Imaging and Dynamic Range Simulations for an SKA with Large Aperture Antennas

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Abstract

We describe initial simulations of an artificial sky as seen by an SKA composed of 200 m diameter radio telescopes. The simulations show that even down to a noise level of about 0.02 μJy or less, dynamic range should not be a problem. A significant number of extended sources whose integrated flux is 0.1 μJy may still be invisible in an observation whose noise level is about 0.01 μJy.

1 Introduction

Several competing designs have been proposed for the components of the Square Kilometer Array (SKA). In order to choose between competing proposals, we need to know how effectively each design could observe the radio sky at sub μJy flux densities. Canada envisages an SKA composed of Large Adaptive Reflectors (LAR) (Carlson et al., 2000). In order to better understand the strengths and weaknesses of this design, we have begun a program of telescope simulations with the eventual goal of simulating the behaviour of an SKA composed of LARs. This paper describes the methodology used for the simulations, progress to date, and plans for future work.

2 Telescope Configuration

In order to simulate an observation we must 'create' a telescope that meets the design requirements of the SKA (Taylor and Braun, 1999). Briefly, at

1.4 GHz, an SKA must have the ability to image one square degree of sky with a resolution of 0.1 arcsec at 1.4 GHz frequency. After an eight hour observation the RMS noise in an image made from a single polarization channel having 640 MHz total bandwidth should be about 0.02 μJy.

An artificial telescope that meets the sensitivity and resolution requirements consists of 32 200m diameter fully steerable dishes situated along a 400 km long east-west baseline. Each telescope has a receiver with a 35K system temperature. A 400 km maximum baseline produces a synthesized beam of about 0.1 arcsec while 32 200m dishes provide just about 1 sq km of collecting area. This telescope is obviously unrealistic, but it does provide a rigorous test of current telescope simulation software.

A 200m dish has a primary beam with a half power width of about 5 arcmin at 21 cm. (An eventual LAR will image a larger field of view by means of overlapping beams created from a focal plane array.) To fully sample a 5 arcmin field of view with pixel separations of 0.03 arcsec (so our synthesized beam has sampling of about 3 points per beam) would require images of minimum size 10000 x 10000 pixels (and depending on the image restoration techniques used), a more realistic size of 20000 x 20000 pixels to avoid aliasing effects in the outer parts of the image.

Sadly, I had no computer available that could handle images with 10000 to 20000 pixels on a side! Indeed, in order to get anything useful accomplished for this meeting I was restricted to imaging areas of 1 arcmin on a side (2048 pixels). This still necessitates processing images of size 4096 x 4096 during image restoration.

To image a 1 arcmin field of view with a 400 km maximum baseline requires integration times no longer than 5 sec and theoretical frequency sub bands of no more than about 2 MHz (see Thompson et al (1986) sections 6.3 and 6.4). The 640 MHz SKA observation should really be split up into at least 300 sub bands. I ignore the bandwidth problem for the observing simulation discussed here, but I shall return to this issue in Section 4. Wide bandwidths will actually provide a significant benefit to an SKA composed of a relatively small number of large antennas.

In summary, our task is to simulate an observation of a 1 arcmin field of view with a 32 antenna array that uses 5 sec integrations and has a bandwidth of 640 MHz but no bandwidth smearing.

3 Artificial Observations

Recently Hopkins et al. (2000) have constructed simulated images of the radio sky as it might appear down to a limiting integrated flux density per source of 0.1 μJy at 1.4 GHz. A minor modification to their glish computer code enabled me to output a model sky in the form of either source component lists or FITS images. This model data could then be fed into telescope simulation software and an 'observation' of the artificial sky made.

