Steps toward the SKA: Simulations with MeqTrees

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Abstract

Future radio telescopes such as LOFAR and SKA present us with a number of unprecedented challenges. To select a design that will be able to achieve the SKA requirements, we need extremely elaborate models of the instrument and the observed sky. This makes detailed SKA simulations a vital part of any design effort. The Measurement Equation (ME) (see e.g. Noordam, 1996) provides a succinct mathematical framework in which an instrument and the observed objects may be described. The MeqTree module provides a flexible software system for implementing MEs of arbitrary structure and complexity, and for solving for arbitrary subsets of their parameters. The poster will examine how the ME and MeqTrees can be applied to SKA simulations. We will focus on one test case, that of a SKA composed of CLAR (Canadian Large Adaptive Reflector) dishes, and show detailed simulations of instrumental effects and their impact on observations with such a SKA.

MeqTrees, CLARs and the SKA

MeqTrees are a simulation and calibration package being developed at ASTRON. The crucial difference between MeqTrees and all other calibration or simulation packages for radio telescopes is that completely arbitrary Measurement Equations may be implemented. Source and instrumental models of any structure and level of complexity may be constructed. This makes the package a uniquely useful tool for simulations of future radio telescopes. Briefly, the package has three main components: a compiled kernel (written in C++) which does the majority of the data processing, a python-based scripting language which tells the kernel how to configure itself, and a python-based GUI (see Fig. 2) which provides the user with an interface to the rest of the system.

Fig. 1 shows the Canadian Large Adaptive Reflector (CLAR) concept. It consists of a very large (250m) stationary dish on the ground with the receiver on an aerostat tethered at the focal point. The telescope is steered by a combination of moving the aerostat and changing the shape of the dish surface. Due to antenna geometry, the primary beam of a CLAR becomes progressively elongated in the elevation direction as it is steered away from the zenith toward the horizon. This produces interesting image-plane effects in a SKA composed of CLARs.

Our simulated SKA consists of 27 CLARs, basically in the VLA C configuration, scaled up by a factor 10. We have an array with 351 baselines, the maximum length being about 30 km. We simulate an observation over the range -4 to +4 hrs in hour angle with 16 frequency channels covering the range 800 to 1370 MHz. The simulated field is at declination 33 deg. At the location of the VLA, this field will pass extremely close to the zenith at transit.

