Lunar University Network for Astrophysics Research

MEMO SERIES

MEMO A-1

Optimization of the DALI array configuration minimizing sidelobes

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ABSTRACT

The goal of this report is to explore array design options for the Dark Ages Lunar Interferometer (DALI), which includes assesing the number and the location of stations, as well as the number of dipoles per station. We apply the algorithm of optimization of an array configuration minimizing side lobes designed by Leonid Kogan. We consider several possibilities for the station configuration of this telescope by varying the number of elements on each station, the minimum separation between the elements, and the diameter of the station.

We arrived at a viable option for the array design consisting of 919 dipole antennas, inside a circle of 120 m diameter and having a minimum spacing between the dipoles of 3 m. The array consists of 469 of such stations, inside a circle of 10 km diameter, with minimum spacing between stations of 125 m. The total collecting area for this array is 3 km^2 at 90 MHz at the zenith.

1. Introduction

The Dark Ages Lunar Interferometer (DALI) is a telescope designed to study highly-redshifted neutral hydrogen (HI) signals from the Universe's *Dark Ages*, namely, the epoch between recombination and the formation of the first luminous objects. The array is assumed to be placed on the far side of the moon, and to have no radio interference (of either solar or human origin) by observing during the long lunar night. The array is assumed to be observing at zenith so that no dimunition of the collecting area occurs by projection. The array is assumed to consist of N roughly circular stations of diameter, D, distributed over a flat surface. The stations are comprised of M dipoles which can be used to form B beams on the sky. These beams are transmitted to a central location, or to the Earth, for correlation. The final product of the array is visibility measurements which can be transformed to create images or analyzed directly. The deployment of the array is assumed to be carried out by one or more rovers.

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The array will observe at 1.5-10 m wavelengths (30-200 MHz; redshifts $6 \leq z \leq 50$) in two polarizations using crossed dipoles. The dipoles will be grouped into stations. For more details on the requirements see Carilli & Taylor (2009).

Our goal is to explore array design options for this telescope, which includes assesing the number and the location of stations, as well as the number of dipoles per station. We use the algorithm of optimization of an array configuration minimizing side lobes designed by Leonid Kogan (Kogan 2000). The algorithm minimizes the biggest side lobe in a given area of optimization on the sky. The algorithm is coded into AIPS task CONFI and the most important input parameters are the number of antennas on the array, the area of optimization on the sky, the maximum size of the array, and the minimum spacing between the antennas.

2. Collecting Area

The sensitivity of an interferometer is generally determined by the system temperature of its component receivers, and its total collecting area. The sky at the low frequencies considered is bright. Even far from the galactic plane, in the coldest regions the sky is 3500 K at 45 MHz (Alvarez et al. 1997). This emission has a steep spectrum and in general we can characterize the system temperature as:

$$T_{sys} = 2000\left(\frac{\nu}{74MHz}\right)^{-2.6}\mathrm{K}$$

For this reason, there is little benefit to building low temperature receivers, and the only way in which we can improve the sensitivity is to increase the collecting area. The collecting area is just set by NMA_e where N is the number of stations, each of which has M dipoles each with an effective collecting area A_e. The collecting area for a Hertz dipole is:

$$A_e = \left(\frac{3}{8\pi}\right)\lambda^2$$

The modified dipole of the DALI station is assumed to have a collecting area of 7 m^2, based on analogy with that achieved for the Long Wavelength Array. Details of the dipole design will be presented elsewhere.

At 90 MHz, we estimate T_{sys} to be 1200 K, the total collecting area of a station to be 3200 m^2, for an SEFD of 1030 Jy in each polarization. The total collecting area (both polarizations) is 3 km^2, and the sensitivity of the array over an 8 MHz bandwidth is 0.3 mJy/beam in 1 second, and 0.076 microJy/beam in one year (observing during the lunar night only). This corresponds to a brightness temperature sensitivity of 0.4 microKelvin in one year (lunar night only). This meets the 0.2 microJy/beam in 1000 hours sensitivity requirement specified by Carili & Taylor (2009).

3. Station configuration

We started the optimization with an initial configuration of a hexagon. We set the size of the antenna station as a circle with diameter 50 m. We carried out the minimization at the highest DALI frequency of 100 MHz ($\lambda = 3$ m), considering that the effective circle of optimization on the sky will be even larger at longer wavelengths. We chose a radius of optimization on the sky of 30°, and we consider a station phased to zenith. We performed the optimization for different values of the number of antennas as well as for the minimum spacing between them. In Table 1 we list the maximum side lobe level in the optimization region reached for each case considered.

There are two important factors to consider when designing the station configuration: having as many antennas as possible and achieving the minimum side lobe levels. For this reason, among the cases that we studied, we considered the case of 169 antennas with minimum separation of 3 m as the more desirable scenario for a 50 m diameter station. Figure 1 shows the initial station configuration for this case and Figure 2 shows the station configuration after optimization. Figure 3 shows the two dimensional beam pattern obtained and Figure 4 shows a one dimensional slice of the beam pattern.

While a 50 m diameter station provides the desired wide field of view (11 square degrees at 90 MHz), to achieve the desired sensitivity (collecting area) requires 2550 stations. We therefore considered next a larger station diameter.

We explored designing a station consisting of 919 antennas[1], with a minimum separation between them of 3 m inside a circle 120 m diameter. This case is equivalent to the case of 169 antennas inside a 50 m diameter circle up to a scaling factor. Table 2 lists the maximum side lobe level in the optimization region reached for this case. Figure 5 shows the initial station configuration for this case and Figure 6 shows the station configuration after optimization. Figure 7 shows the two dimensional beam pattern obtained and Figure 8 shows a one dimensional slice of the beam pattern.

4. Array configuration

The next step in our exploration of array design options was to pick a station configuration, among the many options considered. We decided on the station consisting of 919 antennas inside a circle 120 m diameter with a minimum separation between the elements of 3 m.

We performed the optimization of 469 of such stations, which comprises the entire array, inside a circle of diameter 10 km, and minimum spacing between the stations of 125 m. A radius of optimization on the sky of ~ 1 ° was used, corresponding to the field of view of a 120 m diameter station. The total number of stations was decided based on the total collecting area requirements of

[1]919 was the maximum number of antennas we considered because of software limitations

3 km^2. Similarly to the optimization of each station, we started with an initial array configuration of a hexagon. Table 3 lists the maximum side lobe level reached in the optimization region. Figure 9 shows the initial array configuration and Figure 10 shows the array configuration after optimization. Figure 11 shows the two dimensional beam pattern obtained and Figure 12 shows a one dimensional slice of the beam pattern.