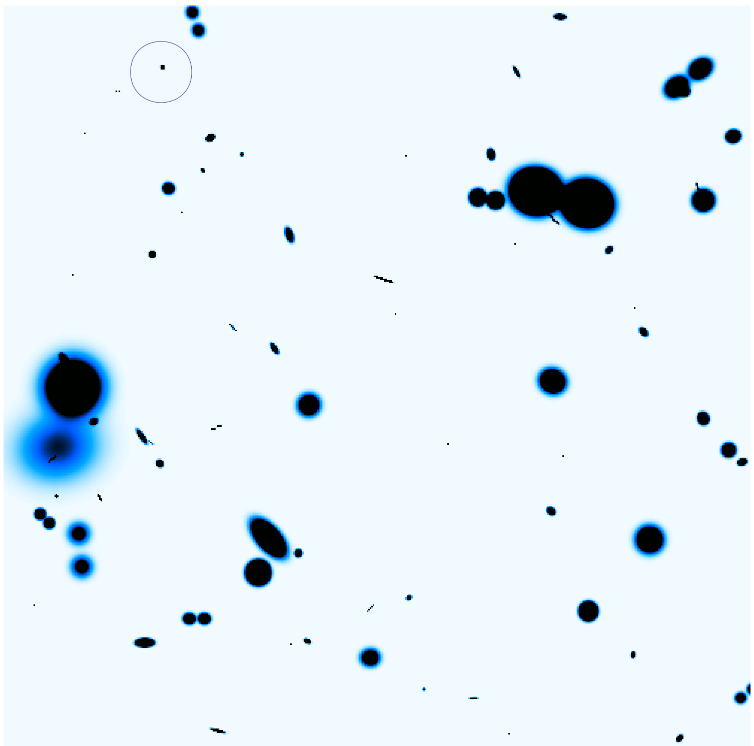

Figure 1: Sample simulated sky 1 arcmin sq in size. The faintest sources have integrated fluxes of 0.1 μJy. The strongest source (circled) is unresolved and has a flux density of 161 mJy. The detection of a source this strong in a field of view a few arcmin or less in size will actually be a rare event. Other simulations show that on average the strongest signal will be a few mJy or less.

I attempted to use telescope simulators in three different packages (AIPS UVCON task, miriad uvgen task, and the aips++ simulator module) to observe the sample artificial sky shown in Figure 1.

All three packages had strengths and weaknesses. However the miriad uvgen task is currently a clear winner on the basis of ease of use and speed of generating model visibilities from direct Fourier transform of source component lists.

Figure 2 shows the artificial sky when placed at declination 60d and 'observed' with the telescope in uvgen for a total on-source time of nine hours. The resulting RMS noise is about 0.02 μJy. The UV data were moved into AIPS and processed as follows: First the AIPS IMAGR task was used to image and clean the field. The AIPS IMFIT task was then used to fit an amplitude and position to the 161 mJy source. IMFIT gave a flux density of 163 mJy and a position that was off by 0.004 arcsec from the nominal position. After using UVSUB to subtract the IMFIT derived parameters of this source from the UV data, IMAGR was used to create a modified image. Some minor artifacts remain around the position of the subtracted source, but signal detection over the majority of the field is noise-limited. In fact many of the sources in the simulated sky are not seen at this noise level. In this simulation I did not introduce any telescope errors; the residual artifacts near the strong source are due to CLEAN errors caused by not having the strong unresolved source located precisely on a grid point.

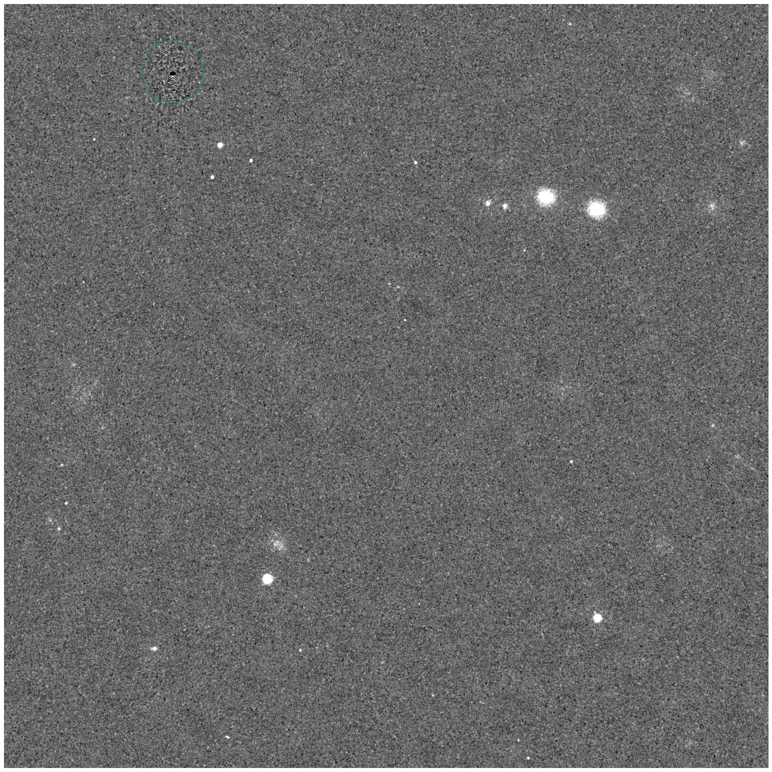

Figure 2: Simulated observation after subtraction of the strong source using parameters derived from the AIPS IMFIT task. The RMS noise is about 0.02 μJy. The image contains 2048 x 2048 pixels.

