UV-plane coverage analysis for the BEST project (SKA-DS)

INAF-IRA Technical Report #417/08

E. Carretti[1], D. Dallacasa[1,2]

[1]INAF–IRA, Via Gobetti 101, I-40129 Bologna, Italy
[2]Universitá di Bologna, Astronomy Dep., Via Ranzani 1, I-40126 Bologna, Italy

1 Introduction

The Northern Cross radiotelescope in Medicina is being used by the Basic Element for SKA Training project (BEST, Montebugnoli et al. 2006) as test bed for technological developments aimed at the Square Kilometer Array (SKA),within the SKA-Design Studies (SKA-DS) programme.

In the framework of these activities, 6 of the 24 East-West arm sections of the original telescope will be refurbished, along with 14 of the 64 North-South cylinders. The upgraded sections will be operated as an interferometer and used to test real-time beam forming procedures and software as well as interference mitigation.

Since only part of the original telescope can be upgraded, it is mandatory to find out the best set of EW sections and NS cylinders which optimize the interferometer beam response.

Some limitations arising from the previous stages of the project (BEST-1 and BEST-2) substantially constrain the choice of the position of the elements to be upgraded (see Sect. 2).

The selection has been carried out first by a 1-D analysis for each arm (Sect. 3). Subsequently, the 2-D response of the full interferometer is computed and analyzed (Sect. 4). We present conclusions and recommendations for sections and cylinders to be refurbished in Sect. 5.

2 Northern Cross geometry and previous stage constraints

The Northern Cross is a transit telescope which operates at a frequency of 408 MHz and consists of two orthogonal arms (Fig. 1). The East-West arm (EW) is one parabolic cylinder of 35-m aperture which is divided into 24 sections, 24-m long each, for a total width of 564-m. Sections are numbered from 1 throughout 24, #1 being the westernmost and closest to the NS arm.

The North-South arm consists of 64 separated parabolic cylinders, 23.5-m wide and with 7.5-m aperture each. The cylinders are 10-m spaced for a total arm length of 640-m. Cylinders are numbered from 1 throughout 64, #1 being the northernmost.

The present activity is the third stage of the BEST project. The first one (BEST-1) consisted in the refurbishment of one NS cylinder (#21). The second stage (BEST-2) upgraded 8 cylinders (#25 throughout #32).

The third phase (BEST-2+) will be carried out in 2008 and will refurbish 5 more cylinders and 6 EW sections. This will lead BEST/Northern–Cross to a final configuration with 14 NS cylinders and 6 EW sections upgraded with new receivers sporting real-time digital correlation and beam forming.

While there are no constraints in locating the 6 EW sections to be refurbished aiming to optimize the beam response, only 5 of the NS cylinders can be freely chosen, the first 9 being locked to the position selected for BEST-1 and BEST-2 aims.

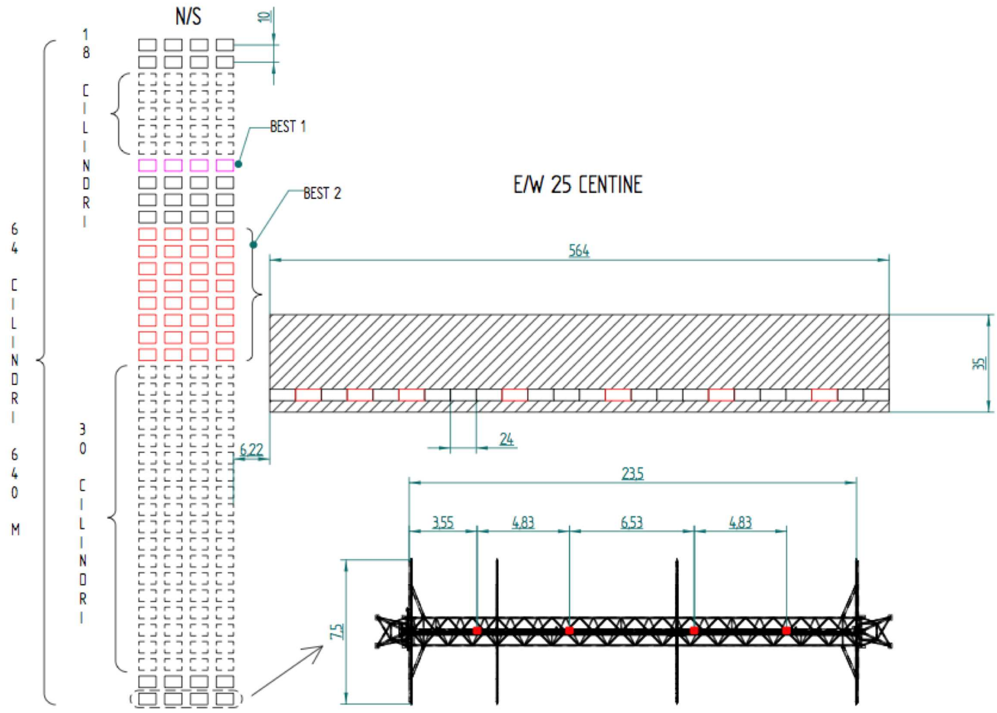

Figure 1: NS Cylinders and EW arm of the Northern Cross radiotelescope. The cylinders used for BEST-1 and BEST-2 phases are also reported.