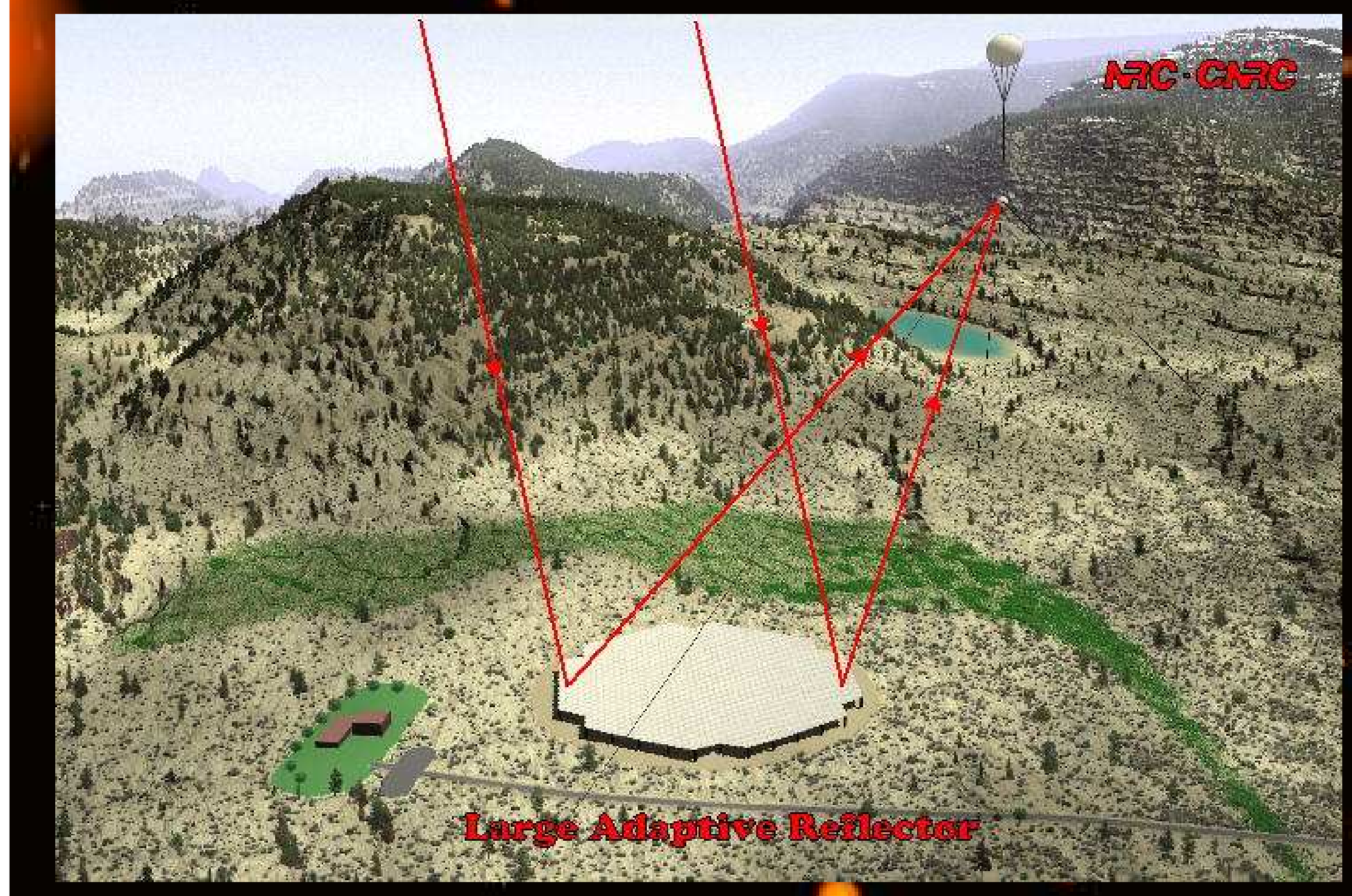

Fig. 1: Artist concept of a CLAR at the DRAO site

Simulated Observations

We have used the SKA configuration described above to make simulated observations of 10 point and extended sources. The sources are given different spectral indices (the extended sources have steep spectra while the compact sources may have steep or inverted spectra). The results of the simulation for the two channels at the outer edges of the frequency ranges are shown in Fig. 3. The apparent changes in intensity in the two figures are due to a combination of three effects: changing brightness of the sources, narrowing of the HPBW toward higher frequencies, and the increase of the UV spacings toward higher frequencies.

