Algorithm Research and Development: Status & Plan

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Abstract

This memo is a follow-up of EVLA Memo No. 139 where the problem of full-beam full-Stokes wide-band imaging with the EVLA and ALMA was broken down into three main categories: (1) Wide-band Stokes-I imaging, (2) Wide-band full-Stokes imaging and (3) High Dynamic range imaging. To separate the problem of instrumental wide-band effects from the spectral variation of the sky emission, the problem of wide-band imaging was further broken down into intermediate mile-stones of narrow-field and wide-field wide-band imaging.

In this memo, we report on the progress made on these fronts, current status of Algorithms R&D and future plan.

1 Introduction

The key instrumental parameter which affords the high sensitivities of modern radio telescopes and which also impact the imaging performance is the wide instantaneous fractional bandwidths.

The telescope field of view (FoV), the in-beam instrumental polarization as well as the radio sky brightness distribution varies with frequency. In addition, the antenna forward gain pattern also varies with time (e.g. due to rotation with Parallactic Angle, elevation dependent shape changes, time-dependent antenna pointing errors, etc.). This results in time- and frequency-varying direction-dependent effects that lead to errors significantly higher than the sensitivity limits of modern radio telescopes. From a scientific astronomical observations point of view, the resulting algorithmic problems can be classified as:

1. Effects of the frequency dependence of the emission from the sky
2. Time and frequency dependent instrumental/ionospheric/atmospheric effects
3. Effects of time- and frequency-dependent antenna primary beam *shapes*

All these effects interact with each other in a negative way in wide-band wide-field full-Stokes imaging. Our approach towards solving the problem has been to identify scientific use-cases which are affected by only a few of these effects. This breaks down the problem into relatively simpler problems and allow independent R&D for the required algorithms. These individual algorithms can then be combined in the sense of "system integration" to enable wide-band wide-field full-Stokes imaging.

Therefore from the interferometric imaging algorithms R&D point of view, the categories are:

1. Stokes-I narrow-field wide-band imaging

   This requires algorithms to account for the frequency dependence of the sky emission, but not for the frequency dependence of antenna Primary Beam (PB).

2. Stokes-I wide-field narrow-band imaging

   This requires algorithms to correct for effects of the antenna PB (rotation with Parallactic angle, time-dependent pointing errors, etc.) but not for the frequency dependence of the PB.

3. Stokes-I Wide-field wide-band imaging

   This requires development of an algorithm for wide-band PB corrections and combining it with an algorithm for handling frequency dependence of the sky brightness distribution.

4. Full-Stokes wide-field wide-band imaging

   This requires developing an algorithm to correct for wide-band PB effects in all polarization products and an algorithm to solve for frequency dependence of the full-polarization model for the sky emission.

In addition to these imaging problems, RFI excision and the post interferometric imaging image-analysis are also areas where new algorithm development is required. We classify these as "Non-imaging algorithms" (Data flagging, image analysis, etc.). Below we describe the status of algorithms for these categories.

2 Current Status

2.1 Stokes-I narrow-field wide-band imaging

The basic algorithm for this is the Multi-term MFS (MT-MFS) algorithm (Rau & Cornwell, 2011) which can account for the frequency dependence of compact sources. The more general MS-MFS algorithm (Rau, 2010) was developed which simultaneously solves for a multi-scale frequency dependent model for the sky and therefore works for compact as well diffused emission. This has now also been deployed in CASA and has been widely used for EVLA and ALMA imaging.

2.2 Stokes-I wide-field narrow-band imaging

2.2.1 Narrow-band A-Projection

This requires corrections for the effects of the antenna PB. The narrow band A-Projection algorithm (Bhatnagar et al., 2008) has been demonstrated to work with narrow-band data. The algorithm also was implemented in the production code-base via the tool-interface only (however see Section 3.1).

2.3 Non-imaging algorithms: Rotation Measure Synthesis

The Rotation Measure Synthesis (RM-Synthesis) algorithm (Brentjens & de Bruyn, 2005) has been implemented in AIPS (by L. Kogan). This algorithms in purely image-plane algorithm and requires Stokes-Q and -U image cubes (made in any package) to be transported to AIPS.