At the moment, the possibility to connect the N-S cylinders in pairs to be operated as single interferometer elements is under consideration. Even though this option can lead to NS elements (each cylinder pair) with collecting area and shape similar to the EW sections, it would leave virtually no degree of freedom to optimize the NS arm response. In fact, the 8 BEST-2 antennas are already arranged as 4 close cylinder pairs, one of the new cylinders would be paired to BEST-1, the remaining four would be arranged in two pairs to be located at the two arm ends, in order to realize the maximum possible angular resolution along the NS direction.

The analysis provided by this document discourage such option, in a view to consider the upgraded/refurbished Northern Cross as an effective standalone astronomical instrument, of interest for some science observing programs.

3 1-D analysis

Each section of the EW and NS arms has been considered as an independent element of an interferometer. The minimum spacing between the elements of the interferometers is 24 m for the EW arm (corresponding to the size of each section) and 10m for the NS arm.

The work consists in the evaluation of the best combination of elements to be "switched on" among the 24 + 64 sections in the EW + NS arms. In first instance, we have computed the 1D beam response (e.g. see Kraus 1986) of the 6 EW antennas for several configurations, i.e. combination ef elements, and then the same from 14 antennas from the NS arm.

First of all, a few statements on the criteria driving the choice of the "best" configuration must be given. Each interferometer **samples** the Visibility function V(u,v) which is a continuous function as well as the Fourier Transform of the sky brightness distribution $B(\theta, \phi)$. The latter is a real funcion and the former is complex instead, but also hermitian, and therefore V(u,v) = -V*(-u,-v). The sampling occurs at a given spatial frequency (u,v) which is the baseline vector whose lenght is expressed in terms of wavelength units. To obtain the measurement of the sky properties, the interferometric signal must undergo to a Fourier inversion. Such operation is better achieved as long as the uv-plane (i.e. orientation and distribution of baselinelengths) has a uniform sampling. In terms of sidelobes, this translated into PSF with the lowest achievable sidelobe level.

A uniformly sampled uv plane, therefore concentrate most of the energy in the main lobe of the beam. In terms of a response to a point source, this means that most of the flux density is recovered at the location of the source in the sky, with a relatively clean background.

It is also clear that resolution is a very important issue, particularly at low frequencies where radio observations may be limited by confusion noise. The best resolution is achieved by using the outermost elements, with little minor adjustements.

With these basic concepts in mind, a number of combinations of elements have been explored and compared.

Among all these, we find that the best configuration of elements from the EW arm is given by (Table 1, field EW)

– EW: 01, 02, 04, 08, 13, 23

whose beam response is shown in Fig. 2.

The beam response is a periodic function because all the antenna spacings are integer multiples of a basic separation. The grating lobes are clearly evident in the Figure.

It is worth to remark that the beam response is very good with low secondary lobes (15–20% of the main lobe), and with no outliers: it would be hard to obtain a better response with these constraints (six sections located on a regular grid).

Pretty different is the NS case, where the fixed positions of the BEST-1/2 cylinders limit the degrees of freedom.

The BEST-2 cylinders are next each other, which is not optimal for the UV-plane sampling with many baselines repeated. The remaining 5 cylinders have then to be spread along the NS arm in appropriate positions to fill as much as possible the frequency space.

We find that the best beam response is given by the configuration (Table 1, field NS):

– NS: 01, 04, 21, 25, 26, 27, 28, 29, 30, 31, 32, 45, 57, 64

and is shown in Fig. 3 (left panel).

The first secondary lobe is about 35% of the main lobe (about -5dB). The other lobes are quite good, with a good uniformity and low levels (<10% of the main peak). We have analyzed a number of configurations trying to decrease the secondary lobes as much as possible. The one described above resulted to be the best.

The paired cylinder configuration does not allow us optimizations and we can only compute the beam response to be compared with that previously discussed. The response is plotted in Fig. 3 (right panel) and it is clear that this case is significantly worse. The main secondary lobes are ∼60% of the maximum (∼ -2 dB), while the other sidelobes have a bad non-uniform behaviour, with high peaks (larger than 15 %, almost a fold 2 larger than the other configuration). Moreover, the period of the grating lobe pattern is about a half of that, which reduces the useful field-of-view of the same factor.

