) School of Physics and Astronomy, University of St. Andrews, St. Andrews, KY16 9SS, UK
* yl790@cam.ac.uk

Abstract

We present a quality assessment (QA) tool developed to test the continuum imaging pipelines for the Square Kilometre Array (SKA) radio telescope. The QA tool produces a set of sources and utilizes metrics to examine the images produced by the pipelines. We demonstrate the results and performance analyzing an image from SKA-Low simulation data and identify functions that perform well and ones that need further improvement. The metrics will provide insights into how to systematically assess imaging pipelines used for telescopes in the big data astronomy era.

1. Introduction

The Square Kilometre Array (SKA) belongs to the next generation of radio telescopes that are designed for deep observations of large areas of the sky [1]. As it achieves significant improvements in coverage and precision from the current radio observatories and will generate unprecedentedly large amounts of data, the SKA also brings challenges to the data processing pipelines and algorithms used in radio astronomy.

One of the key aspects of the development of initial SKA processing workflows is a set of continuum imaging pipelines that involves self-calibration and imaging [2]. The scientific quality and accuracy of these pipelines need to be tested in parallel with the development process, calling for a quality assessment (QA) tool that can check the effect of various calibration and imaging algorithms on the image.

Before real data become available, initial continuum imaging pipeline prototypes are tested using a set of simulations. These simulations use a known sky model and generate mocked visibilities that act as inputs to the pipeline. As a result, the central functionality of the QA tool is to extract sources from the images generated by the pipelines and compare them with the original sky model. The results of the pipelines are impacted by antenna effects (including the primary beam [3]) as well as the choices made in the parameters used to run the pipeline. The QA tool therefore allows us to understand the effects of these choices.

We outline the details of the QA tool in Section 2 and demonstrate its results on a test image in Section 3. In Section 4 we further summarise the results and discuss potential improvements needed in the future.

2. The Quality Assessment (QA) Tool

The QA tool is designed as a command line Python application that reads in a set of image files in FITS format including the residual and restored images (in different Taylor terms) as well as an image of the primary beam. It also can read in the input source catalogue either as HDF or text files. Three primary aspects are considered in developing the metrics of the QA tool:

1. Dynamic range and sensitivity: statistics of images as well as their power spectra.
2. Fidelity to simulations: Matching of sources, the direct statistics of the matches including positions and fluxes.
3. Wide field accuracy: The statistics above as a function of location in the field of view.

The details of its functionalities are as follows.

2.1 Source Finding and Comparison

For source extraction, we take advantage of the source finding tools that are widely used in radio astronomy (see [4] for a review). We use the source finder package PyBDSF as the main source finding tool [5]. This choice is made because PyBDSF was developed primarily to work with the large field of view and frequency range used by the LOFAR telescope. SKA-Low, which is the low frequency array part of SKA, will also operate with similar properties, hence PyBDSF is an ideal tool for source finding in SKA-Low data. The basic functionality of PyBDSF includes reading in the input image as a FITS file, calculating background rms and mean images, finding emission islands and fitting Gaussians to them, and grouping the Gaussians into sources. As most of the images are multi-frequency spectral cubes, the source finder collapses the images into 2D Stokes-I images, which we use to find source positions and peak flux values.

After the source finder outputs the source catalogue, the QA tool reads in the coordinates of the detected sources and their peak fluxes. The coordinates are compared with an input source catalogue which is typically an idealized sky model, while allowing for a separation tolerance. The QA tool then generates a series of plots containing information about the statistics of the positions and fluxes of the sources, to indicate if the pipeline systematically affects them.

2.2 Taylor Images and Spectral Index

The spectral index of a source indicates how its brightness varies as a function of frequency. The source catalogues used in the simulations contain spectral index information that can be used in assessing the fidelity of the pipeline. Spectral information in results from the pipeline are assumed to be in the form of Taylor moment images.

In cases where Taylor images are provided by the pipeline, the QA tool finds the sources in the image, extracts the flux values, and calculates the spectral index by dividing the total flux of the higher order Taylor images over the 0^{th} term Taylor image.

2.3 Primary Beam Effects

Typically, a primary beam is applied to the fluxes of sources from the input catalogue during the simulation, and this must be corrected in the processing pipeline to make the input (known sky model) and output (from QA tool) source flux values match. Approximations made in the model of the primary beam used by the pipeline will cause sources further from the centre of the image to have larger errors on their fluxes. Therefore, QA tool also needs to have the capacity to correct for the effect of the primary beam across the field of view, and this can be done by providing an image cube of the primary beam, and it can be provided as a function of time, frequency, and polarisation.

2.4 Parallelization and Software Deployment

Due to the long baselines and the need to adequately sample the point spread function well, the simulated images are large and push the limits of most current source finders. Thus, good performance is a key requirement for the QA tool. We parallelize our QA code using the Dask Python library [6] to improve performance. Currently, we can analyze image sizes up to 32,000 * 32,000 pixels with an eight-core machine, where the tool takes around 35 minutes to execute, finding and fitting over 20,000 sources.