5. Summary and Future Plans

We have demonstrated that an array with the desired sensitivity can be designed using 469 stations of 919 dipoles each. This can be accomplished by deploying 431,000 dipoles which requires that each dipole be extremely lightweight. Alternatively, if the effective area for each dipole can be increased then the total number of dipoles could be reduced.

Future studies should be carried out to examine the trade-offs between number of stations and number of dipoles in each station. This may require some modification of the software that has been used as we are currently up against a limit of less than 920 dipoles/station. This trade is linked to the desired field of view, to the number of beams that can be formed simultaneously for each station, and to the computation and communication needs of the array.

Another area of study for the future is to include realistic toplogical constraints for a specific site. We also plan to analyze how the beamshape and sensitivity degrades as stations are removed. Furthermore, it is desirable to simulate the response of the array to a realistic sky, using the dipole power patterns rather than the approximations used in this memo.

We thank Leonia Kogan for instructions on how to use his CONFI task for the configuration simulations.

REFERENCES

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Carilli, C. & Taylor, G.B., Specifications for a Lunar radio telescope to study cosmic reionization and the Dark Ages, 2009, memo

Kogan, L. Optimizing a Large Array Configuration to Minimize the Side lobes, IEEE Transactions on Antennas and Propagation, vol 48, NO 7, July 2000, p 1075

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Table 1. Results of configuration optimization for stations 50 m diameter.

Number of antennas	Minimum spacing between antennas (m)	Maximum side lobe level (%)
91	3	0.58
91	4	0.48
91	5	2.28
127	3	0.28
127	4	0.52
169	3	0.13
217	3	0.46

Table 2. Results of configuration optimization for a station 120 m diameter.

Number of antennas	Minimum spacing between antennas (m)	Maximum side lobe level (%)
919	3	0.15

Table 3. Results of the array optimization. Total size of the array 10 km.* .

Number of stations	Minimum spacing between stations (m)	Maximum side lobe level (%)
469	125	0.68

*Each station consists of 919 antennas, inside a circle 120 m diameter, with a minimum spacing of 3 m.

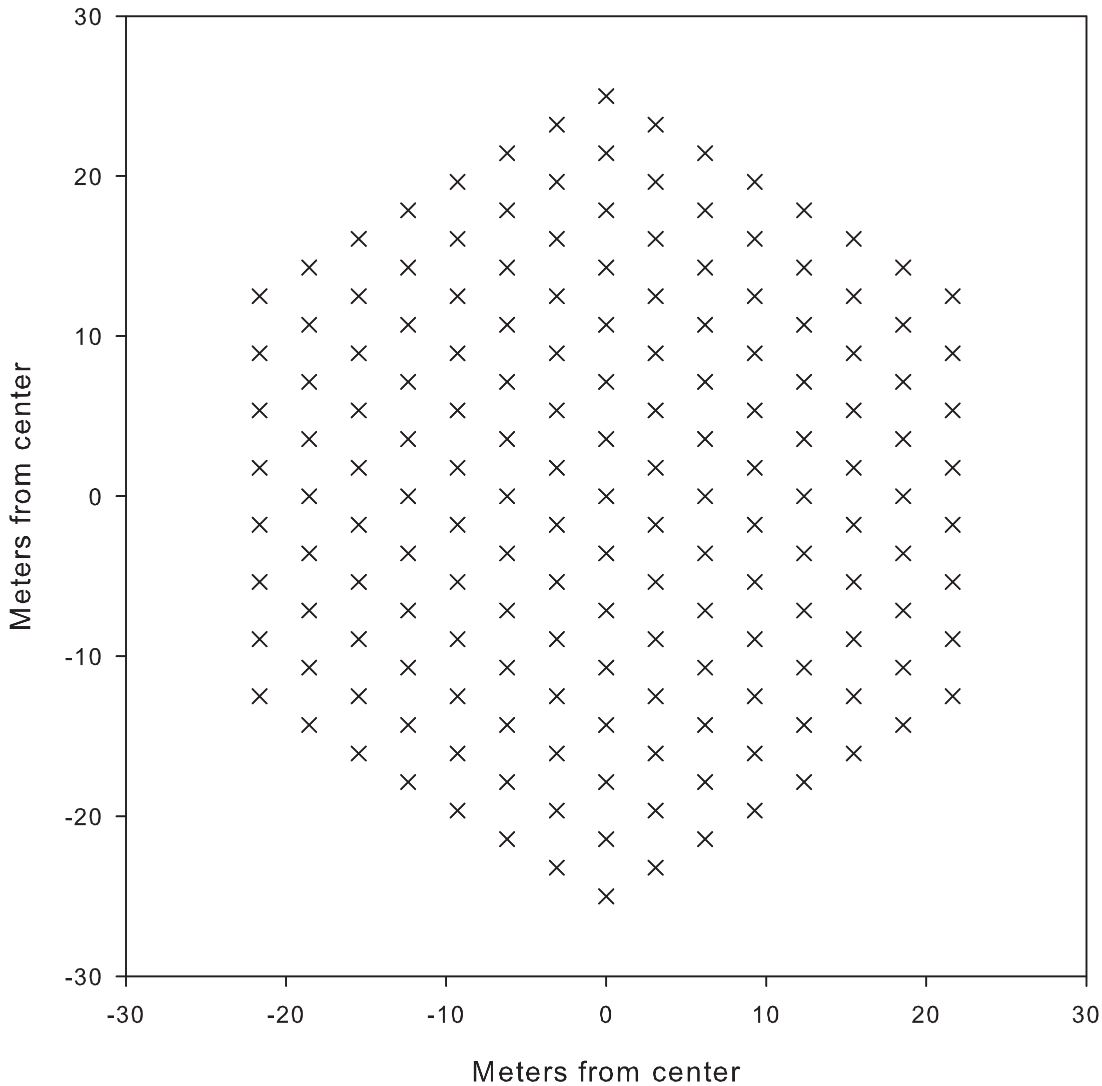

Fig. 1.— Hexagonal station configuration used as a starting point for the optimization of 169 antennas inside a circle of diameter 50 m. A minimum spacing of 3 m between the elements was used.