4 2-D beam response

The positions of the 6 EW sections and 9+5 NS cylinders found in Sect. 3 are shown in Fig. 4 (left panel). Figure 4 (right panel) shows the uv-coverage using all the EW and NS antennas. This is valid for an instantaneous observation toward the Zenith. Projections ($\cos(\theta)$, where θ is the zenit angle)

Table 1: EW sections and NS cylinders of the configurations giving the best beam response for the two arms. The new systems to be refurbished are boldface, while the already installed ones in BEST-1/BEST-2 stages are normal.

ARM	#section/cylinder
EW	**01**, **02**, **04**, **08**, **13**, **23**
NS	**01**, **04**, 21, 25, 26, 27, 28, 29, 30, 31, 32, **45**, **57**, **64**

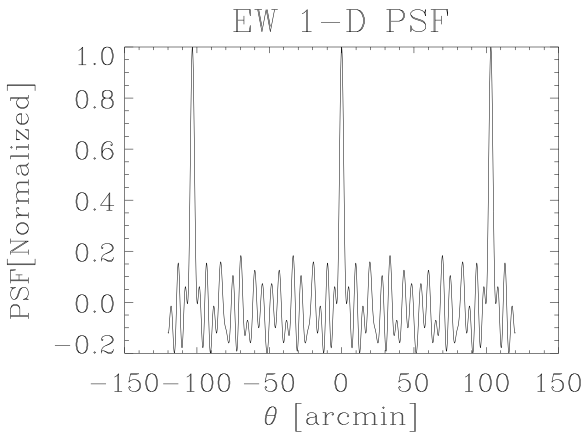

Figure 2: 1-D PSF of the EW arm of the best configuration (see text)

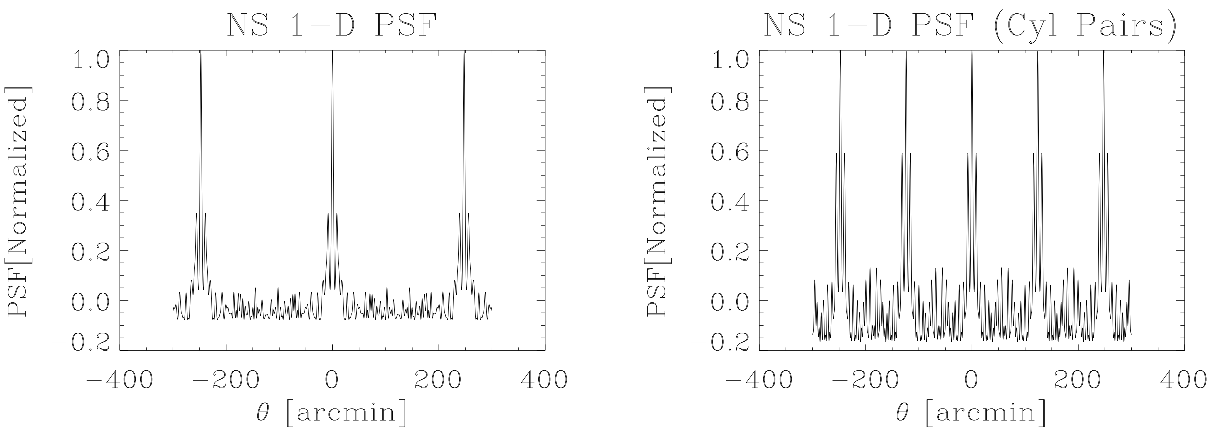

Figure 3: **Left:** 1-D PSF of the NS arm of the best configuration: this has been found out by assuming to be free to chose any of the available cylinders for the 5 new antennas to be added to BEST-1 and BEST-2 (see text). **Right:** as for the Left panel, except assuming the NS cylinder to be paired 2-by-2. This does not leave almost any freedom to locate the new 5 cylinders: one has to be paired to BEST-1, and the other four are to realize two pairs, one at each end of the NS arm (see text).

