ATA Memo 11

Astronomical Imaging with the Allen Telescope Array - II

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Re- visiting BIMA MEMO 75 - 2 years later

Summary.

The One Hectare Telescope is envisioned as an instrument which produces final, calibrated images as its output. A doughnut shaped array with overall size ~ 700 m provides good brightness sensitivity with excellent instantaneous uv coverage. A calibration system maintains the signals from the antennas with the correct delay and phase. Images are produced either by cross correlations and FFT of the uv data to the sky plane, or by beam formation over the region of sky of interest.

1) Array configuration

The science cases presented require good brightness sensitivity with modest resolution. The table below shows the percentage of collecting area in uvranges from 0-1, 1-2, 2-4, and 4-8 kilolambda at 1.4 GHz for various array configurations, as well as the uniform and natural weighted beam FWHM. The VLA d-array is shown for comparison. The percentage of collecting area in each uv-range gives the brightness sensitivity on angular scales of ~ 140, 70, 37, and 20 arcsec at 1.4 GHz.

Table 1 - Percentage of collecting area in uvrange

Array configuration	beam FWHM uniform	(kilolambda at 1.4 GHz)= 0-1 ~140	1-2 70	2-4 37	4-8 20 arcsec	natural
Gaussian close packed	62 x 60	63	35	2	0	111 x 105
Gaussian loose packed	39 x 37	32	47	21	0	70 x 66
Filled triangle	42 x 40	22	45	25	0	72 x 60
Doughnut or open triangle	42 x 40	25	40	35	0	60 x 55
Filled triangle + NS extensions	34 x 19	16	31	41	9	60 x 36
VLA d-array	36 x 35	31	31	34	2	63 x 61

The Gaussian array configurations have the highest brightness sensitivity to large scale structure. The NS extensions give the highest angular resolution, but little sensitivity on 20" scales, unless a large fraction of the collecting area is placed in these locations. The higher resolution comes at the cost of sensitivity on 140 to 37" scales, and results in poorer synthesised beam patterns. The best match to the science cases presented appears to be the doughnut array, which distorts to an open triangle if the maximum EW resolution is sought in the available space at Hat Creek. The doughnut array has excellent snapshot uv-coverage, ensuring nice images in difficult interference conditions when uv-coverage cannot be obtained from long uv-tracks as required for the NS extensions.

The doughnut array has a number of practical advantages, such as low cost of the supporting infrastructure - roads, trenching etc. The filling factor for a 700m outer diameter, and 100m wide doughnut with 500 5m diameter antennas is about 5%, with an average antenna separation of 19m, and antenna shadowing at ~ 14 degrees elevation. A doughnut which is more extended in the NS direction is desirable to reduce shadowing and produce rounder synthesised beams at low declinations, but is not easily accommodated on the available land.

2) sensitivity

Assuming tsys=40, bandwidth=10 MHz nants=500 antdiam=5 freq=1.4 GHz theta=70"

The continuum sensitivity in 1 minute gives an Rms Flux density = 1 mJy, sufficient for 1 degree RMS array phasing on a 60 mJy source.
Kellerman gives N(S) = 60 S^{-1.5} Sr^{-1}; implying one 60 mJy source within 1 degree on the sky.

For Galactic HI, a 1 MHz bandwidth with 1 kHz resolution (0.2 km/s at HI) in 1000 channels gives an Rms Brightness: 0.5 K in 10 hours at 70" resolution.

For cold molecular cores in CCS at 11.2 GHz with 0.2 km/s resolution, the Rms Brightness is 0.16 K in 10 hours at 9" resolution.

For Extragalactic HI, a 10 MHz bandwidth gives a velocity coverage of 2000 km/s. With 50 kHz resolution (10 km/s) in 200 channels we get an Rms Brightness 0.06 K in 10 hours at 70" resolution which corresponds to an HI column density ~ 10^18 cm^-2.

3) Imaging

The doughnut array has excellent uv coverage and has a very high data rate, which will rapidly saturate any conventional human data reduction and imaging. The array should produce final, calibrated images as its normal output. Thus the calibration system should leave little room for improvement by post processing, and the uv-data, if any, need not be kept. For the highest image fidelity, it may be necessary to sample the images on a fast time scale to remove residual atmospheric, calibration and interference artifacts.