We support both Docker and Singularity container images for deploying the QA tool.

3. Tests with Existing Pipeline

3.1 Test Data

We used a simulated SKA LOW dataset to evaluate the QA tool. The simulation is an ideal case with no direction dependent effect, so we only use symmetric primary beams with appropriate radial profile (a scalar Gaussian beam), with isoplanatic screens applied to demonstrate direction independent calibration errors. This is achieved via using the gain table of a single component for every ionospheric component found. The sky model is based on the GLEAM catalogue [7] with extra, fainter sources added. We have used OSKAR [8] to generate the simulated Measurement Set.

When built, the SKA LOW telescope will have a maximum baseline length of approximately 80km. Our simulated observation used 100 frequency channels from 140-160 MHz. Imaging was done with the continuum imaging pipeline of the RASCIL library [9], using multi-scale cleaning with robust weighting. The size of the image generated by the pipeline had 24576 * 24576 pixels.

The central portion of the image is shown in Figure 1. We can see some of the bright sources, however due to lack of sub-pixel cleaning they are not quite clear.

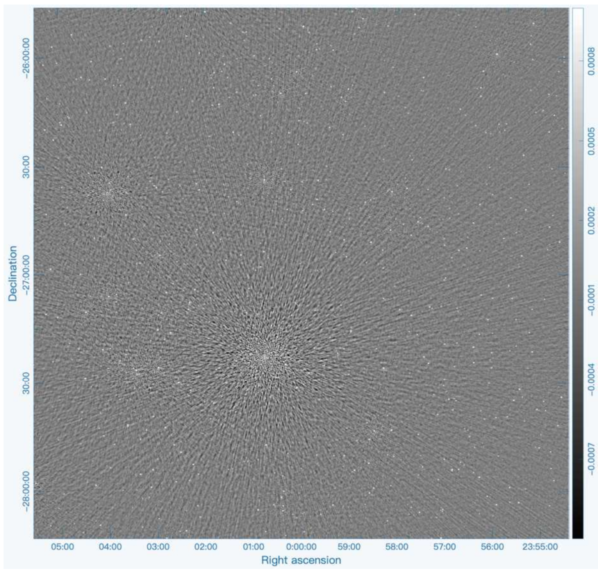

Figure 1. Grey-scale image for the test data at 0^{th} Taylor term, restored. The field of view is zoomed in twice (showing ¼ of the entire image) , and the flux is clipped to the range -0.001 Jy to 0.001 Jy.

3.2 QA Metrics: Source Positions

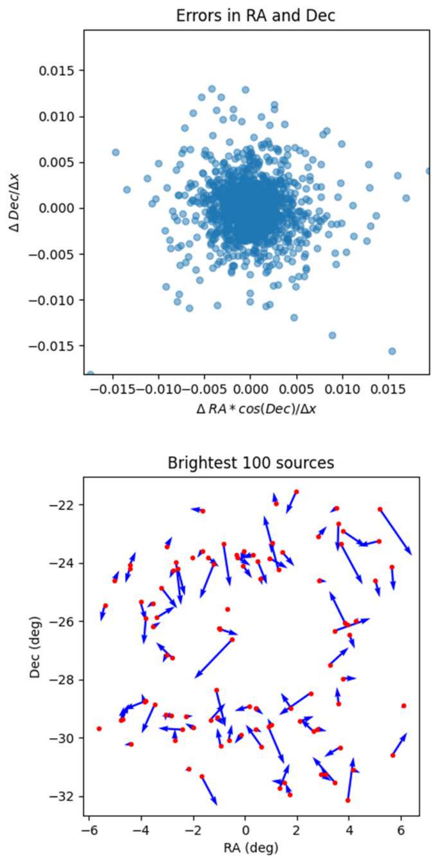

Figure 2. Top: The errors between identified and input source positions, with respect to image resolution in (RA, Dec). Bottom: The quiver plot of source positions for the brightest 100 sources. The red dots are the input source positions and the blue arrows are the vector with which the output sources identified by QA have moved (compared to original input sources). The sizes of arrows are scaled larger for visualization purpose thus does not represent the actual distance on the image.

We first look at the metric of the positions of the sources and their movements. In Figure 2 we have shown the error and quiver plot of the sources in (RA, Dec). We can see that all sources identified in the source finder are within 2% of error in both directions compared to the input source catalogue, with most of the sources having an error of less than 0.5%. This is good indication of the accuracy of the pipeline. According to the position quiver information, the changes in positions are small and in random direction, indicating that imaging does not result in systematic offsets of sources.