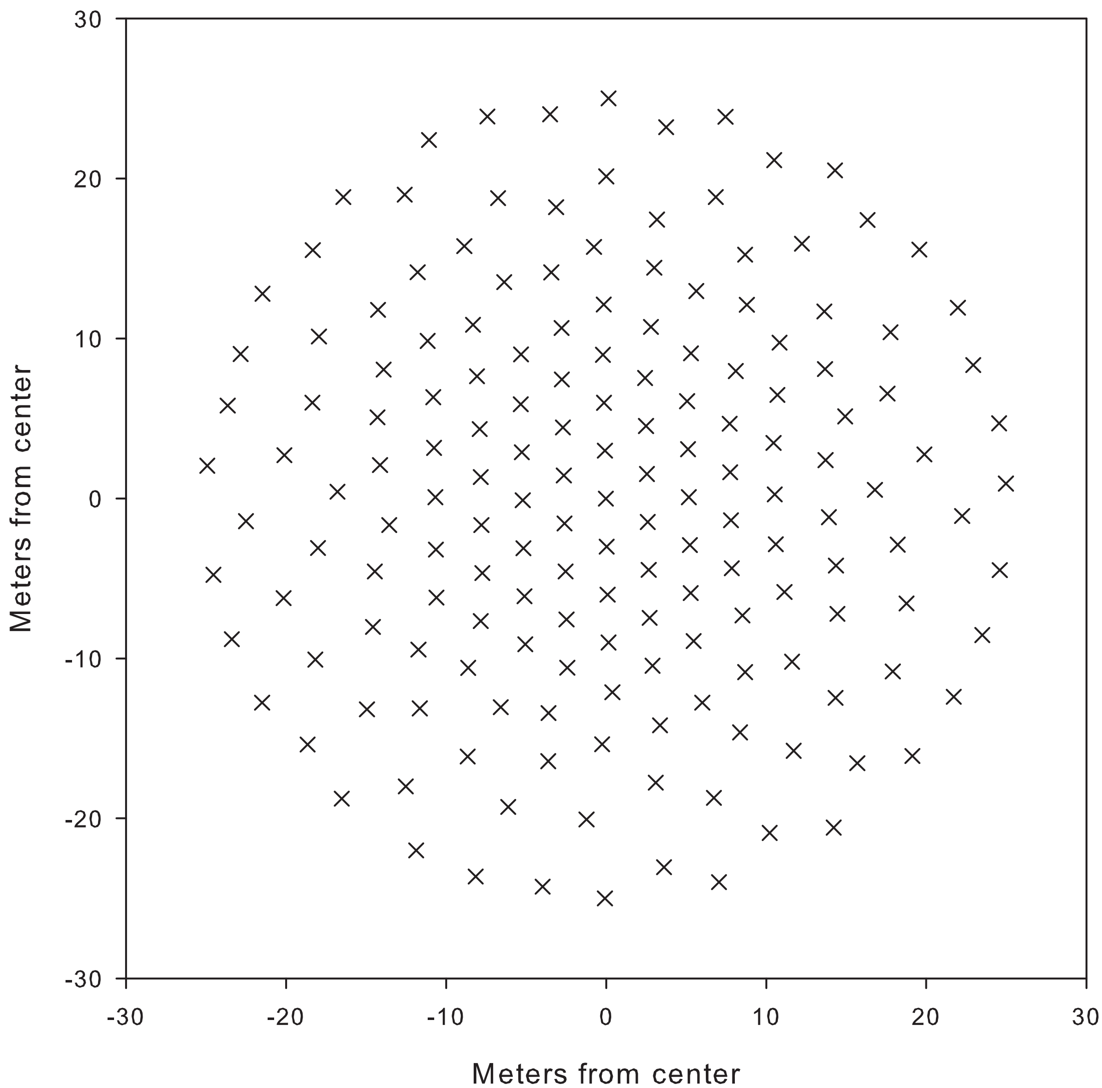

Fig. 2.— Configuration after optimization of a station consisting of 169 antennas located inside a circle 50 m diameter with minimum spacing of 3 m.

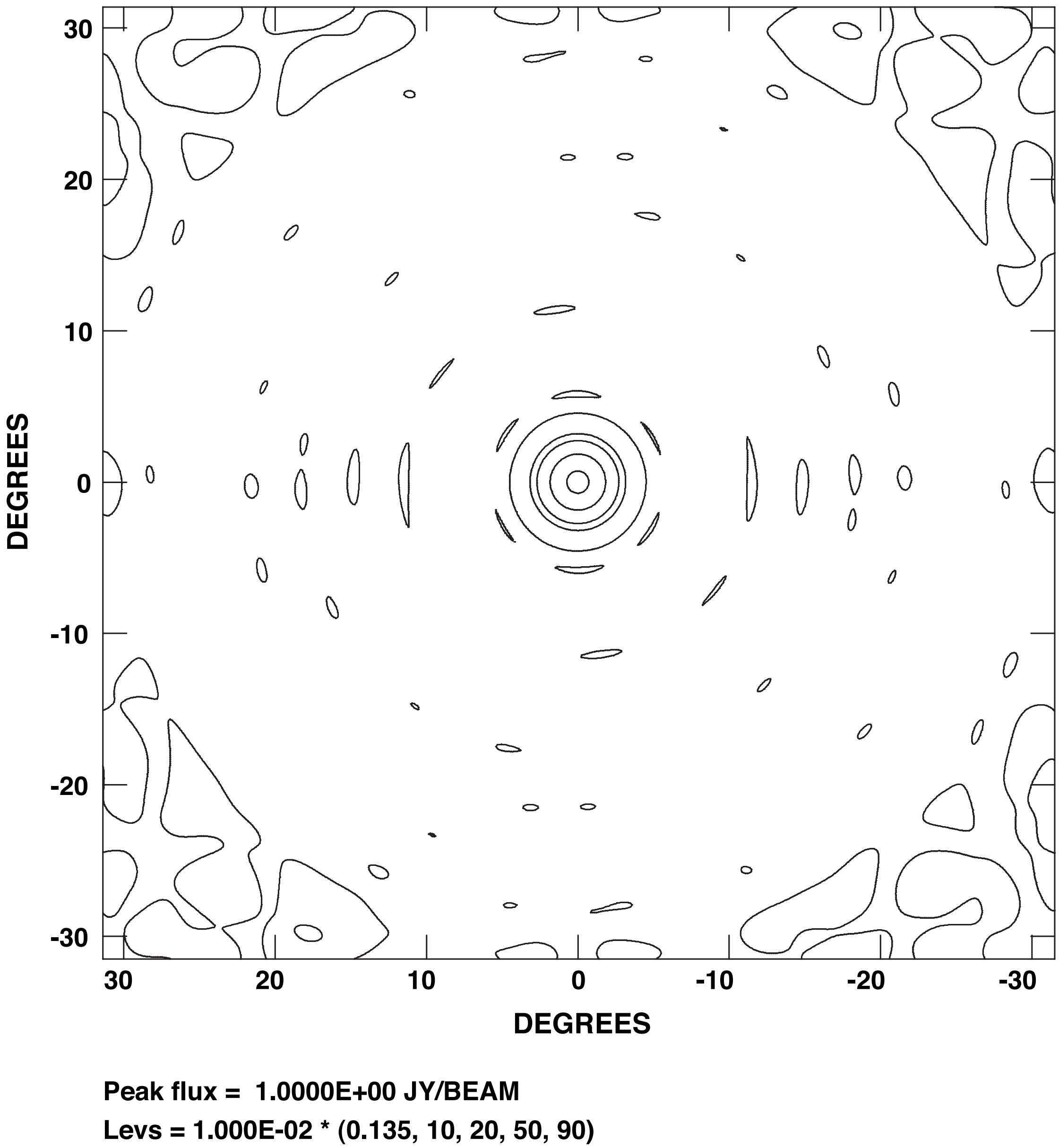

Fig. 3.— Two dimensional beam pattern created as a result of the optimization of a station consisting of 169 antennas located inside a circle 50 m diameter with minimum spacing of 3 m.

