EVLA Memo: #139
Plan for Imaging Algorithm Research and Development

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Abstract

Many scientific deliverables of the next generation radio telescopes require wide-field imaging or high dynamic range imaging, or both. Some next generation telescopes nearing completion (EVLA and ALMA) indeed promise at least a ten-fold increase in the sensitivity compared to the existing telescopes.

High imaging dynamic range requires removal of systematic errors to high accuracy and for long integration intervals. In general, many source of errors are directionally dependent and unless corrected for, will be a limiting factor for the imaging dynamic range of these next generation telescopes. This requires development of new algorithms and software for calibration and imaging which can correct for such direction and time dependent effects.

This memo discusses a plan for research in imaging and calibration algorithms. The resulting high performance computing needs and a plan for the required work is not discussed in this memo. In terms of imaging sensitivity and data rates, EVLA and ALMA are important milestones and a significant step towards SKA. Research on developing techniques for high dynamic range imaging with the EVLA and ALMA will therefore provide the *earliest and most practical* input for design constraints on the SKA and will be a significant contribution to the international SKA efforts.

1 Introduction

For the purpose of developing a plan for algorithms research, post-processing can be divided into two broad areas of work:

1. Algorithms research
2. Scientific computing

Algorithms research requires radio astronomical domain expertise and practical experience in imaging and calibration with real data. Many of the algorithms, fundamentally required for imaging with the next generation telescopes, also demand significantly higher data rates and computing. Scientific computing addresses the resulting computing requirements. This field requires more computer science domain expertise involving use of new hardware and software development platforms. Clearly, these broad areas of work have strong dependence on each other and scientists involved in these areas of research often have overlapping interests and skills.

In the sections below, we have attempted to develop a plan for algorithms research and development. This is further refinement of the plan for algorithm development in earlier memos (Bhatnagar, 2004; Owen, 2008). The goal is to first address the more immediate scientific requirements of NRAO telescopes (ALMA and EVLA) as a development path towards addressing SKA imaging and calibration issues on the longer term. Once a plan for algorithms research and development is finalized, a plan for development related to the required computing will also be developed.

In the path towards the final goal of high dynamic range wide-band wide-field full-Stokes imaging, some intermediate algorithmic milestones can be identified. These milestones correspond to usable algorithms which enable new scientific capabilities in a staged manner. These also approximately match the improvements in the telescope capabilities with time.

1.1 Areas of work not discussed here

The plan in this document largely focuses on the research and development in the area requiring most work, namely algorithms for imaging. Following are some other areas which require significant work, but not discussed in this memo:

1. Development of heuristics for automatic pipeline processing
2. Algorithms as well heuristics development for removal of bad data and RFI
3. Evaluating interactions of advanced imaging algorithms with instrumental calibration issues
4. Algorithms for atmospheric calibration – particularly for ionospheric calibration
5. Post deconvolution image analysis

Many of these require significant development for which expertise already exists in NRAO. While CASA has advanced software implementations for many of these tasks, other projects/groups/individuals at NRAO outside the CASA group have demonstrated significant advances in some the areas enumerated above as well.

1.2 Time-lines in this document

Since the algorithmic milestones discussed in this note involve significant research, it is difficult to be very accurate about the timescales. Our estimate of the timescale on which various milestones can be met are written in the side margins of various sections – *the timescales refer to the time of delivery*. Timescales for imaging problems for which the algorithms either do not exist or are in a state of active research are more uncertain. Those timescales are written as a range of times when we think it is plausible to meet these milestones.

2 Guiding principle: Enabling new capabilities

The guiding driver for the plan proposed in this document was that the focus of algorithm research and development should be to develop algorithms to enable new scientific capabilities of the instruments as soon as possible. The algorithms developed by the research group will also be tested by the researches and at least written up as a scientific document (a scientific memo but preferably as a journal paper) for the production-line software group to implement in the off-line data processing software[1]. Starting with the simplest scientifically interesting and useful capabilities, the plan progresses towards addressing the more difficult problems for enabling full scientific potentials of the new instruments.

For the EVLA, this involves moving along three axis of imaging: (1) wide-band, (2) wide-field, and (3) full polarization. Wide-band, narrow-field imaging capability is the simplest scientifically useful capability. Work towards delivering this should be the priority.

Recent progress towards correction for primary beam effects can be coupled with wide-band image deconvolution algorithms. The combined algorithm can be leveraged to deliver wide-band wide-field imaging capability. Stokes-I wide-band wide-field imaging is therefore the next priority. This should either be followed by extending this work for full Stokes imaging or, if possible, pursued in parallel.