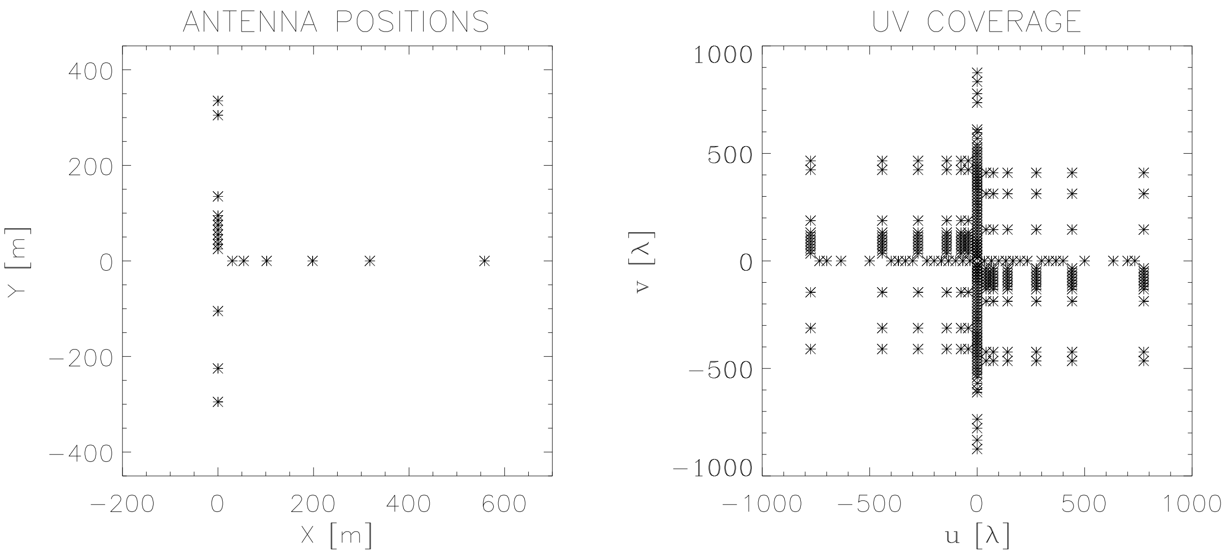

Figure 4: Antenna positions (left) and uv-plane coverage (right) of the configuration which optimizes the Northern Cross beam response. The uv-plane coverage is given in case of instantaneous observation of a source at transit (Hour Angle = 0) and at the Zenith (unit is wavelength: $\lambda = 0.735$ m)

apply in NS direction in case of other elevations. As expected, the sampling is very good along the axes (u, v), while the rest of the plane features a poorer coverage.

That is reflected in the 2-D beam response shown in Fig. 5, where three Declination cases are reported. A 30-m long observation (± 15 min from transit) is assumed here, to exploit the whole source transit through the field of view of the instrument. In addition, each baseline has been weighted with the effective area of the two section/cylinder realizing it, which accounts for the right contribution to the total sensitivity.

The beam shape is good, with the 3-dB main beam well confined within the ∼4-arcmin resolution allowed by the maximum baseline. However, many secondary lobes are present especially along the two axes.

The response get substantially worse if the cylinder pairs case is considered. Figure 6 shows the antenna positions (each NS pair is considered as one antenna), the uv-plane coverage and the beam response. The beam response shows two high secondary lobes well above the -3dB level along the NS axis. Furthermore the main beam is elongated toward these two lobes. All of that jeopardizes the instrument beam and the good performance of the EW axis.

We mentioned above the poor off-axis uv-plane coverage. Only observations for a wide range of Hour Angle (ideally, 12-h centred on the meridian transit) would allow a better sampling thanks to the baselines rotation due to the Earth revolution. This would be possible with the Northern Cross only if two conditions would be respected: 1) wider field of view; 2) tracking of the source in elevation. The first condition would be possible if one receiver per dipole is installed, instead of the present design which collects the signal of several dipoles in just one receiver (this is because of funds constraints). In such a case, the field of view would be $\pm 60°$ along the EW direction. The second condition can be matched if the elevation motors can smoothly move following the source in its elevation path.

At present, both these two conditions are unmatched. However, just for exercise, we have computed the beam response in case a source is observed for 12-h. The result is shown in Fig. 7, where three Dec cases are reported. The normalized beam response is very good, comparable to those of modern interferometers, despite the limited resolution. Even the Dec=0° case, which is usually problematic for any aperture synthesis interferometer (baselines draw lines instead of arches in the uv-plane), features a good response thanks to the NS antennas which enable a decent sampling.

For comparison, Fig. 8 reports the cylinder pair configuration case.

In any case the limiting factor of the instrument is the confusion noise, which is the dominant factor even for short observations.

5 Conclusions

We have analyzed the beam response of several configurations of the 6 EW sections to be refurbished as well as of the 14 NS cylinders. Main conclusions of the analysis are

1. The set of 6 EW sections can give a very good beam response with low and uniform secondary lobes, provided that they are located in the positions reported in Table 1 (field EW).