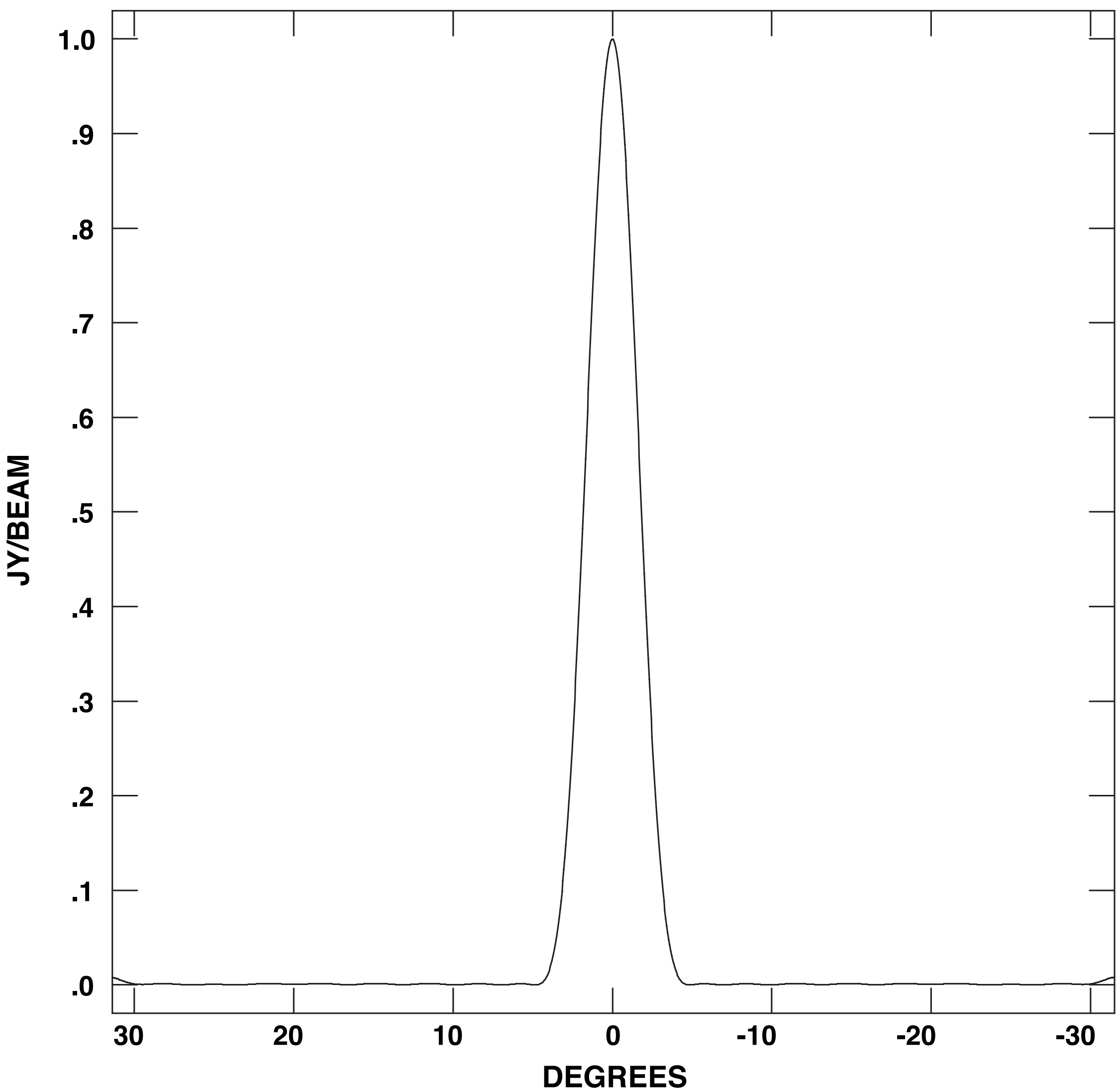

Fig. 4.— One dimensional slice of the beam pattern shown in Figure 3.