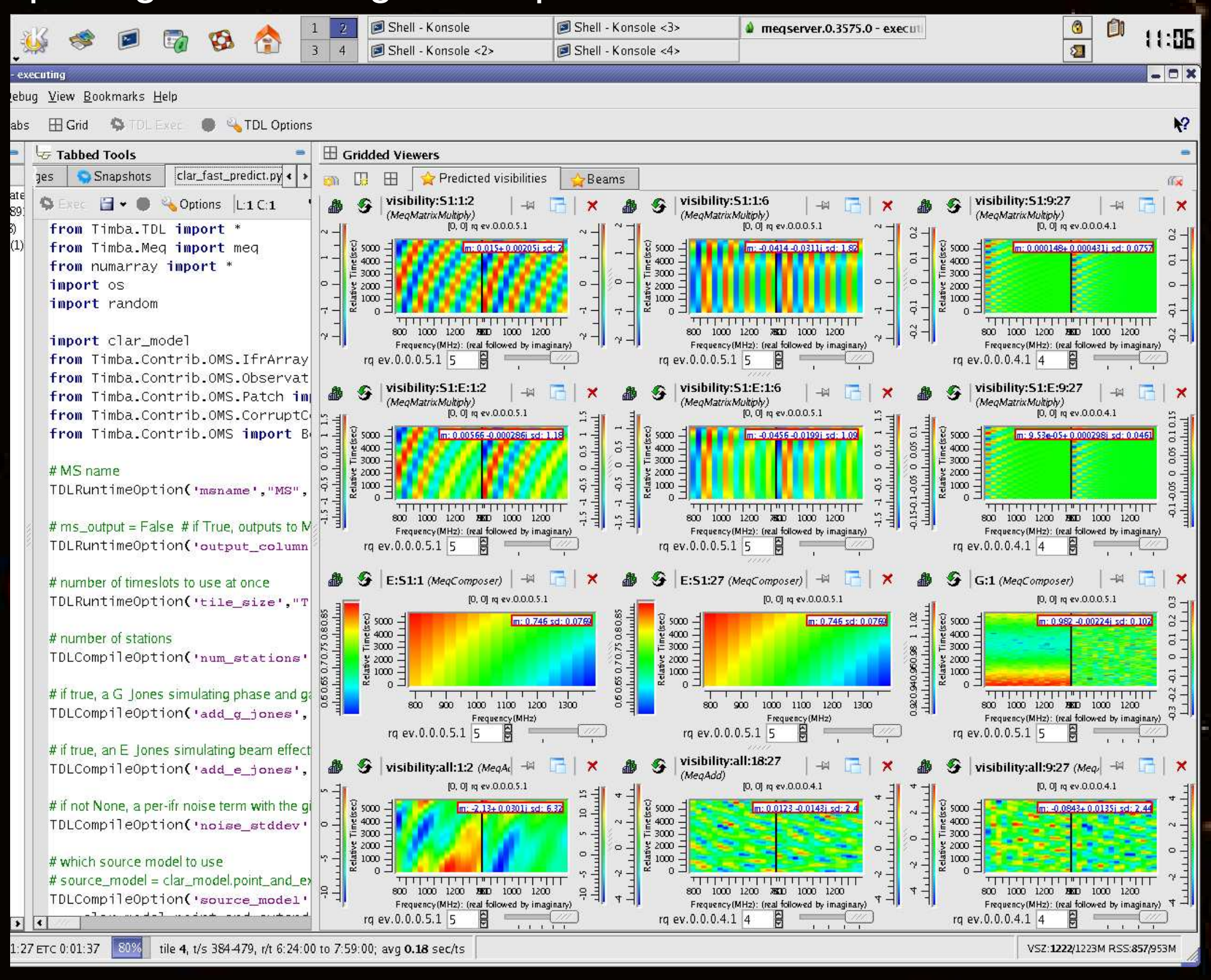

Fig. 2: Screenshot of the MeqTrees browser GUI. It shows observed visibilities as a function of time and frequency for selected baselines in the simulated CLAR array. In the lower middle of the screenshot are the voltage pattern responses for source 1 as seen by antennas 1 and 27 in the array. The response is strongest at the lower frequencies and decreases toward the higher ones, as expected. Note how the response increases with increasing time as we move toward the extreme hour angle of the observation and the beam broadens.