2. Even though not optimal because of previous stage constrains, the set of 14 NS cylinder can give a good beam response, provided that the 5 cylinders yet to refurbish are kept independent and single cylinders are the basic interferometer elements. The cylinder positions which make best the NS beam response are reported in Table 1 (field NS).

3. The option coupling the cylinders so that the basic interferometer element is a cylinder pair leads to no degree of freedom in positioning the NS elements. In turn, this leads to a bad beam response, with secondary lobes just 2-dB below the main beam. This makes the cylinder pairs not a real option, at least from the point of view of the beam response.

4. In case the system would be able to follow a source for 12-h centred at the meridan transit, the beam response would greatly improve, with strong mitigation of the secondary lobes. This can be enabled by feeding each dipoles of the Northern Cross with independent receivers., which is not possible at present, however, being a major upgrade of the present design requiring a substantial re-funding.

As a results, our recommendations are:

1. To use the option of single cylinders, with the 14 cylinders independent and the 5 new cylinders to be positioned accordingly to Table 1.

2. If others funds would be made available in future, we recommend to increase the number of receivers per cylinder/section (hence the number of independent dipoles per cylinder/section), instead of the number of refurbished cylinders/sections. The beam response is much more improved by following the source for several hours, rather than to add a few points in the instantaneous uv-plane.

3. In case funds become available, also an increase of the resolution should be considered in order to escape the confusion limit which is rapidly reached and makes tracking of sources useless. At least an additional element (better two), even with small collection area, should be placed along the direction of the EW (and NS) arm(s), at a distance sligty larger than the actual Northern Cross. This would increase by a factor of 2.5-3 the resolution in each direction and reduce the confusion noise by a factor of 6-10, making tracking observations ($\sim 1 - 2hr$) not limited by confusion noise.

References

[1] Kraus, J.D., 1986. Radio Astronomy (Ed. CygnusQuasar Books: Powell, OH)

[2] Montebugnoli S., Bianchi G., Perini F., Bortolotti C., Cattani A., Maccaferri A., Cremonini A., Roma M., Roda J., Zacchiroli G., 2006, Astron. Nachr. 327, 624