2.4 Non-imaging algorithms: Data Flagging

The "tfcrop" algorithm developed by U. Rau and the "rflag" algorithm developed by E. Greisen, and have been implemented both in CASA and AIPS.

3 Work in progress

The software framework used for testing the narrow-band A-Projection algorithm was however not suitable for wide-field wide-band imaging. Hence, for further algorithms R&D and exploring algorithms for wide-field wide-band calibration and imaging we concluded that it is best to re-factor some of the code for the required flexibility and efficiency for full wide-field wide-band imaging (see Section 3.1).

3.1 Imaging software framework

Since the WB A-Projection algorithms corrects for the wide-band wide-field effects as part of the iterative image deconvolution process, it must not only interface with image-plane algorithms like the MT-MFS algorithm but also with W-Projection and Mosaic imaging algorithms.

Existing imaging software framework, while usable, was not designed to be efficient and flexible for these cases. For the implementation of the wide-band wide-field imaging algorithm including W-term effects and which can scale to include wide-band mosaic imaging, our conclusion was that it is best to re-factor the software framework and implement it in a way that is scalable and flexible. This is also required to efficiently handle the low and the high frequency imaging including mosaic imaging.

Significant effort was therefore invested in developing a modified software framework. This framework is now in use for algorithms R&D to implement and test the wide-band wide-field imaging algorithm.

3.2 Stokes-I wide-field wide-band imaging

We investigated three fundamentally different approaches for an algorithm to simultaneously account for the frequency dependence of the antenna PB as well as of the frequency dependence of the sky brightness distribution:

1. Absorb the frequency dependence of the PB in the MT-MFS solutions followed by a post-deconvolution correction for the PB effects.
2. Another variant of the same idea which involves modifying the MT-MFS solver.
3. Develop a wide-band A-Projection algorithm to correct for wide-band PB effects during imaging and interface it with the MT-MFS deconvolution algorithm to solve for the frequency dependence of the sky emission (see section 3.3).

In retrospect, we found that (1) works for compact as well extended emission, but cannot account for the time-dependence of the PB (e.g. rotation of the PB with Parallactic Angle). Note that the effects of the time-dependent PB are stronger than the thermal-noise limit, e.g. due to the polarization squint of the EVLA and ALMA antenna beams. (2) works well only for a single point source but fails for multiple point sources or extended emission. We also found that the computing cost of (1) is comparable to that of case (3) while the complexity is much higher. We therefore concluded that case (2) is not usable for fundamental reasons and case (1) is useful *only if* case (3) does not work. Case (1) in itself also offers no scientific advantage in terms of computing, complexity or achievable dynamic range-limit.

3.3 Wide-band A-Projection

The narrow-band A-Projection which accounts for time varying PB effects is straight forwardly usable for spectral-line imaging where the data from each channel are imaged independently.

Continuum imaging requires averaging of all channels prior to deconvolution. The frequency dependence of the PB must also be corrected prior to deconvolution, which is a harder problem. While initial ideas of straight forward extension of the narrow-band A-Projection algorithm for the wide-band case did not work well, we have recently tested the Wide-band A-Projection (WB A-Projection) algorithm that adequately accounts for the frequency dependence of the PB up to the $\sim$10% point of the PB (see Figure 1). The images made using WB A-Projection do not have the effects of the frequency dependence of the PB allowing the use of a modified MT-MFS algorithm for simultaneous total power and spectral index wide-field imaging.

