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SELF-CALIBRATION OF M.O.S.T. DATA

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ABSTRACT The Molonglo Observatory Synthesis Telescope (MOST), located near Canberra, Australia, is an east-west earth-rotation synthesis array which, unlike conventional synthesis arrays, generates multiple real-time fan-beams and forms images by the back-projection of the recorded intensities rather than by Fourier inversion of visibilities. The images produced in this fashion are often marred by the presence of radial artefacts emanating from strong sources due to residual calibration errors. An algorithm devised to self-calibrate these errors is discussed.

INTRODUCTION

The Molonglo Observatory Synthesis Telescope (MOST; see Mills 1981) is an east-west interferometric array operated by the Department of Astrophysics within the School of Physics at the University of Sydney and used for high resolution, high sensitivity, wide-field imaging at 843 MHz. By combining signals from the 44 receiver units ('bays') on each of the east and west arms, 64 real-time fan-beams are generated. These may be time-multiplexed to cover up to 70′ with 11″ spacing. Images are formed from the beam flux densities by back-projection onto the image grid (Crawford 1984). The dynamic range of MOST images is limited to about and phase not removed by the usual calibration procedures.

Solving for individual receiver complex-gains [as per Cornwell and Fomalont (1989)] is not possible since baseline-dependent visibilities cannot be recovered from the beam flux densities, so the algorithm (Subramanya 1984; Cram 1989) takes advantage of the fact that, since MOST is east-west linear, temporal errors in gain and phase appear in the Fourier domain as radially oriented spikes.

SOURCES OF ERROR

Gain Errors

The major correction made to MOST data is a correction for the meridian distance gain curve, an empirically determined curve tabulated at 30′ intervals. The curve has a cosine envelope due to a decrease in the projected aperture when viewed from off the meridian and modulation due to standing waves

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between radiation received by the feeds after undergoing a single reflection from the mesh and radiation which has undergone multiple reflections between the mesh and feed structure. Uncertainties and short-term changes in the gain curve result in radial structures emanating from strong sources in the image, degrading the image quality. The gain of MOST also varies with temperature and since the coefficient of this dependence is uncertain at the 10% level, a slowly varying gain error occurs through an observation.

Phase Errors

The local oscillator (LO) signal is distributed by troughline waveguides, one on each arm. The characteristics of these waveguides depend on environmental factors and to ensure a stable phase reference the LO frequency is servoed to keep the phase constant between monitor points on the west arm. The MOST is sufficiently large, however, that the east and west waveguides may be affected differently, resulting in phase slope and phase offset errors on the east arm. Moreover, at a frequency of 843 MHz the MOST is influenced by ionospheric irregularities which can produce random phase errors of $\sim \pm 10°$ at the telescope.

SELF-CALIBRATION

Although the MOST does not record Fourier data it is useful to examine the effects of the above-mentioned errors in the Fourier domain. The observed visibility at any point (u, v) in the Fourier domain can be written

$$V_{obs}(u,v) = G(u,v)P_o(u,v)V_{true}(u,v) + \epsilon(u,v) \tag{1}$$

where V_{obs} is the recorded visibility and P_o is the Fourier transform of the ideal synthesised beam, both of which are known, and V_{true} is the true (sky) visibility, G is the complex gain error and ϵ is a zero-mean noise term, all three of which are unknown. To find G we must eliminate the other two unknowns. We begin by approximating the true sky brightness distribution with a model determined by some means (CLEAN components, for example) such that

$$V_{true} = V_{mod} + V_{err} \tag{2}$$

where V_{mod} is a model of the true visibilities and V_{err} is the deviation between the true and model visibilities. Substituting equation 2 into equation 1 and rearranging gives

$$G = \left(1 + \frac{V_{err}}{V_{mod}}\right)^{-1} \left(1 - \frac{\epsilon}{V_{obs}}\right) \frac{V_{obs}}{P_o V_{mod}} \tag{3}$$

Provided that the model is good enough we may assume that V_{err} is everywhere small compared to V_{mod}. In general we may also assume that ϵ is small compared to V_{obs}. Substituting these approximations removes the first two terms in equation 3, giving

$$G(u,v) \simeq \frac{V_{obs}(u,v)}{P_o(u,v)V_{mod}(u,v)} \tag{4}$$

We now have an expression for G in terms of known quantities. Note that for ideal data G will have an amplitude of unity and zero phase at all points in the (u,v)-plane.

It remains to characterise the telescope errors through the use of an appropriate but simple model for G. As mentioned above, the error in the correction is generally assumed to be determined by three parameters - the gain g, the phase offset ϕ and the pointing offset θ. From the above discussion of the source of the errors we expect G to be well approximated by

$$G(u,v;t) = g(t)\exp\{i[\phi(t) + 2\pi \sin\theta(t) r]\} \tag{5}$$

where $r = \sqrt{u^2+v^2}$. Thus by calculating G from equation 4 (making use of FFTs to obtain Fourier data from MOST images) and fitting, using a least-squares technique, for the three parameters according to equation 5 we can extract information about the time-dependent gain and phase errors. The fit is made by taking a weighted average of the amplitude of G along a radial cut and by fitting a least-squares line to the phase of G as a function of r to obtain estimates of θ and ϕ. The weighting factor used in this fitting process is the normalised amplitude of the model visibility at each point. This prevents nulls in the visibility distribution (where the signal-to-noise ratio of the data is small) from adversely affecting the fit obtained. After fitting, the data are corrected according to equation 1 to give a better approximation of the true sky brightness distribution. This process may be repeated to further refine the solution.

INITIAL RESULTS

Testing was performed on an artificial 1 Jy point source. This has the advantage that (a) the errors imposed on the artificial data are known and can can be used to check the accuracy of the solution obtained by the self-cal fitting and (b) noise can be introduced in varying amounts to determine the effects of noise on the fitting process. Results from these experiments proved that the method works. Various combinations of gain, phase offset and phase slope errors were introduced and the self-calibration process used to correct for them. It was found that after three cycles of self-calibration virtually all trace of the errors had disappeared, the exception being at hour angles near the ends and the middle of the observations. This is because at these hour angles many samples lie in the same row/column of pixels in the FFT and it is therefore quite difficult to determine accurate corrections for each sample. However, even these residual errors fall well below the noise level of a typical MOST image (< 1 mJy), corresponding to a dynamic range of 1000:1. Applications of the algorithm to real data also show a marked improvement in dynamic range, to a value of $\sim$300:1. Further improvements will require a better model of the errors in the telescope.

CONCLUSION

Self-calibration for Molonglo is a promising method for improving the dynamic range of images. Tests have shown that it is possible to extract sufficient information from the FFT of a MOST image to correct the raw data on a sample by sample basis and to use that information to significantly improve the image quality. Furthermore, the same tests have shown that this process converges rapidly, giving excellent results after only three iterations.

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