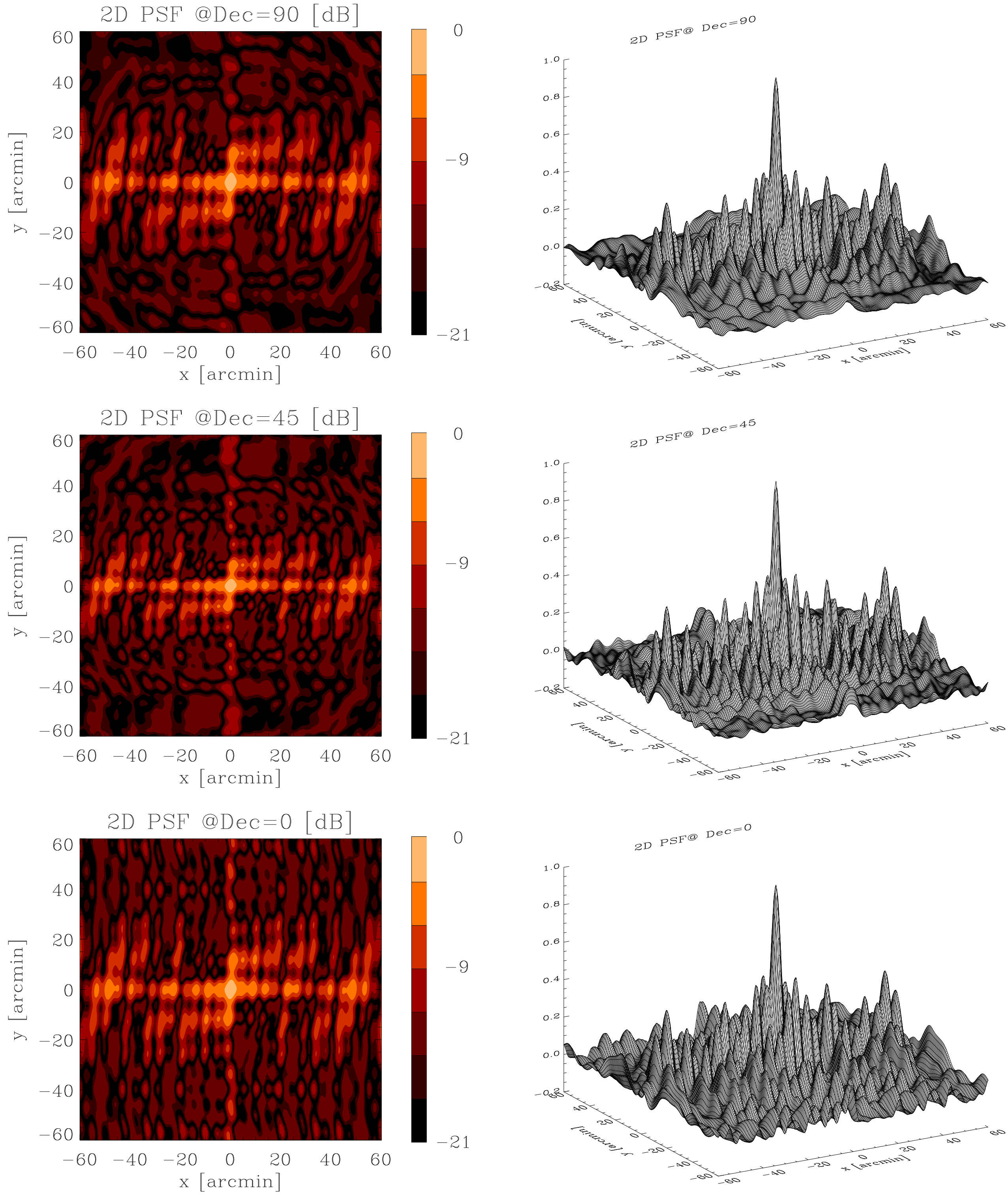

Figure 5: **Left:** Normalized 2-D beam response (PSF) of the 5-free antennas case. All 14 NS and 6 EW antennas has been assumed. The case of a source at Dec $= 90°$, $= 45°$, $= 0°$ is reported in the top, mid, and bottom panel, respectively. A 30-min observation centred at the transit has been considered, which is minimally different from the results of an instantaneous one. Units are dB normalized to the maximum, with contour lines 3-dB spaced. The most central contour is the -3-dB beam. **Right:** Surface plot of the same PSFs. A linear scale is used here.