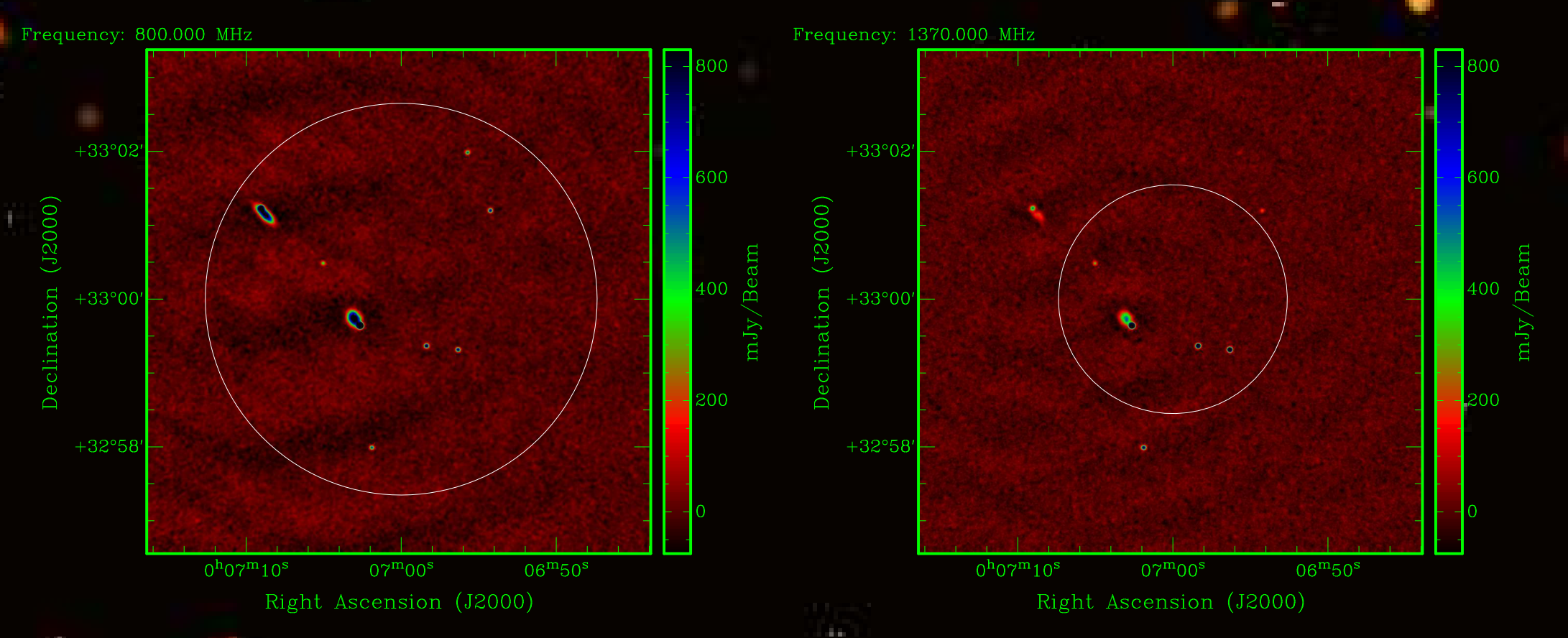

Fig. 3: Images of simulated observations at 800 MHz (left) and 1370 MHz (right). The circles in the images show the HPBW at transit: 5.3 arcmin at 800 MHz and 3.1 arcmin at 1370 MHz. The low-level wave-like features seen in the images are partly due to the fact that the CLEAN algorithm used here cannot compensate for a time-variable primary beam.

Although not readily apparent in Fig. 3, our observations include the effects of the elevation dependent CLAR beam. Since each antenna is at a different geographic position, each antenna will observe the field at a slightly different elevation. Therefore the beam of each antenna will have a slightly different degree of elongation. With a maximum baseline of only about 30 km we might expect this effect to be insignificant and we can try to save some computing time by using an average elevation for the entire array. In order to test this hypothesis, we created 10 point sources, all with flux densities of 2 Jy at 800 MHz and varying spectral indices, and put them at the same locations as the sources in Fig. 3. Then we created visibilities where we computed the elevation separately for each station and differenced these visibilities with ones computed using an average elevation for the entire array. Fig. 4 shows the resulting images made from the differenced visibilities.The errors seen in Fig. 4 are at about the 1:10000 level. Thus, using an average elevation for the entire array is unacceptable for the SKA, where we must attain a dynamic range of approximately 1:1000000.