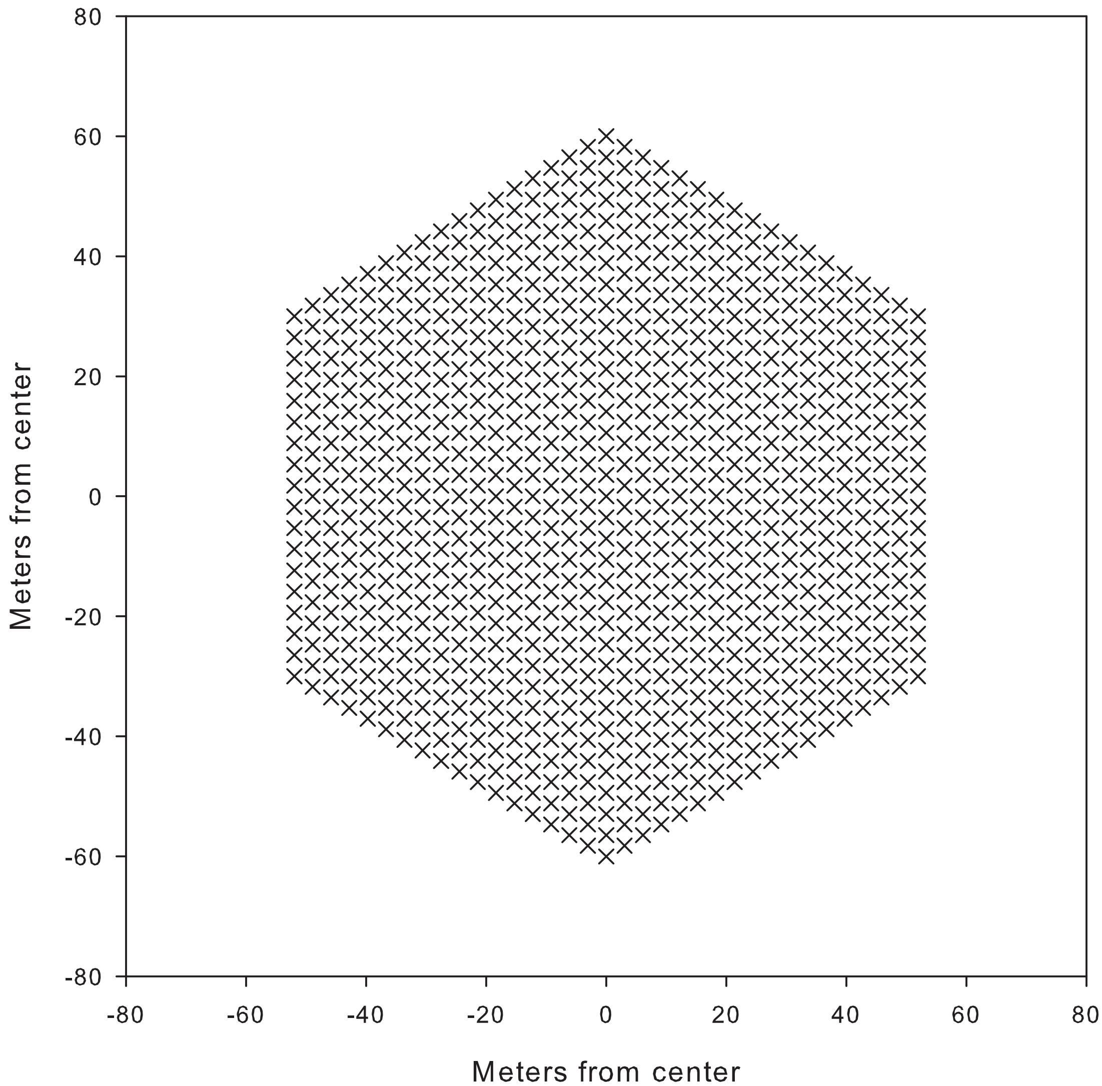

Fig. 5.— Hexagonal station configuration used as a starting point for the optimization of 919 antennas inside a circle of diameter 120 m. A minimum spacing of 3 m between the elements was used.

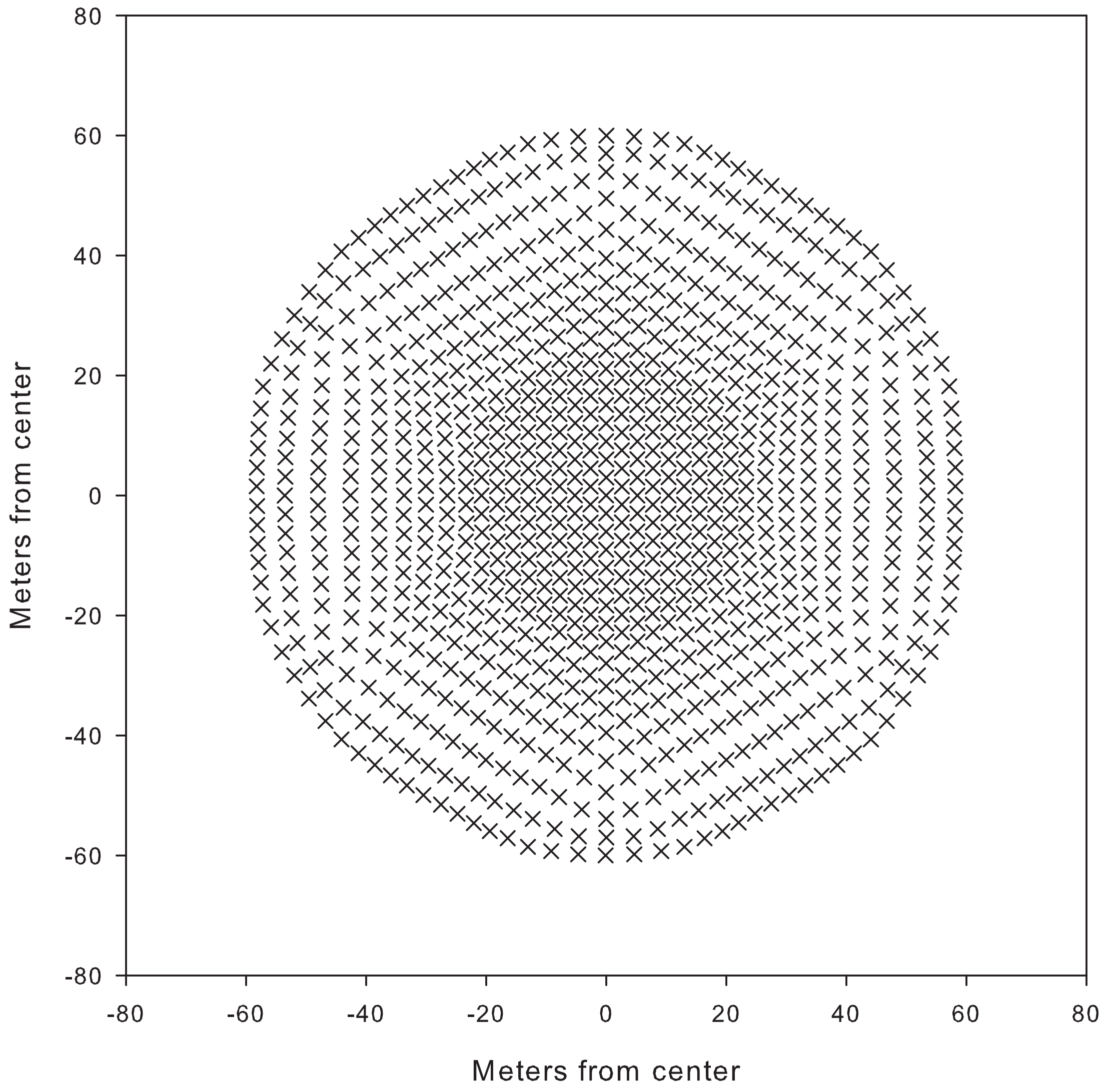

Fig. 6.— Configuration after optimization of a station consisting of 919 antennas located inside a circle 120 m diameter with minimum spacing of 3 m.