To see what a faint field might look like if it was observed for several days, we re-ran the simulation without the 161 mJy source, and lowered the noise to about 0.01 μJy. Figure 3 shows the resulting image. A number of extended sources whose integrated flux is at least 0.1 μJy are still not visible at full resolution in this image. This lack of detection is not due to the array configuration. The array should have had spatial frequency sensitivity to any structure less than about 30 arcsec in total angular extent.

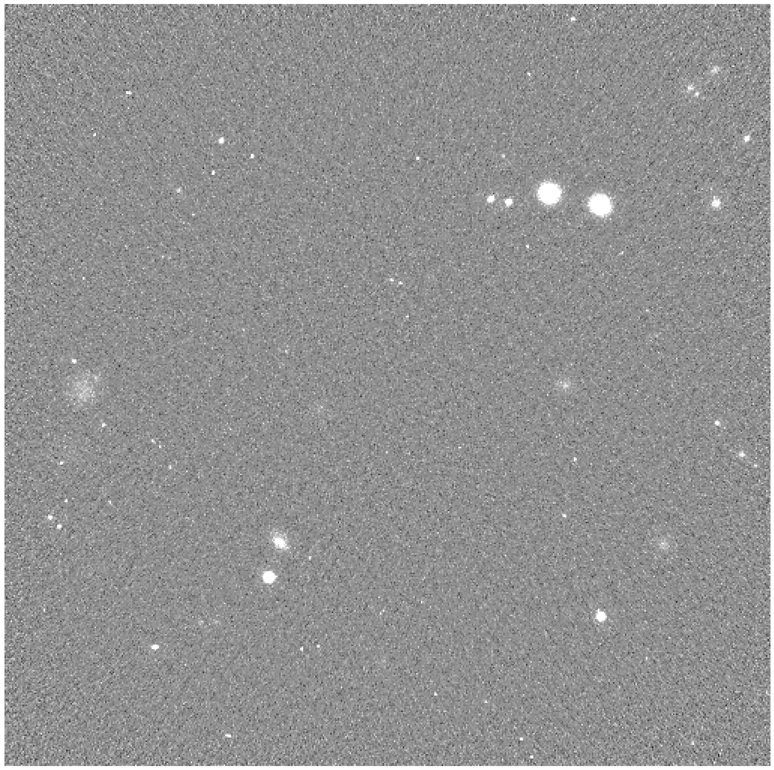

Figure 3: Simulated observation after reduction of noise to about the 0.01 μJy level. The 161 mJy source was not included in this simulation.

4 Bandwidth Benefits

One of the arguments against an SKA composed of a small number of antennas is that the instantaneous UV coverage will not be very good. I argue that if the SKA spends most of its time observing faint objects with maximum bandwidth, then good UV coverage will generally be available because of the huge bandwidth specified for the array. Figure 4 shows the instantaneous UV coverage at 1.416 GHz of a 50 element array whose positions were computed with Kogan's (1997) AIPS task CONFI using the constraint that the maximum baseline should be 400 km.