While the basic mosaic imaging capabilities exist in CASA (both linear and non-linear mosaicking capabilities), for ALMA imaging the dominant problem involves dealing with the heterogeneous nature of the array as well as possible limits due to antenna pointing errors. Solutions for these problems are closely related to the issues in wide-band imaging with the EVLA. Depending upon the priority of the observatory and that of the scientific interests of staff involved in algorithms research, the priority of these targets will change. E.g. while antenna pointing errors might be a second priority in an only-EVLA plan, in an ALMA-EVLA combined plan it might need to be at a higher priority. Similar will be the case for full Stokes imaging capabilities.

[1] Although not necessary, in practice, the software developed during the research phase, in at least some cases, will be developed in the production-line software itself to be released after the research phase is over (or withdrawn depending upon the outcome of the research).

2.1 Connection to SKA imaging problems

While the plan discussed in this document is oriented towards EVLA and ALMA, we argue that this plan will also result in work which will be a significant contribution to the global SKA efforts. The long term goal of the plan proposed here is indeed algorithm research and development for the SKA.

Many scientific goals for the SKA require very high dynamic range imaging (10^{6-8}), not achieved yet with any of the existing radio telescopes. Several orders of magnitude improvement in the sensitivity of the SKA is also achieved by a very significant increase in the number of stations (filled aperture dishes or Aperture-array stations) as well as increased bandwidth of observations. Improvement in sensitivity therefore comes at the cost of very large increase in the data rates. Consequently, research in new algorithms for very high dynamic range imaging which can also efficiently process very large data volumes (up to 100s of Tera Bytes) is crucial for a practical design for the SKA.

Experience of most researches in the area of imaging algorithms shows that every order-of-magnitude improvement in the imaging dynamic range requires 5–10 FTE-year worth of research and development effort. Estimated imaging dynamic range limit of the existing algorithms is $\sim 10^{4-5}$ using smaller data volumes compared to the expected data rates from the SKA. Clearly, to achieve SKA science goals, a very significant investment in imaging and calibration algorithms research may be required ($\sim 30 - 40$ FTE-years).

It is estimated that the algorithms for correcting direction-dependent effects is the most crucial for achieving the required imaging dynamic ranges with the SKA. This includes correcting for the effects of antenna far-field power patterns, frequency dependence of the instrument and the sky, deconvolution errors for confused fields and errors due to non-isoplanatic ionosphere. High dynamic range imaging with the EVLA will require solving the first three of these problems and possibly even the fourth problem (at least for imaging at lower EVLA frequencies).

EVLA and ALMA will therefore be the first telescopes to be commissioned which, in principle, will have sensitivity to achieve an imaging dynamic range of up to 10^6 and which require new algorithms to solve imaging problems which are common to ELVA, ALMA and SKA – there is a very significant overlap in terms of the outstanding unsolved problems for high dynamic range imaging with these telescopes. Research and development for high dynamic range imaging with EVLA and ALMA will therefore also represent a significant contribution towards solving the imaging problems of SKA-class telescopes. With the large bandwidth and a versatile correlator, EVLA can also generate high quality data with data volume of up to a Tera Byte. NRAO telescopes will therefore also be the first realistic testing ground and reality check for the imaging and run-time computing performance of any new algorithm. The data rates from these telescopes, available and affordable computing power and the high sensitivity of these telescopes together will provide the crucial reality check on any future SKA design.

We therefore think that while the plan for algorithms research and development discussed in this memo is for EVLA and ALMA, it also not very different from a similar plan required for SKA.

3 Stokes-I Imaging

The ultimate goal of the research in imaging algorithms is to develop algorithms for full-beam wide-band imaging. Since this also fundamentally involves large data volumes, such an algorithm will also need to be computationally efficient.

The first order error term in wide-field wide-band imaging is due to the scaling of the antenna primary beam (PB) with frequency. With 2:1 bandwidth ratio, the PB area changes by a factor of 4 from one end of the band to the other. For narrow-field wide-band imaging, the dominant error is due to the frequency dependence of the sky. Error in the deconvolution of confused fields is of the similar order and significant for both wide- and narrow-field imaging. Clearly, for high dynamic range wide-field, wide-band imaging, algorithms to simultaneously correct for all the three error terms are required.

The basic algorithms to account for the three dominant errors in wide-field wide-band imaging exist: A-Projection (Bhatnagar et al., 2008) to correct for the effects of the PB , Asp-Clean (Bhatnagar & Cornwell, 2004) and MS-Clean (Cornwell, 2008) for scale-sensitive modeling of the sky and MS-MFS (Rau, 2009) for modeling frequency dependence of the sky. However significant work is still required for (1) the integration of these algorithms, (2) careful testing of the combined imaging software, and (3) deployment of the algorithm for efficient computing (possibly on a cluster of computers).