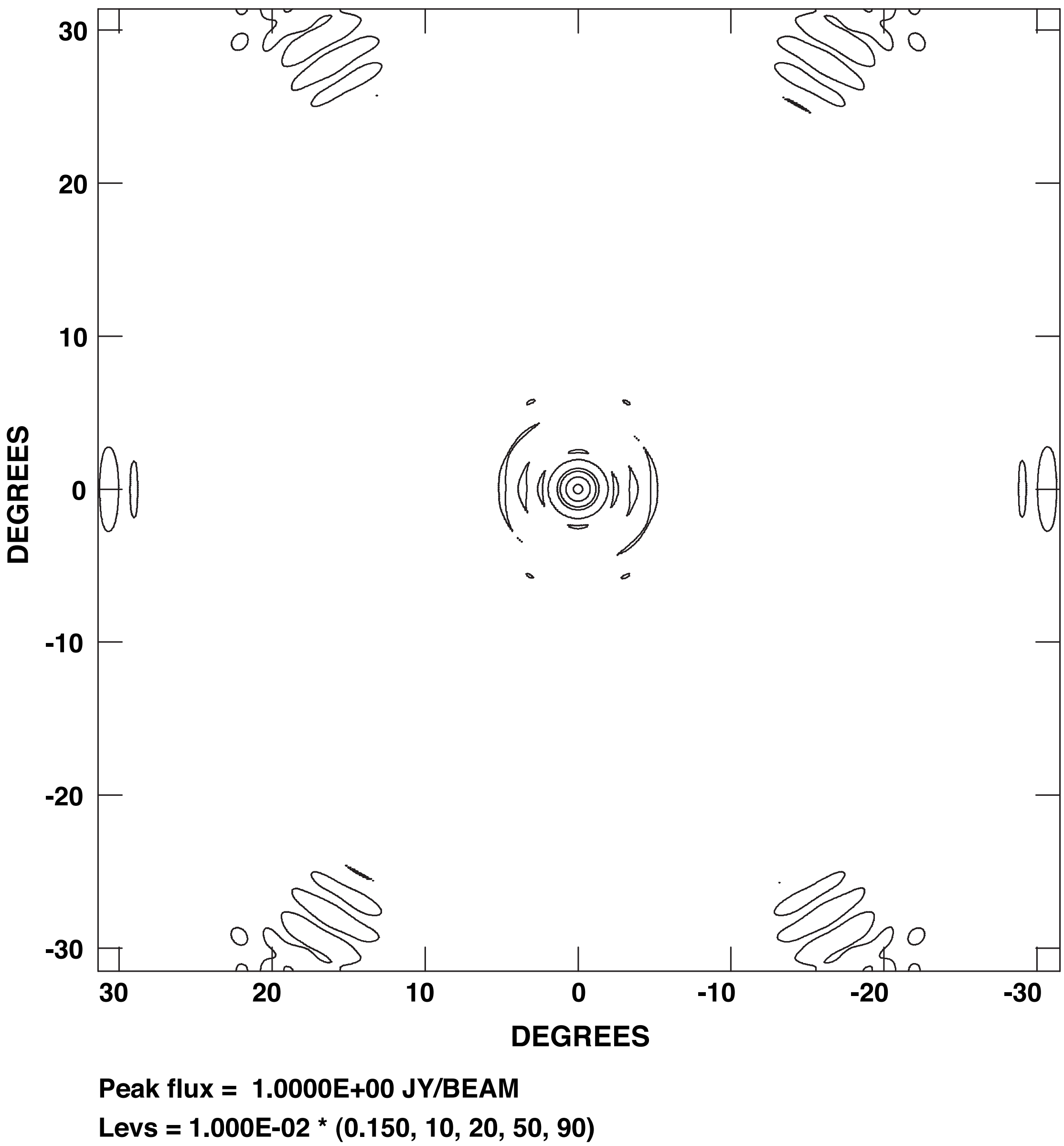

Fig. 7.— Two dimensional beam pattern created as a result of the optimization of a station consisting of 919 antennas located inside a circle 120 m diameter with minimum spacing of 3 m.

