Non-imaging Analysis and Self-calibration

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ATNF Astronomical Synthesis Imaging Workshop

Narrabri, 24 – 28 September, 2001

Self-calibration (self-cal)

The first half of this talk borrows heavily from chapter 10 of the synthesis imaging book by Cornwall and Fomalont (1999).

Following the calibration of interferometer data by tracking instrumental effects and observing an astronomical calibration source, self-calibration can allow further calibration using the data for the target source itself, under certain conditions.

Why do we need self-cal?

The complex visibility output of a well-designed interferometer can be closely approximated by:

$$V'_{ij}(t) = g_i(t) g_j^*(t) V_{ij}(t) + \epsilon_{ij}(t)$$

- Temporal and spatial variations in the atmosphere distort the incoming wavefront;
  - Varies with elevation, frequency, weather etc;
- Weak or resolved calibration source;
- Errors in the geometric model;
- After ordinary calibration, residual errors remain in the gains.

ow does self-cal wor ?

Self-cal can be used to estimate these residual errors by *treating the complex gains as free parameters*. There is enough data to solve for the source structure as well as the complex gains.

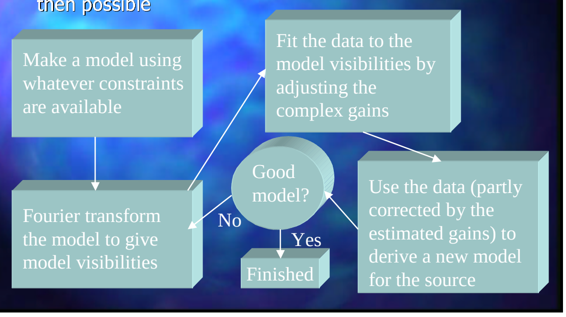
For an array of N elements, this means that there are N unknown gains corrupting the ½N(N-1) visibility measurements. Therefore there exist at least ½N(N-1)-N “good” complex numbers in the data that can be used to constrain the intensity distribution of the target source.

In allowing the gains to be free parameters, something is lost:

- The absolute position of the source;
- Absolute source strength information;
- The ability to distinguish between various types of source structures;
- But as N increases, the ratio of constraints to the number of unknown gains increases without bound, so for large N little is lost.

The degrees of freedom introduced due to the gains are balanced in self-cal by *a priori* knowledge of the source. For example, the corrupted data may still be used to produce an adequate model for the structure of the source.

The model of the source derived from the corrupted data can then be used to partially correct the data (similar to calibration using an astronomical source – self-cal). An iterative approach to estimating the unknown gains is then possible



Why does it wor ?

That this iterative procedure should converge has never been rigorously proven. However:

- Self-cal is most successful in arrays with large N, when the number of constraints is far greater than the degrees of freedom due to the gains;
- Most sources are simple relative to the uv plane coverage of an observation and are effectively oversampled, allowing the addition of a small number of degrees of freedom bearable.

Caveats

- Self-cal fails in low signal to noise regimes – quantitative estimate is possible - ~100 mJy with the ATCA, 100 MHz bandwidth;
- Self-cal can also fail when the source is too complex relative to the model.

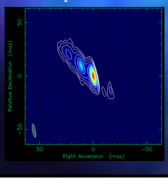
Miscellany

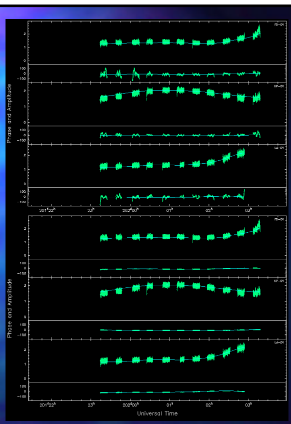
- Amplitude/phase self-calibration;
- Different weighting schemes;
- Averaging times;
- Spectral line self-cal;
- Image errors;
- Implemented in all major software packages.

An e am le

VLBA data for Centaurus A:

- 8.4 GHz;
- 7 antennas;
- Elevation ~ 20 deg;
- Clean/phase self-cal





Non-imaging Analysis

Again I borrow heavily from a chapter in the synthesis imaging book, chapter 16 by Tim Pearson (1999).

Interferometer data are measured in the uv plane. Thus the most direct analysis of the data occurs in this plane. Errors are also often easier to recognise in the uv plane than in the image plane and are generally better understood in the uv plane. Sometimes datasets are too sparse to image and analysis in the uv plane is the most sensible option.

ns ection of visibility data

- Plots of amplitude and phase against time and distance (along various position angles) in the uv plane;
- Closure quantities – amplitude and phase;

$$\phi'_{ij}(t) = \phi_{ij}(t) + \theta_i(t) - \theta_j(t) + noise$$

$$C'_{ijk}(t) = \phi'_{ij}(t) + \phi'_{jk}(t) + \phi'_{ki}(t)$$

$$C'_{ijk}(t) = \phi_{ij}(t) + \phi_{jk}(t) + \phi_{ki}(t) + noise$$

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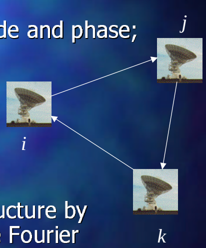

- Get a feel for the source structure by comparing the uv data to the Fourier transforms of basic intensity distributions;

odel-fitting

This is what is generally meant by non-imaging data analysis – a method of building a detailed model for the source structure that does not involve Fourier transforms of the uv plane data, or de-convolution.

- Model is generated in the uv plane by operations on the uv plane data, as opposed to operations in the image plane when using clean;
- Certain similarity to self-calibration.

Three steps to model-fitting success:

- The user defines (guesses) a model for the source, parameterised by a known number of free (adjustable) parameters.
- The *model* is then Fourier transformed into the uv plane to produce model visibilties
- Compare the model visibilities to the uv plane data and adjust the free parameters of the *model* so as to fit the model visibilities to the data (this is the similarity to self-cal).

odel-fitting s ccess

1. est-fit val es for the free arameters of the model
2. A meas re of the goodness-of-fit for the best-fit model (relative to the meas rement errors)
3. stimates of the ncertainty in the best-fit arameters

Limitations to this approach include:

- May be difficult to define a starting model parameteristion;
- Solutions are not unique;
- Slower than conventional imaging (Fourier invert/clean);
- Least-squares method probably not strictly appropriate;
  - assumes that the errors are Gaussian, uncorrelated, and no calibration errors;
  - degrees of freedom introduced during self-cal should be taken into account.
- Uncertainties on the model parameters can be difficult to quantify.

odel-fit errors

- Covariance matrix to see which parameters are constrained and how they are correlated;
- Contours of constant chi-square for single parameters or sets of parameters;
- Caution must be exercised when using any theoretical measures of confidence since they assume fully independent data for which the visibility errors are fully understood and are distributed appropriately for the statistical tests being used;
- Monte Carlo tests are useful but time-consuming!!!