3.3 QA Metrics: Source Flux

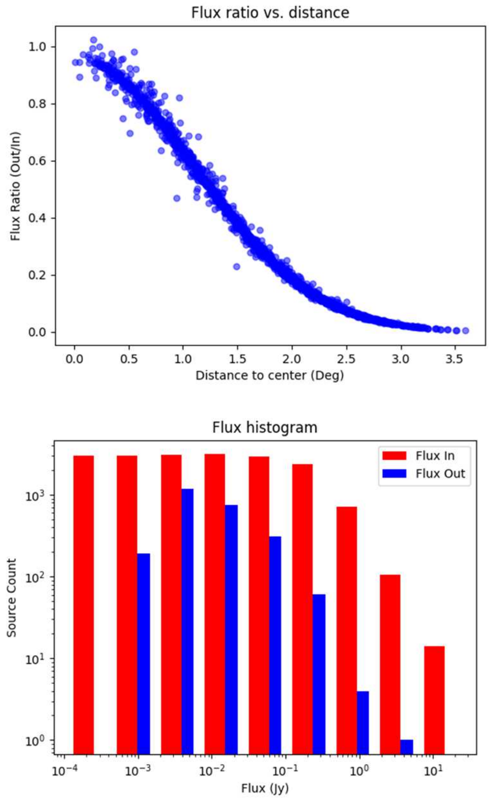

Figure 3. Top: The flux ratio (flux out/flux in) of all sources plotted with respect to the distance to the center of the image. Bottom: Histogram of the fluxes of all sources, binned logarithmically, where red represents the input catalogue and blue represents the output catalogue.

Another important metric is the comparison of fluxes of the sources. Contrary to positions, primary beam will inevitably affect the fluxes. From the top panel of Figure 3 we can see that the flux ratio does not stay around one (expected value for idealized scenario) but decreases with distance. This is mostly due to the primary beam correction not being accurate for the side lobes, which are on the edge of the image. This is also shown in the flux histogram, as the fluxes for output sources have been scaled down, which is expected from how the beam was applied in the imaging pipeline. Many of the fainter sources are also not identified by the source finder because they are too dim.

3.4 QA Metrics: Spectral Index

The comparison of input and output spectral indexes for the sources on the test image are shown in Figure 4. Most of the sources in GLEAM catalogue have spectral index values between 0 and -1.5. This is also true for many sources in the output catalogue but for many others, the magnitudes of the spectral indexes have been overestimated, which means the source fluxes on channels further away from the central channel are less accurate. We have further examined the scaling between spectral indexes and the positions of the sources, and we find that the sources with less accurate estimation tend to fall towards the edge of the image grid, another indication of the effect of the primary beam, as well as the effect the general imaging algorithm has on the edge of the image, where the source finder may not extrapolate sources accurately. This provides us valid feedback on adjusting for better imaging parameters at the image edge.

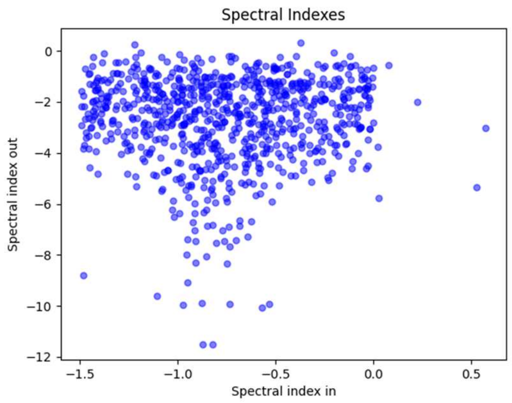

Figure 4. The comparison of spectral indexes for input and output source catalogues.

4. Discussion and Future Development

Generally speaking, the QA tool can produce a robust catalogue of sources from a large image and mostly accurate measurements of position, flux and spectral index for these sources. It can also provide a reliable matching algorithm to an input source catalogue, which can be used to test the quality of the imaging pipeline.

Most of the inconsistencies seen by the QA tool tend to come from poor primary beam correction as well as routines for spectral index estimation. The approach to read in beam information as a sensitivity file itself is appropriate considering the beam is in an idealized form, and the current errors seen come mostly from the pipeline itself. However, this approach will need to be improved if the primary beam is time dependent. The effect of the side lobes is also not considered, which makes it harder to analyse whether the flux discrepancies are from the side lobes or other processes in the imaging pipeline. The estimation of spectral index is based on calculating higher order Taylor terms, which is improved from directly reading it through the source finder. However, the estimation is still poor at the edge of the image.

We have so far not considered the effect of polarisation leaking in the QA tool and have been primarily working with Stokes-I images or extract only Stokes-I information for other polarisations. Future development will thus require modelled polarisation information of the sky catalogues as well as better handling of polarisation conversion in the tool.

As more complex processing functions are developed in the forthcoming continuum imaging pipelines, more information will be available for the images and hence the QA tool, such as ionospheric activity, polarsation errors etc. Furthermore, to model the entire baseline for SKA, the image size will need to be at least around 60, 000 pixels in each dimension, which requires further speedup of the QA tool. In future development, we will need to further explore the limit of multi-processing in python and use GPUs to accelerate the source finding. We also plan to automate the process when analysing a large number of images simultaneously and optimize the storage and visualization of the outputs. The QA tool will be eventually used to analyse images with real observations as the SKA starts its early science commissions in 2024.

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