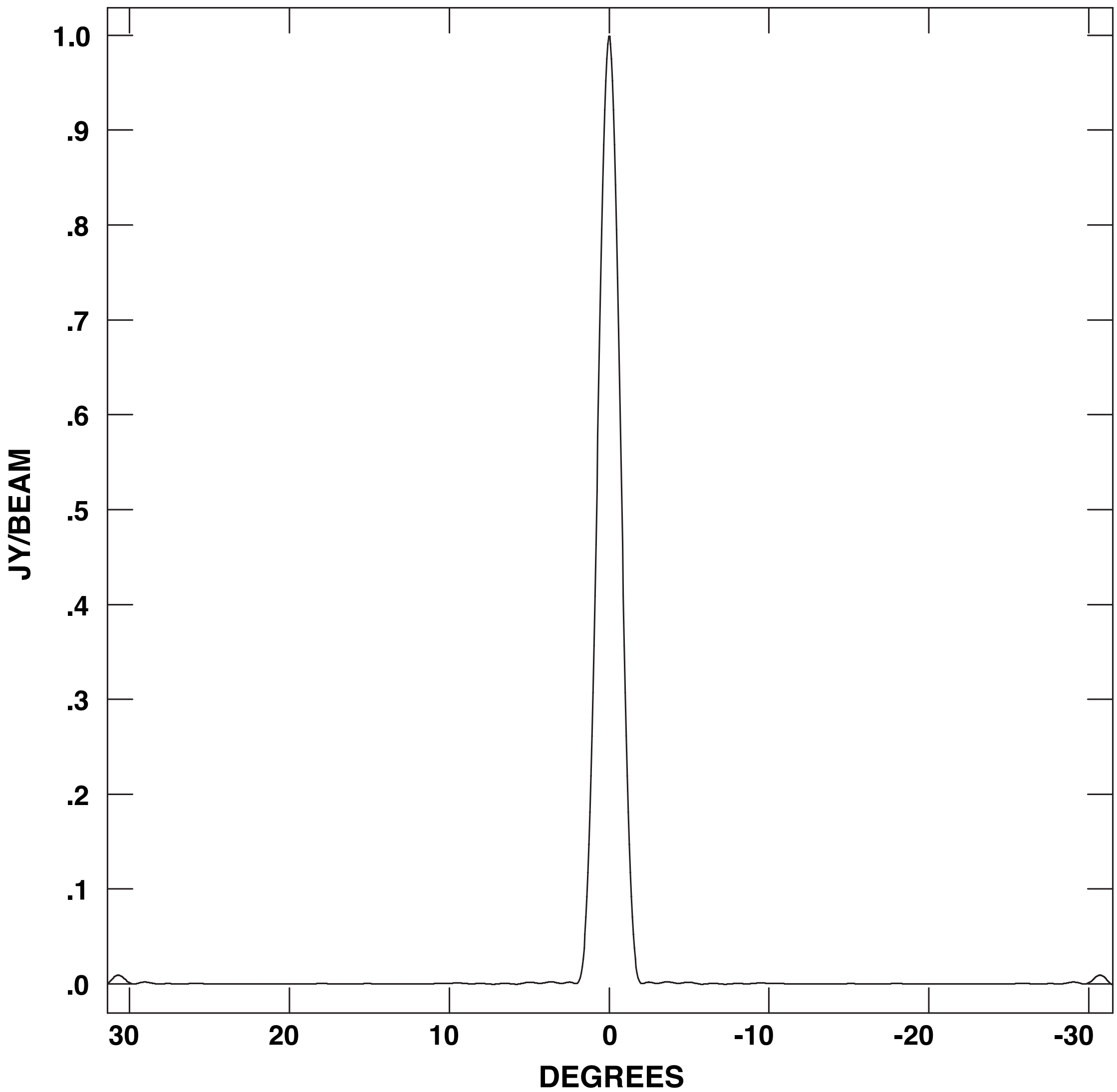

Fig. 8.— One dimensional slice of the beam pattern shown in Figure 7.

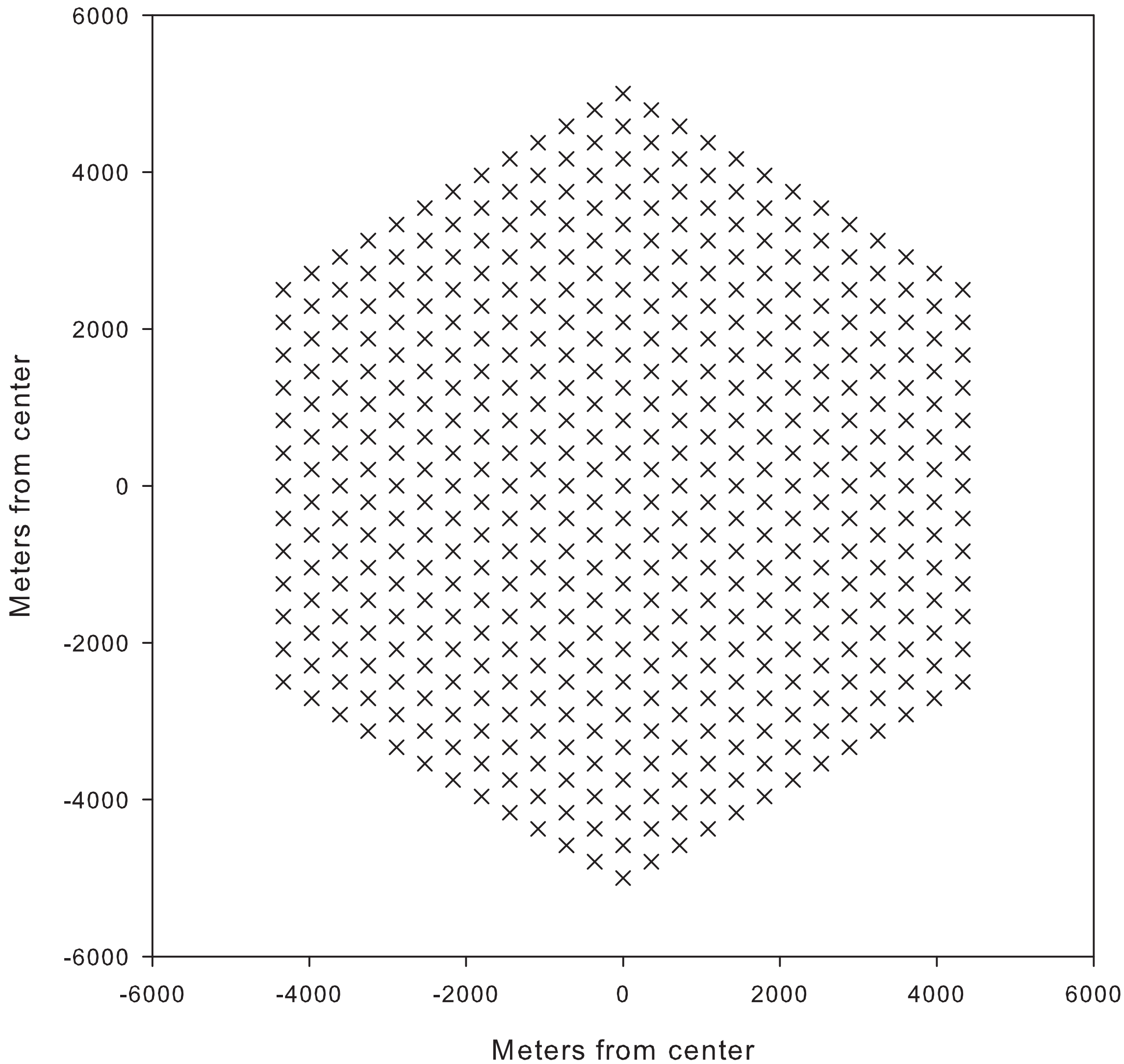

Fig. 9.— Hexagonal array configuration used as a starting point for the optimization of 469 stations inside a circle of diameter 10 km. A minimum spacing of 125 m between the stations was used.