There are two possible routes for producing images: 1) cross correlations, followed by gridding and FFT of the uv data to the sky (xy) plane. 2) direct imaging by beam formation over the region of sky of interest. In either case, we must have a calibration system which maintains the signals from the antennas with the correct delay and phase.

With 500 antennas and 10 MHz bandwidth, the input bandwidth is 5 GHz.
For interference suppression we may need 8 bits per sample.

For a ~ 1 km array, the maximum delay is 1 km/3 10^5 km/s = 3.3 microsecs
This requires 3.3 10^-6 x 10 MHz x 8 bits = 300 bits per delay line.

Correlator: conventional processing requires a 125000 baseline correlator with ~ 1000 spectral or lag channels per baseline. An FX correlator does the time to frequency FFT for each antenna, and then cross correlates the antennas. An XF correlator first cross-correlates, and then makes the spectral channels from the correlation lag channels. The XF correlation needs fewer bits, but there is a spectral FFT for each antenna pair. Development time and connectivity are an issue for a 125000 baseline correlator. An FX correlator reduces the bandwidth for each spectral channel to ~ 10 kHz in 1000 frequency channels which can be processed in parallel. A 10 kHz correlator may be sufficiently small to solve the connectivity problem.

Nyquist sample rate for a 1 km array is 12*3600/(pi*1000)*2.5 = 34 secs.
- correlator output = 125000 x 32 bits x 1000 channels / 34 secs
= 1.2 10^8 bits/s or ~10^13 bits/day.

Images: Full field images for FWHM have ~ 1.2 lambda/5m / lambda/2 km ~ 480 pixels.

Direct Imaging: An alternative to a correlator is direct beam formation for each pixel. The sampled IF for each antenna is summed with a phase shift appropriate for each pixel, uv sample interval and frequency channel. For a regularly sampled xy image, the phase shift increment per pixel is constant and need only be computed at each uv-sample interval. This is a similar data rate to the correlator. A possible architecture is a separate processor for each antenna/IF data stream, summing the processed output (phased shifted frequency channels) into a common image matrix.

4) array calibration.

i) phase array = find delay0 which maximizes central pixel on strong point source
- this suggests a minimum correlator with 500 baselines, or alternatively, a software correlation, to cross correlate each antenna with the phased array minus that antenna. One starts the process by phasing the antennas whose phases have been determined and cross correlating with the unknown antennas in order to determine the antenna phase. So perhaps we don't need to build a hardware correlator.
ii) set delay0 + geometric delay into delay register
iii) sample at 1 to 10 MHz bandwidth; FFT to frequency channels.
iv) cross correlate, or use a sum of antennas to determine the phase.
v) use planets and quasars to calibrate without additional gizmos on antennas.

5) Image formation and self-calibration

The high data rate lends support to the idea of forming images, and not storing correlation data. One can still make an image of the instrumental response (the synthesised beam) and do image deconvolution. The images can be written out at some reasonable data rate for evolving sources such as comets. Not storing correlation data precludes the conventional self-calibration. The tropospheric path fluctuation at cm wavelengths is around 1 mm on a 1 km baseline in 5 min. This is only 1/30 wavelength at 10 GHz and is probably not limiting the image quality. At wavelengths longer than about 30 cm, fluctuations in the ionosphere may limit the resolution. The calibration system should measure the tropospheric and ionospheric delays for each sample interval using strong point sources within the field, and apply the phase corrections to the data streams from each antenna before the data feeds into the imaging, or beam forming hardware. If the calibration system uses the same frequency as the observations, then the measured delay (tropospheric + ionospheric) is appropriate for the observations. If the calibration is done at a widely different frequency, it may be necessary to solve for the tropospheric and ionospheric delays. This can be done if the calibration data contain simultaneous observations of centimeter and decimeter wavelengths. To further complicate long wavelengths, the primary beam size could be larger than the isoplanatic angle - the coherence scale of the ionosphere. In this case it may be necessary to observe multiple calibrators within the primary beam in order to determine the appropriate calibration across the field of view. This correction is easily applied as a phase shift for each pixel in direct imaging, but could be applied as a correction in the case of a correlation back end.