The milestones in this line of work are:

3.1 Stage 1: Wide-band, narrow-field imaging

This corresponds to wide-band imaging of area covering a relatively narrow field of view around the center of the antenna PB at the highest frequency. In this, errors due the frequency scaling of the PB and its rotation on the sky with Parallactic Angle (time) are minimized.

3.1.1 Un-confused fields

The MS-MFS algorithm ((Rau, 2009), which can be configured to the simpler case of Sault-Wieringa MFS (Sault & Wieringa, 1994) algorithm where appropriate, is sufficient for this. In some (many?) cases, post deconvolution correction for wide-band PB will be sufficient. **Q4, 2009**

3.1.2 Confused fields

While the Sault-Wieringa algorithm (S-W MFS) may still be applicable for fields with weak frequency dependence, the multi-scale capabilities of the MS-MFS algorithm might be required. Note - as mentioned earlier, the MS-MFS algorithm can be run to use full multi-scale capabilities to model confused fields better, but with S-W MFS to limit the computing load. **Q1, 2010**

Status:

1. **The MS-MFS algorithm:**

   The basic implementation of this exist in CASA for Stokes-I imaging and has been applied to real data for a few fields (Rau, 2009). To reproduce the Sault-Wieringa MFS algorithm, the MS-MFS algorithm in CASA can be used with two Taylor terms (to model the frequency dependence of the sky) and a single scale.

2. **A-Projection:**

   Using a model for antenna aperture illumination (Brisken, 2003), this computes the effective sensitive pattern (average PB) averaged over wide-band and rotation with Parallactic Angle (Bhatnagar et al., 2008). This average PB can be used for post deconvolution correction.

Work required:

1. Some work for integration of the MS-MFS with A-Projection.

2. Further testing and commissioning of the MS-MFS algorithm, particularly at higher frequency bands.

Fall-back option

While we do not anticipate using them, the following fall-back options have been proposed:

1. Hybrid algorithm using multi-channel imaging and MFS on the resulting residuals. While this has been shown to reach full sensitivity, there are no numerical or computational advantages over the MS-MFS algorithm (Rau et al., 2006). **Q4, 2009**

2. Multiple narrow band images using fraction of the band followed by post-deconvolution image-plane averaging in frequency. This can limit the imaging dynamic range and not deliver full benefits of EVLA wide-band capabilities.

3.2 Stage 2: Wider-field, wide-band imaging

For frequency spread of $> 10\%$ imaging beyond approximately inner 10% of the PB, residual errors due the frequency and time dependence of the PB become significant. Errors due to frequency scaling of the PB and time dependent errors due to antenna pointing errors and rotation of the PB with Parallactic Angle (PA) are maximum at the half-power point of the PB[2].

[2] In observations with 2:1 bandwidth ratio, sources beyond the half-power point at the lowest frequency appear in the first side-lobe at the highest frequency in the band.

Therefore, for wide-band continuum imaging of fields wider than the inner 10% of the sensitivity pattern, integration of the MS-MFS algorithms with the A-Projection algorithm is required.

Status:

The basic implementation of the A-Projection algorithm exist in CASA and has been tested with real wide-band data for a few fields for Stokes-I and -V imaging.

Preliminary integration with the MS-MFS algorithm and testing is in progress.

Work required:

1. Full integration with the MS-MFS algorithm.
2. Testing using WIDAR data (i.e. data with large instantaneous bandwidth)
3. Numerical and computational optimization **Q3, 2010**
4. Evaluate the accuracy as a function of distance from the center of the PB
5. Parallelization on a cluster.

3.3 Stage 3: Full sensitivity, full-beam, wide-band imaging

Full sensitivity imaging, particularly at lower frequencies will require image deconvolution out to at least the first side lobe and correcting for time variable antenna pointing errors.

Status:

1. Idealized model for the antenna PB including side-lobes and rotation with Parallactic Angle.
2. Integration with deconvolution algorithms to correct for the resulting time-varying gains due to PB rotation is in an advanced stage.
3. Pointing SelfCal algorithm to solve for time varying antenna pointing errors exists in CASA. This has been tested with simulations including expected EVLA noise levels. Tests with real data, initially with narrow bandwidths is in progress.

Work required:

1. Test imaging performance out to the first sidelobe of the antenna power pattern.

2. Estimate the impact of pointing errors on high dynamic range imaging, particularly at high frequencies (where the PB is narrow), and for fields with sources throughout the PB and potentially in the first side-lobe. **2011-2012**

3. Test the Pointing SelfCal algorithm with real wide-band data.

4. Test achievable imaging dynamic range in a full imaging-pointing SelfCal loop.

4 Full Stokes Imaging

Instrumental polarization effects in general are time, frequency and direction dependent. With the final goal of wide-field full-Stokes imaging using full available bandwidth, algorithm development can be done in stages with each stage independently focusing on direction dependence and frequency dependence of instrumental effects. As in the case of Stokes-I imaging, these can be integrated later for a complete imaging algorithm.