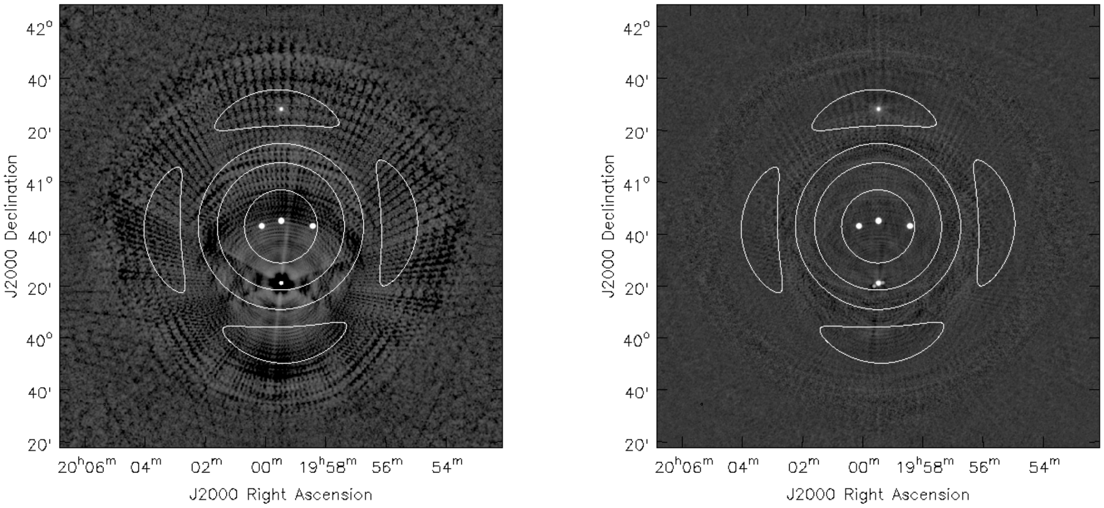

Figure 1: Figure showing comparison of the imaging performance before and after correction for the time and frequency dependence of the PB. The contours trace the 50, 20, 10 and 2% gain of the PB at the reference frequency. The left panel shows the image using the MT-MFS algorithm without correction for the frequency and time dependence of the PB. The right panel shows the image made using the combined MT-MFS and WB A-Projection to also correct for the PB effects.

3.4 Combined WB A-Projection and MT-MFS algorithm

Prototype code for the combined WB A-Projection and MT-MFS algorithmhas been developed and we are now in the process of further testing it via simulations and application to real wide-band data from the EVLA. The details of our investigation and algorithmic details will be reported as a scientific publication soon.

4 Plan for 2012-13

4.1 Integration of WB A-Projection and MT-MFS

At this time there are a few outstanding numerical issues and bugs in the software. Our immediate goal is to work towards understanding the numerical issues due to which the combined algorithm diverges for imaging beyond ~10% point in the PB. This is also required to write the associated paper (in preparation) for a peer reviewed journal.

4.2 Wide-band mosaic imaging

This requires some algorithms research and additional software development and testing.

4.3 Address the memory footprint issues

Imaging large data sets requires use of High Performance Computing (HPC). Deployment of wide-band imaging algorithms (like MT-MFS) on HPC platforms leads to high run-time memory footprint. The following two approaches will be explored for a proper solution:

Software solution: Explore if efficient paging of images is possible and if that adequately solves the problem.
Algorithmic solution: Implement Asp-Clean and investigate its application to wide-band imaging.

4.4 Wide-band wide-field full polarization imaging

High sensitivity full polarization imaging requires averaging the full available bandwidth for optimal deconvolution (as against per-channel imaging followed by post-imaging RM-synthesis). This requires significant R&D and software development work.

For low sensitivity imaging, the interim solution of a per-channel image cube and use of the image-plane RM-synthesis can be used. This will suffer from the effects of time-dependence of the PB and the frequency dependence of the sky brightness distribution, but not from the frequency dependence of the PB.

4.5 Non-imaging challenges

We also recognize the need to development techniques and software for handling Radio Frequency Interference (RFI), image analysis and post interferometric-imaging analysis in general. However we distinguish the needs for image analysis from those listed above due to the very different nature of the problems and required skills. E.g., while the process of imaging interferometric data requires narrower radio astronomy domain expertise, the final product of interferometric post-processing is often fundamentally not very different from other kind of images. Many more tools and people with the required skills are therefore available in the Imaging Science, Computer Science and Digital Image Processing communities. Since this also requires less of narrower, RA domain-specific knowledge and skills, it is reasonable to expect to be able to harness the available resources in these communities as well as in the Physics and Astronomy departments in the universities and even in the astronomy community in general for this kind of work. NRAO will be happy to facilitate the integration of community-developed analysis tools into CASA and explore avenues of useful collaborations where the domain expertise at NRAO can be combined with similar expertise in the community outside NRAO for algorithms R&D in general and post interferometric imaging image-analysis in particular.

References

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