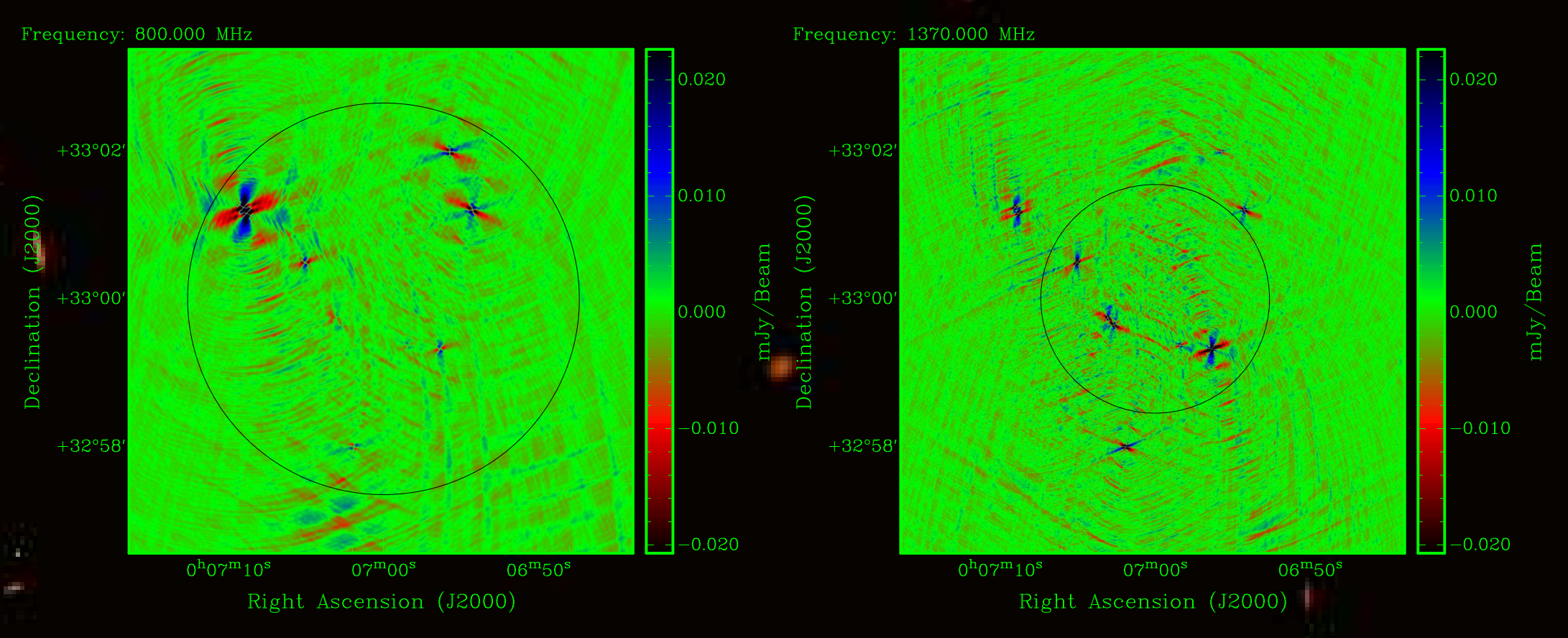

Fig. 4: Difference images between observations made with an average elevation for the whole array and correctly simulated observations at 800 MHz (left) and 1370 MHz (right). The errors change as a function of frequency because of varying spectral indices and a shinking field of view.

Obtaining Source Parameters

In the real world, if we are given some observational data, we want to derive source parameters and flux densities. Here, we have created simulated data, but we can pretend that we do not know the exact source flux densities and spectral indices or the HPBW of the telescope, and make them solvable parameters. This situation presents us with a tricky problem since e.g. beam width effects may be difficult to separate from spectral index effects. We provide MeqTrees with initial guesses to the source and instrumental parameters - flat spectral indices, source flux densities off by 20% from their actual values, and a HPBW off by 20%. Then we let MeqTrees do a least-squares fit of this model to the simulated observations, varying the source and beam parameters until the best fit is achieved.