4.1 Stage 1: Wide-field, narrow-band

Full-Stokes Cube: Faraday Rotation Synthesis (Brentjens & de Bruyn, 2005) using observations covering large bandwidths involves narrow band Stokes imaging (per frequency channel).

In this the dominant source of errors will be due to PB polarization away from the center. Ignoring frequency dependent effects, algorithms to measure or solve for direction dependent instrumental polarization can be developed.

Status:

Only basic software machinery to use antenna full-Stokes antenna illumination during image deconvolution. Full Stokes imaging has not yet been implemented.

Work required:

1. Research to determine the best way forward for correcting full-Stokes PB effects. **2010-2011**

2. Implementing wide-field, narrow-band full Stokes imaging.

3. Integrating it with direction-independent polarization calibration and testing the extend and accuracy to which this can be used.

4.2 Stage 2: Narrow-field, wide-band

Full-Stokes imaging close to the center of the PB, where direction dependence of the PB polarization is relatively weak. This will involve extending the MS-MFS algorithm to the full-Stokes case.

Status:

Nothing that has been tested even conceptually.

Work required:

1. Extending the narrow field MS-MFS algorithm for full Stokes case requires significant research and development. **2012**
2. Testing the stability of instrumental leakage at the center of the PB, as a function of time and frequency.

4.3 Stage 3: Wide-field, wide-band

As in the case of Stokes-I imaging, this is the final goal and will involve integration of algorithms to correct for direction and time dependent polarization effects with MS-MFS algorithm.

This will probably also require incorporating Faraday Rotation Synthesis.

Status:

The basic Faraday Rotation Synthesis algorithm, with application to WSRT data exists (Brentjens & de Bruyn, 2005).

Work required:

1. Implementation of RM Synthesis algorithm in CASA/AIPS. >**2013**
2. Significant research, development and testing.

5 High Dynamic Range Imaging

In addition to the corrections for the direction dependent gains varying with time and frequency, high dynamic range imaging will also require algorithms for better modeling of complex emission as well as accounting for pixel quantization errors for compact emission.

Conventional deconvolution algorithms (CLEAN and its variants and MEM and its variants) model the sky in the pixel bases. This fundamentally ignores coupling between image pixels in images with extended emission and the fact that even compact emissions may not be centered on an image pixel. Both these problems lead to residual deconvolution errors which limit the highest achievable imaging dynamic range.

Several algorithms which model the sky in a scale-sensitive basis have been recently developed. Most promising of them are the Asp-Clean and the MS-Clean algorithms. Note that in principle, some approaches to multi-scale deconvolution can also correct for the pixelation errors (Voronkov & Wieringa, 2004). An alternate approach based on multi-facet imaging to correct for pixelation errors also exists (Cotton & Uson, 2008). While the MS-Clean algorithm exists in CASA, Asp-Clean algorithm has not yet been ported from AIPS++.

5.1 Stage 1: Wide-band

This involves extending the multi-scale deconvolution techniques for scale-sensitive modeling of the emission along the frequency axis as well. Run-time efficiency of the available algorithms for large data volumes will be the crucial parameter to determine the optimal algorithm to use.

Status:

The MS-MFS algorithm combines the wide-field imaging algorithm with the MS-Clean algorithm.

Work required:

1. Evaluate the run-time cost of MFS with MS-Clean, Asp-Clean or any other appropriate scale-sensitive deconvolution approach.
2. Evaluate the `autoCentering` technique for performance and integrate with algorithms that correct for other effects of similar magnitude.
3. The narrow-band Asp-Clean algorithm can be deliver higher accuracy at relatively modest increase in run-time cost. **2011-2013**

   Research required to explore extension of this to the case of wide-band imaging.

5.2 Stage 2: Direction dependent calibration

Achieving high imaging dynamic range depends on calibration and correction for direction dependent errors. Since it is nearly impossible to measure these direction and time varying gains at the required accuracy and time resolution, algorithms to solve for these effects will be required.

Status:

1. Two basic but fundamentally different approaches to solving for direction dependent errors (Cotton et al., 2004; Bhatnagar et al., 2004).

Work required:

1. Significant research and development to determine the optimal way forward. **2011-2015**

5.3 Stage 3: Full-Stokes

None of the scale-sensitive deconvolution techniques have been tested carefully for imaging performance in full-Stokes.

Status:

Nothing exists.

Work required:

1. Research to extend the scale-sensitive method of choice to full-Stokes imaging.
2. Research to further extend it for wide-band full-Stokes case.

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