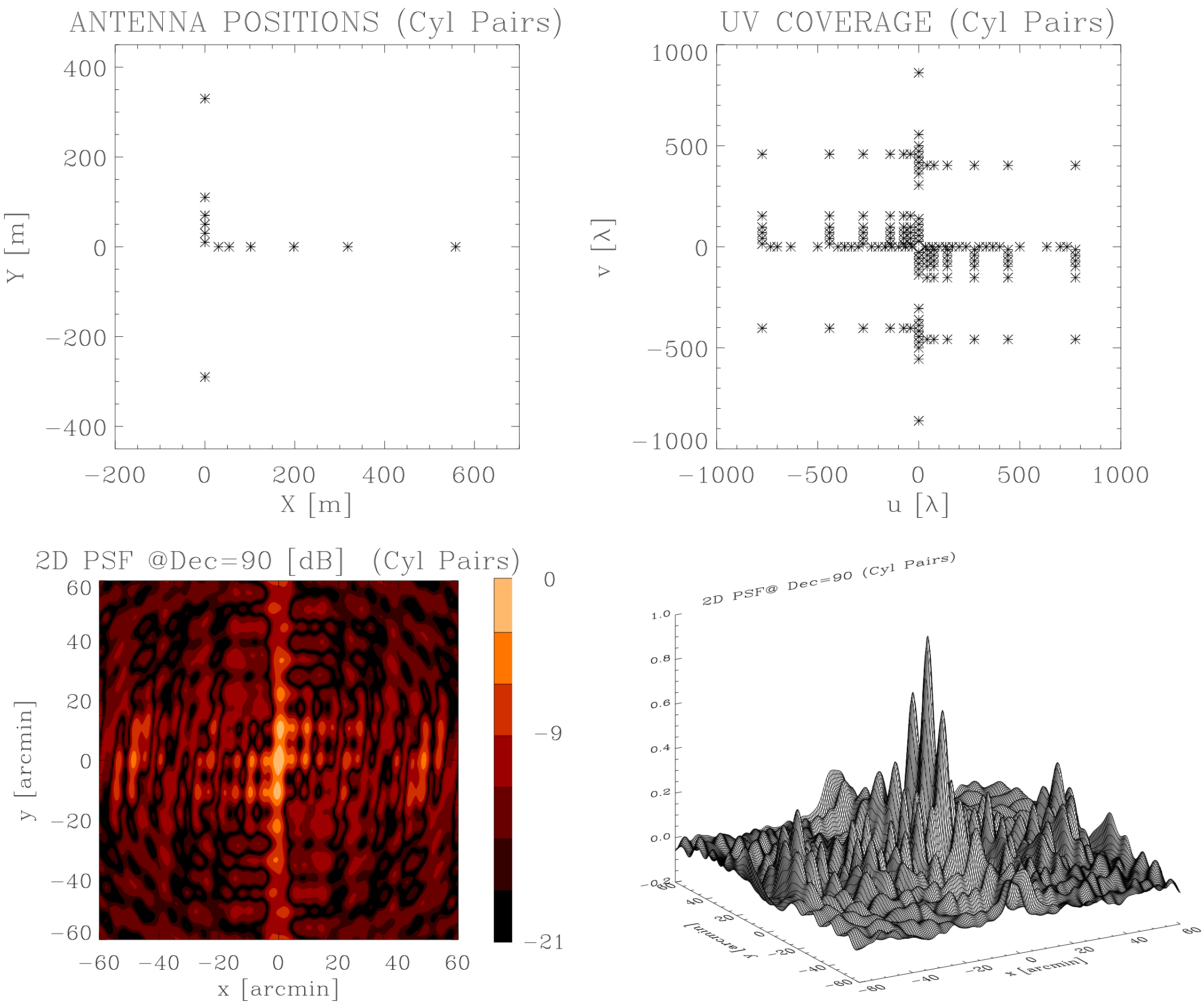

Figure 6: **Top:** Antenna positions (right) and uv-plane coverage (right) for the cylinder pairs case (other details are as for Fig. 4). **Bottom:** As for Fig. 5 except that it is for the cylinder pairs configuration and for the Dec=90° only. The main secondary lobes of the NS direction are high, being at about -2dB.

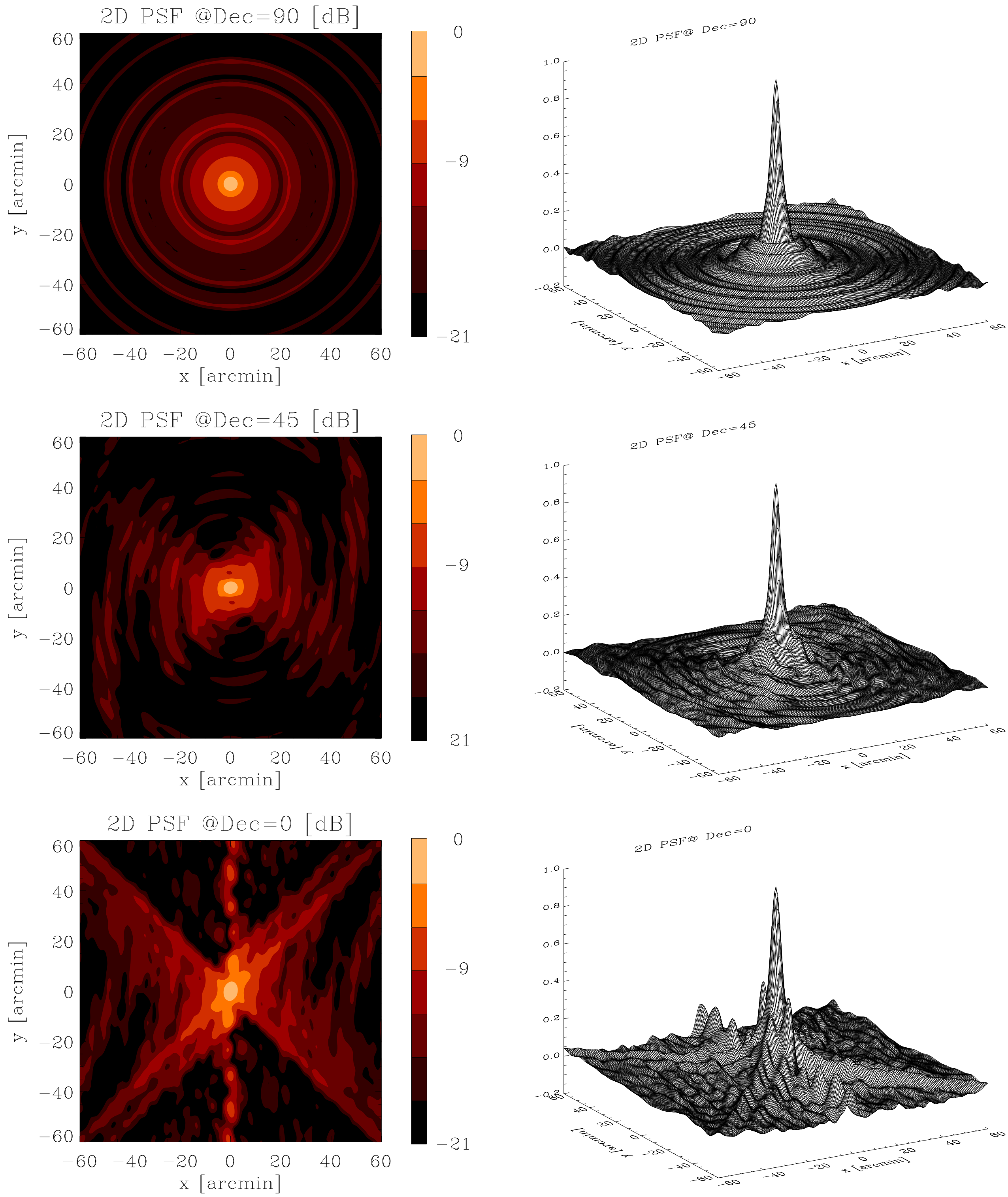

Figure 7: As for Fig. 5, except an observations of 12-h centred at the source transit is considered.