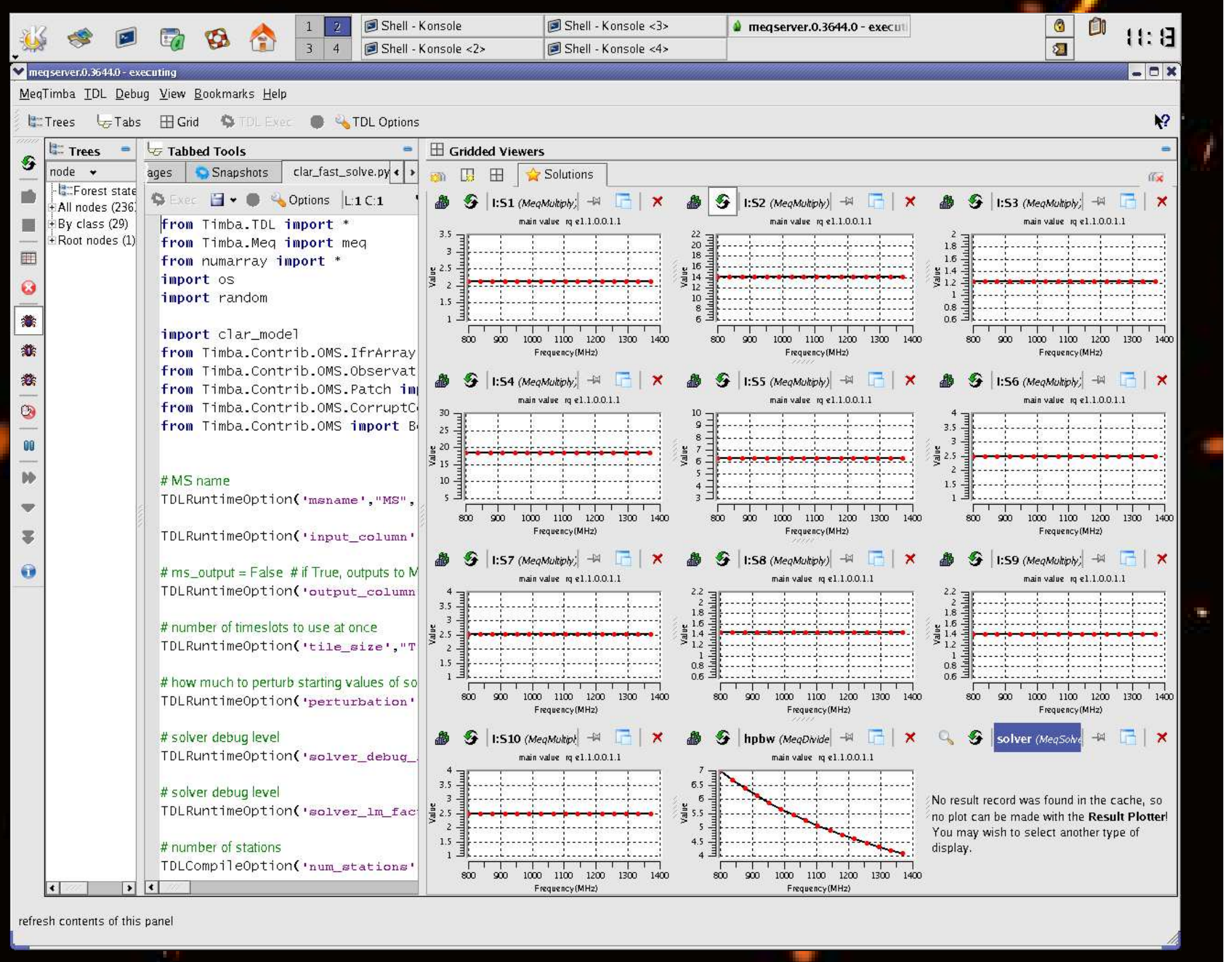

Fig. 5: This screen shot shows the initial guesses of source parameters that are provided to MeqTrees - constant flux densities as a function of frequency and a HPBW that is 20% too high.

In the present case, after about four iterations, we end up with the final solution parameters shown in Fig. 5. These values are very close to what we specified in the original simulated observations.