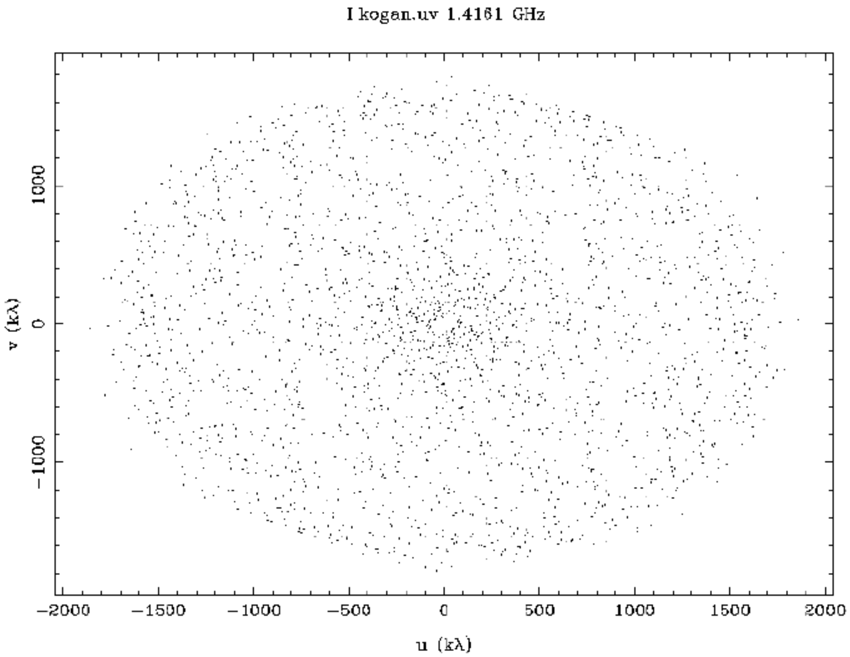

Figure 4: Simulated instantaneous UV coverage of a 50 antenna Kogan array at 1.416 GHz.

This random coverage of the UV plane is quite good, but look at the improvement obtained (Figure 5) if we observed the 600 MHz total bandwidth centred on 1.415 GHz in 300 separate channels and put each of the channel data at the proper UV location.

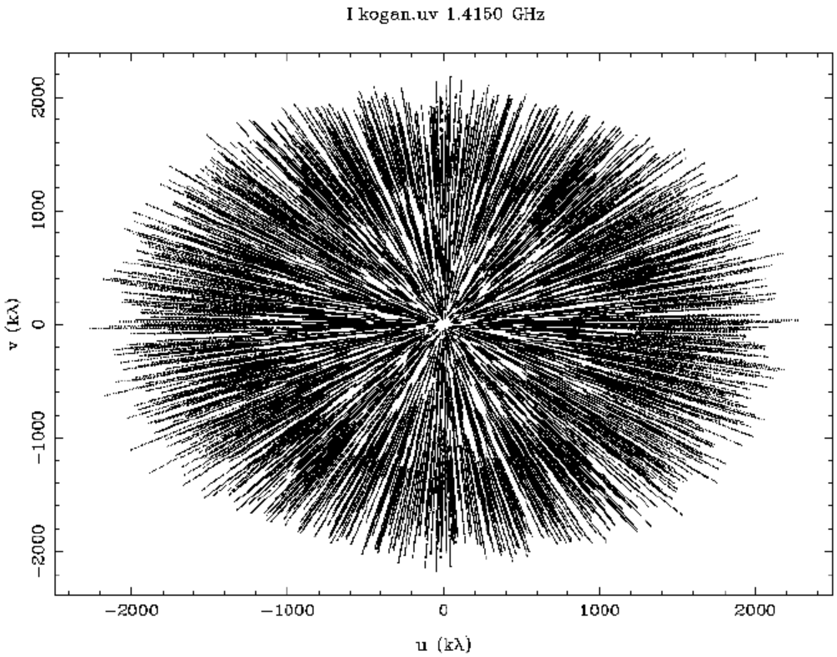

Figure 5: Simulated instantaneous UV coverage of a 50 antenna Kogan array at 1.415 GHz when 300 separate frequency channels are gridded.

5 Conclusion and Future Work

Although it is dangerous to generalize from a few simulated observations, dynamic range effects should not seriously affect the sensitivity of an LAR-based SKA observation at 1.4 GHz that has noise of about 0.02 μJy. Also, if the Hopkins et al (2000) sky simulations are correct, SKA observations with a 400 km array will not be confusion limited down to noise levels of 0.02 μJy. However some extended sources with an integrated flux density of 0.1 μJy may not have sufficient surface brightness to be visible in even a long-term full-resolution observation where the noise is lowered to about 0.01 μJy. Consequently we may want to have the majority of SKA baselines less than about 200 km in length. Further, full bandwidth observations made in line mode will allow an SKA composed on a relatively small number of antennas to obtain good UV coverage through the technique of multifrequency synthesis.

The next step in this work will be to more accurately simulate the behaviour of an array of LARs. In particular we need to model the influence of a time-variable primary beam on the observed images and develop an effective procedure for image restoration under such conditions. We will also investigate more realistic array configurations than the one used for the observations presented here.

A serious limitation of current software simulators is the lack of parallel processing capability for computing model visibilities from source component lists via direct Fourier transform. This severely limits the rate at which visibilities can be generated and inhibits serious investigation and accurate simulation of instrumental effects such as a time-variable primary beam. Degridding of visibility data from FFT-inverted images unfortunately tends to introduce various aliasing artifacts into the model visibility data and is also only an acceptable procedure if the model image is assumed constant over the duration of the observation. We plan to add a parallel processing capability to one of the simulation packages.

6 Acknowledgments

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