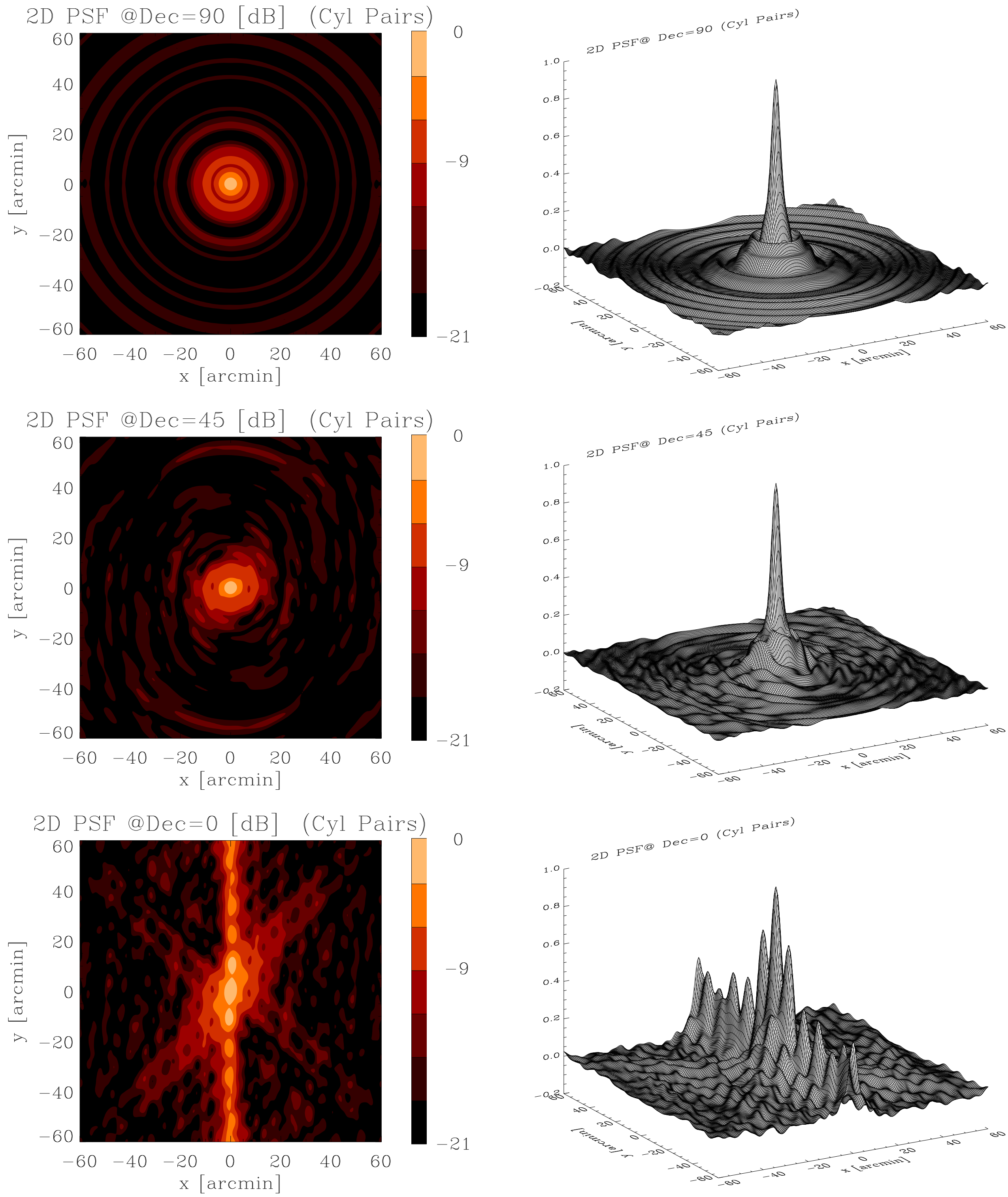

Figure 8: As for Fig. 7, except the cylinder pairs case is considered here.