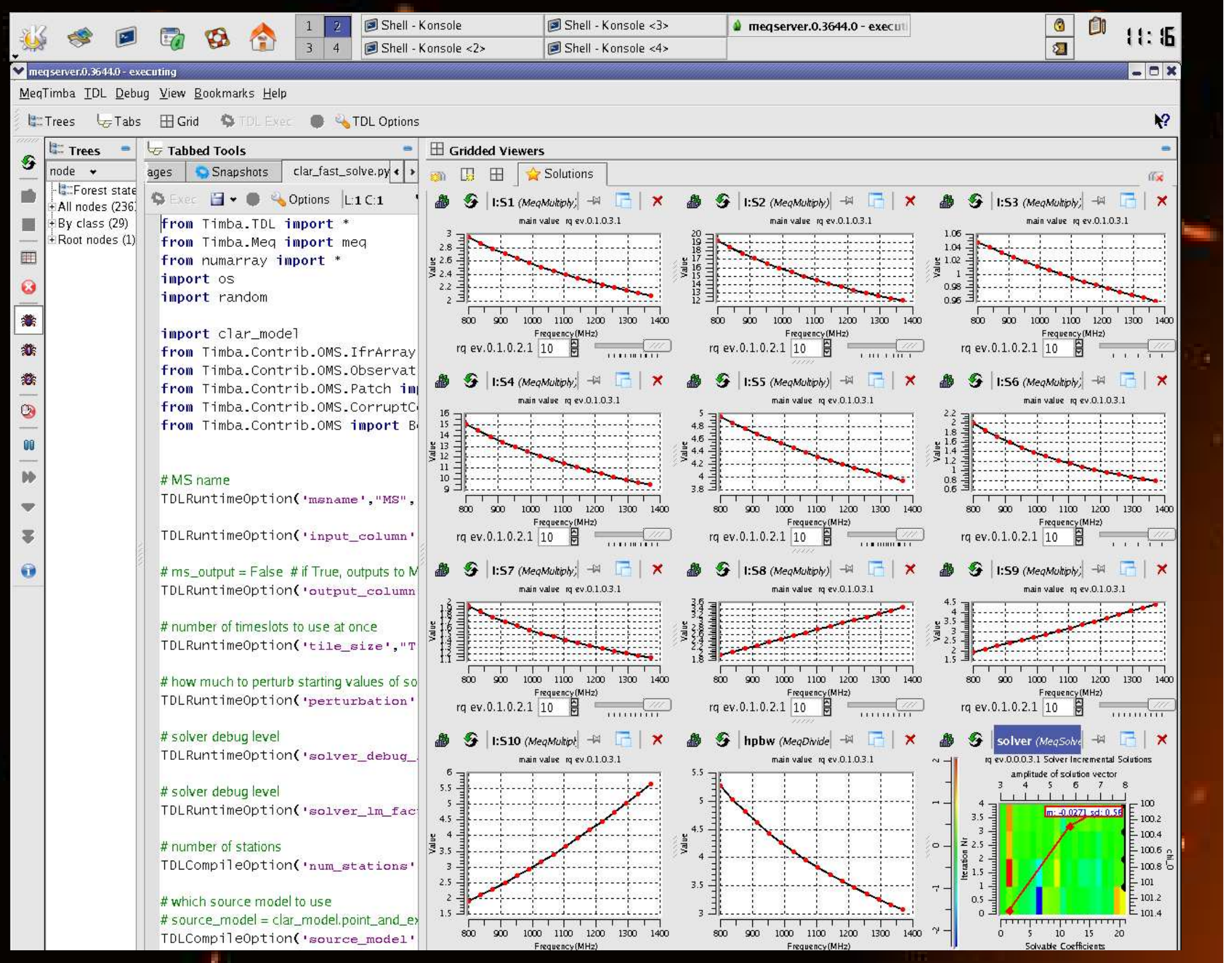

Fig. 5: A screen shot showing the final fitted flux densities, spectral indices and HPBWs as a function of frequency.

Summary

The MeqTrees package has proved to be a powerful tool to simulate observations made with a SKA composed of CLARs. We also emphasize that other SKA telescope designs whose instrumental behaviour can be described in terms of the Measurement Equation are equally amenable to analysis with the MeqTrees package.

References

- Noordam,J, 1996, http://aips2.nrao.edu/stable/docs/notes/185/185.html