Imaging/calibration algorithm research

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August 2, 2004

This note discusses the proposed plan for research on imaging and calibration algorithm development related to EVLA/ALMA. Attempt here is to describe briefly a work plan to address two problems which will need to be addressed in a few years from now, which also look tractable and towards which some work has already been done. In the sections below, the problems of continuum imaging with a bandwidth ratio (BWR $\equiv \nu_{max} : \nu_{min}$) of 2:1 and pointing offset calibration are discussed and possible plan of action suggested. Wideband imaging will be required for EVLA observations. Pointing offset calibration will be necessary for higher dynamic range mosaicing observations as well as very high dynamic range, full primary beam single pointing imaging (particularly for crowded fields) with both EVLA and ALMA.

Such research, apart from the obvious benefits of improved imaging and calibration algorithms, will also help in getting a realistic estimate of the computing requirements for these new telescopes. Current computing cost estimates are based on simple scaling laws (for the required and available computing in the future). A better, more realistic estimates of the actual algorithms (not yet implemented) required for the advertised sensitivities and imaging dynamic ranges, can have a significant impact on these estimates.

1 Wideband imaging

Wide bands are used for continuum imaging to improve the sensitivity of observations. However for imaging, the band needs to be split into multiple narrower channels to reduce the effects of chromatic aberration (band-width smearing) away from the phase center. Multi-channel continuum observations will therefore be necessary for full primary beam imaging with the

EVLA, where the BWR can be 2:1. At such wide bandwidth, the image cube becomes a function of frequency due to three major reasons:

1. **Field of view (FOV) effect:** The field of view changes by a factor of two across the band. This effectively means that the source model changes significantly across the frequency range, purely due to the change in the field of view.

   This is assuming a perfectly known, no-squint primary beam pattern. In practice however, the rotation of the, potentially frequency dependent polarized beam pattern on the sky along will further introduce frequency dependent errors which need to be incorporated in the imaging process.

2. **Spectral index effect:** With a finite spectral index, the source strength itself can change as a function of frequency. Further more, this dependence on frequency can potentially change across the image and for some cases even across the same (extended) object. Single power law dependence on frequency also may not be applicable, particularly at low frequencies (e.g., L-band observations in the Galactic plane involving thermal and non-thermal sources).

   Spectral line observations of sources where the spectral lines vary across the field of view will also suffer from similar errors.

3. **Rotation measure effect:** For polarization observations of objects with significant rotation measure (particularly at low frequencies), the spectral variations will come also due to the intrinsic Faraday rotation across the frequency band.

All these effects can be combined to form an effective spectral index (which becomes a complex number when the third effect is also included). Conway et al.[1] have shown that errors due to the position dependent source flux variations as a function of frequency can be ignored for a dynamic range of 1000:1 for a frequency spread of less than $\pm 12.5\%$. At L-band, e.g., such frequency dependant errors limit the usable bandwidth to 125MHz, limiting the improvement in the continuum sensitivity compared to VLA bandwidth of 50MHz to a factor of ~ 1.5. This is clearly insufficient for the EVLA bandwidths (which are required for the advertised sensitivities).

[1] Conway, Cornwell & Wilkinson, MNRAS, 246, 490, 1990

Multi-frequency synthesis (MFS) has been demonstrated [2] with observations from the ATCA (BWR ≈ 1.3). These observations were done at 5.18GHz and essentially used model fitting as a function of frequency to improve upon the original double-deconvolution scheme of Conway et al. to account for the possible non-linear dependence of the source structure on frequency. In the final deconvolved image, the dominant errors were due to the brightest part of the source which also had the largest effective spectral index (primarily due to the FOV effect).

1.1 Work needed

For full band imaging, full primary beam imaging with the EVLA, further development on improving the MFS imaging algorithms is required. Various issues that need addressing that come to mind are:

1. Existing MFS algorithms model the emission with a single power law as a function for frequency. Algorithm to model the sky emission using more sophisticated spectral dependence of the source structure (e.g., multiple power law dependence, various spectral breaks/turn-overs, etc.) is required. This is almost certainly necessary for imaging at L-, and C-band.

2. Such algorithms need to also ultimately account for smooth variation of spectral index across extended emission. For better understanding, when designing algorithms we should attack this more general problem and if required (due to run time efficiency reasons) implement special cases for simpler fields.

3. For extended emission, modeling of the smooth variation of the spectral index across the sources will result in better model image. One can expect improvements in the image fidelity if this information is incorporated in the deconvolution process, for the same reasons as the improved imaging quality when using scale-sensitive deconvolution for total power imaging. Effectively then, work to develop scale-sensitive MFS deconvolution algorithms is needed.

4. Sault & Wieringa approach to MFS is in principle same as the Asp-

[2] Multi-frequency synthesis techniques in radio interferometric imaging, Sault & Wieringa, A&AS, 108, 585-594, 1994

Clean[3] approach for scale-sensitive deconvolution. Asp-Clean components can be further generalized to include wide-band effects. However that will certainly be even more compute intensive and development of acceleration techniques will be the challenge in this area.

5. Asp-Clean machinery has to be incorporated into the imaging tool of AIPS++ (it, as of now, exist as a separate Glish client written in C++ using STL (C++ Standard Template Library) and GSL (GNU Scientific Library). Moving this code into AIPS++ will probably form the first piece of work in this direction.

2 Pointing offset calibration

The measurement equation for a mosaicing observation on a baseline $i-j$ can be written as:

$$V_{ij}^{\circ} = (E_i \star E_j^{*}) \star V_{ij}^{M} \tag{1}$$

where $\star$ is the convolution operator, V_{ij}° and V_{ij}^{M} are the observed and model visibilities for a single pointing and E_i is the complex illumination pattern for the i^{th} antenna. It is the Fourier transform of the *full* primary beam pattern and can be written in the form:

$$E_i(u) = E_{\circ}(u) e^{2\pi \iota u l_i} \tag{2}$$

where $E_{\circ}$ is the complex ideal illumination pattern and l_i is the pointing offset. The error term in the image domain will be proportional to the the derivative of the primary beam. Flux towards the edge of the primary beams will therefore contribute significantly to the error in the presence of antenna based pointing errors, even if the primary beam is assumed to be symmetric. Pointing error would correspond to position dependent antenna based complex gain across the field. Sources beyond, say, the half power point in the primary beam (where the derivative is high) will not be correctly deconvolved. Sidelobes of the PSF due to such sources will limit the dynamic range in the rest of the image.

[3]Adaptive Scale Pixel (Asp) Clean models the emission as a collection of components parameterized by their location, amplitude and scale (Bhatnagar & Cornwell, 2004, A&A, in press)

For identical illumination pattern at each antenna with no pointing offset, $E_i \star E_j^*$ represents the ideal illumination pattern applicable for cross correlation.

One can set up a minimization scheme which minimizes the χ^2 with respect to these antenna based offsets (l_i). In an iterative non-linear minimization, each iteration requires the computation of the derivative, which is of the form:

$$\frac{\partial \chi^2}{\partial l_i} = -2\Re \sum_j \left[V_{ij}^M \star E_j^* \star \frac{\partial E_i}{\partial l_i} \right] \left[V_{ij}^{\circ} - \left(E_i \star E_j^* \right) \star V_{ij}^M \right] \tag{3}$$

This involves evaluation of complex convolutions for every trial step taken. Since that can be expensive, faster, even if approximate, methods to compute this derivative need to be developed (possibly by either using a linear approximation for $E_i \star E_j^*$ and $E_j^* \star \partial E_i / \partial l_i$ or approximating the latter as a function of the former) to solve for the pointing offsets only (as against solving for the full complex function E_i which requires evaluation of $\partial \chi^2 / \partial E_i$).

2.1 Work needed

Various components of the work required towards this are listed below:

1. Formulate a "pointing-offset selfcal" to solve for the antenna based pointing offsets, given a model for the primary beams.

2. Computation of the residual visibilities for Eq. 3, will be the most expensive step. From the point of view of algorithm development, the problem of devising a scheme to compute this quickly (even if approximately) will be addressed.

3. The simplest test case for this would be just a single pointing observation, with a time varying antenna based pointing-noise. Any such scheme will need to be tested on simulated data. Some work will be required no the AIPS++ simulator for such a simulation.

4. AIPS++ environment is best suited for such algorithm development. It is unclear if this can be done, at least for the testing stage, purely at the Glish scripting level (if required, computationally expensive parts of the algorithm can be fairly quickly coded in C++).

5. Integrate such an algorithm with imaging, particularly for mosaicing. This will involve computation of model visibilities as $(E_i \star E_j^*) \star V^M$ in the major cycle and computation of residual image as the Fourier transform of $(E_i \star E_j^*)^T \star V_{ij}^\circ$.

3 Resource requirements

The dominant human resource needed for such research is of course the time of astronomers with active interest in the inter-disciplinary area of scientific computing in general and for data analysis algorithms for radio astronomy in particular. The sensitivity of EVLA and ALMA, and consequently the data rates from these telescopes will be substantially higher than the data rates handled by the current algorithms. Research in the scientific computing aspects of such new telescopes will therefore require, exploration of the developments in numerical computing in general as well as in processing large data volumes (apart from the developments in the algorithms specifically for astronomical applications).

Most of the work done in the area of algorithm development currently is done in "free time" plus the available "science" time. The available time for algorithm development currently limits the rate of progress, as well as the intellectual focus. Reasonable progress in these areas will require one full time person for 3 years to be devoted to such research. Since this work will inevitably require software development using the AIPS++ package, incorporating this research and development work as part of the AIPS++ project plan is a possibility. Note that algorithm development work is incorporated as part of the AIPS++ plan - but at a lower priority for the next couple of years (the main focus of the AIPS++ project, going by the planned investment of the resources, is regular production software for ALMA, connect with the ACS Framework, etc.) Overlap between the current AIPS++ development plan and the development required for this work is likely to be high and it is conceivable that it will feedback into AIPS++ development at some level. The support required from the AIPS++ project will be for the software infrastructure (astronomical software and system software infrastructure). Development required specifically for this research will be part of the work plan for this research. Implicit in such a plan is the assumption of intellectual access and involvement of Tim Cornwell and possibly of others interested in such work.

In my opinion, this kind of work is really scientific research, functionally not very different from research in other fields. It is therefore hard to define fixed time-line "deliverables" in the project management language. However it is reasonable to expect that, starting from the ideas we have at this point of time, demonstrable progress can be achieved on the time scale of 3 years. This can be done by developing and demonstrating the fundamental viability of the algorithms from a numerical standpoint using simulated data within an year. Real data from test observations designed to test the performance of the algorithms can form the next step forward. Development of user application programs, usable by astronomers in general, and which can handle the higher data rates will then have to be incorporated in the development plans of the AIPS++ project.