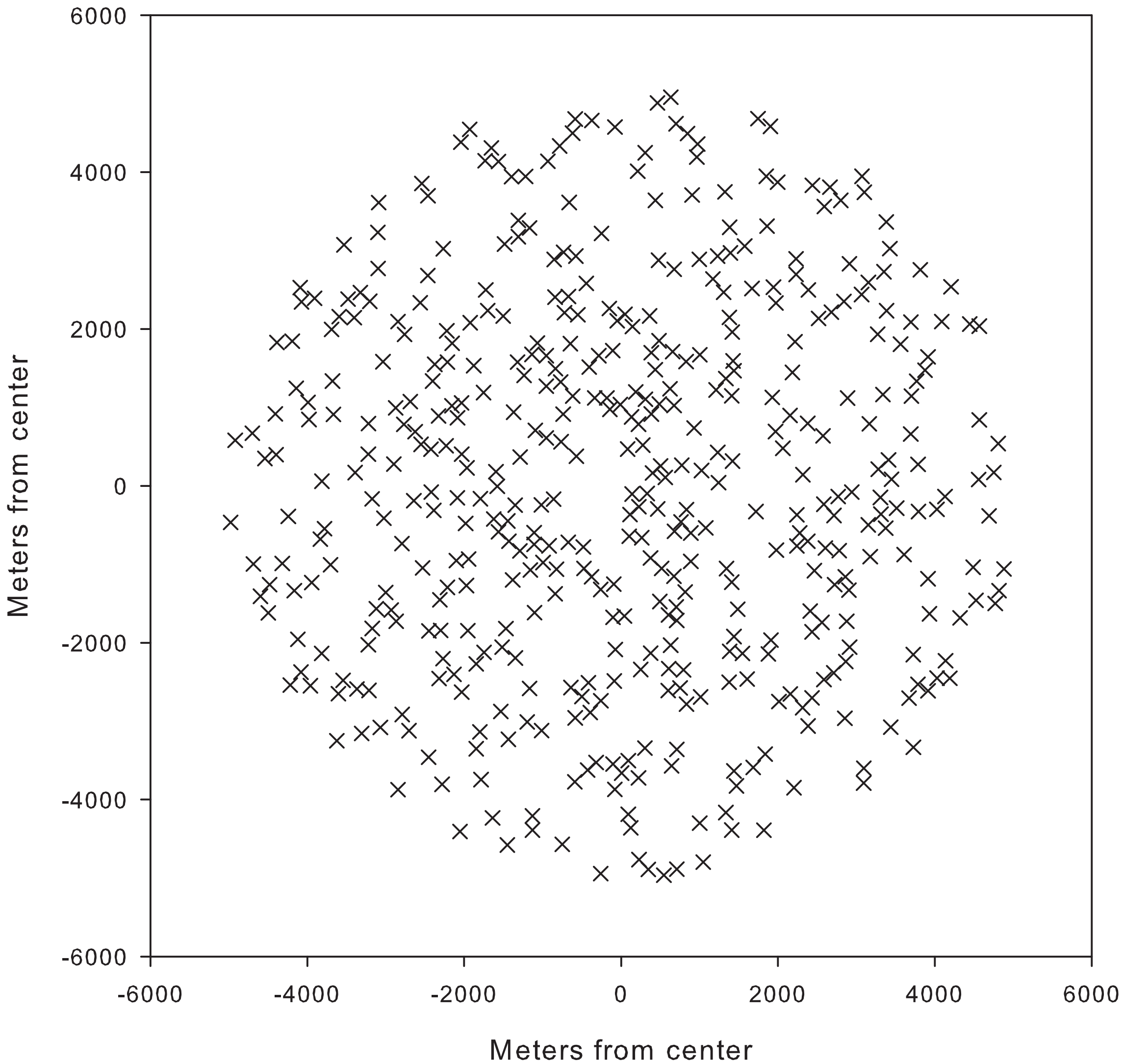

Fig. 10.— Configuration after optimization of an array consisting of 469 stations located inside a circle 10 km diameter with minimum spacing of 125 m between stations.

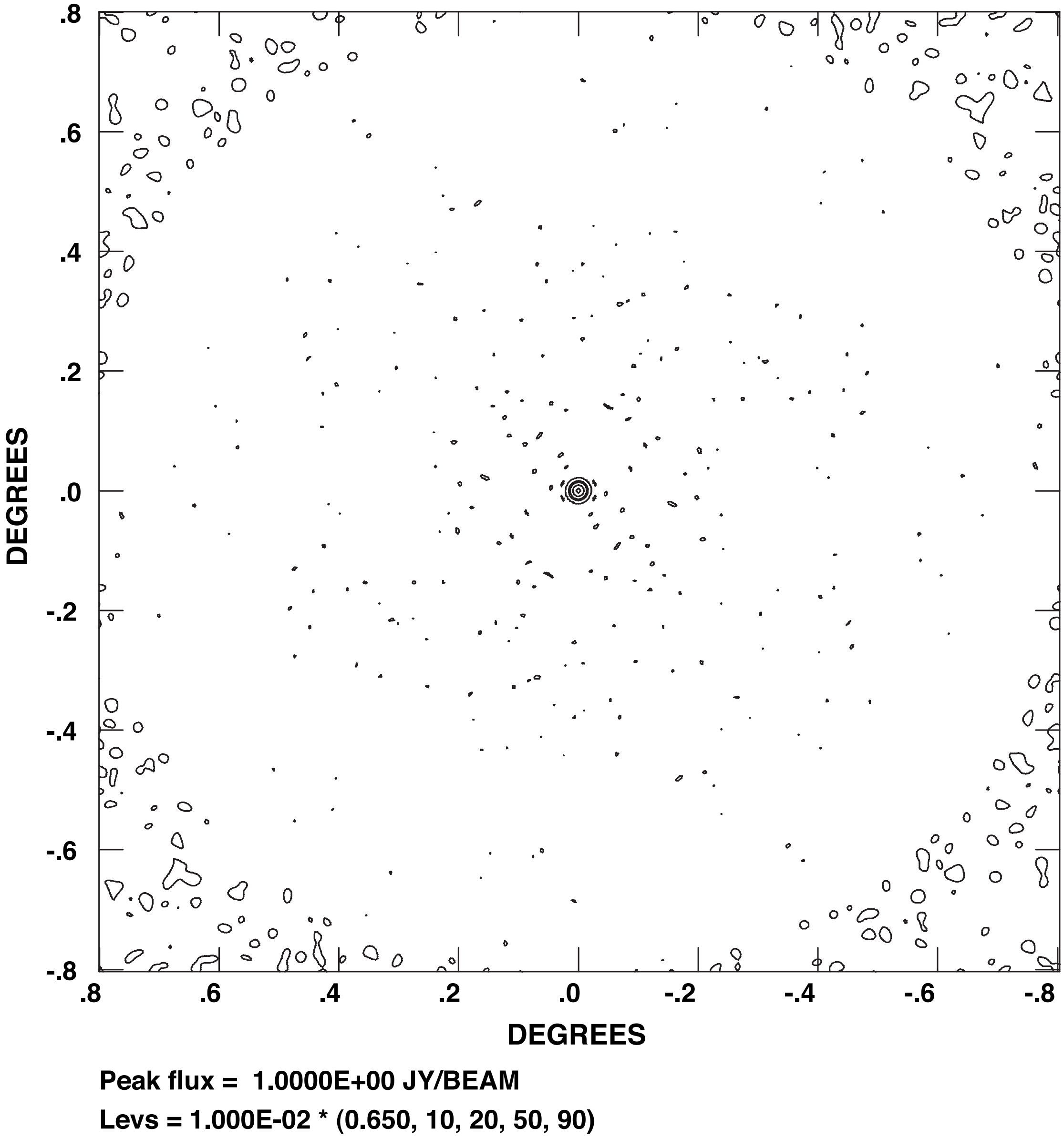

Fig. 11.— Two dimensional beam pattern created as a result of the optimization of an array consisting of 469 stations located inside a circle 10 km diameter with minimum spacing of 125 m between stations.

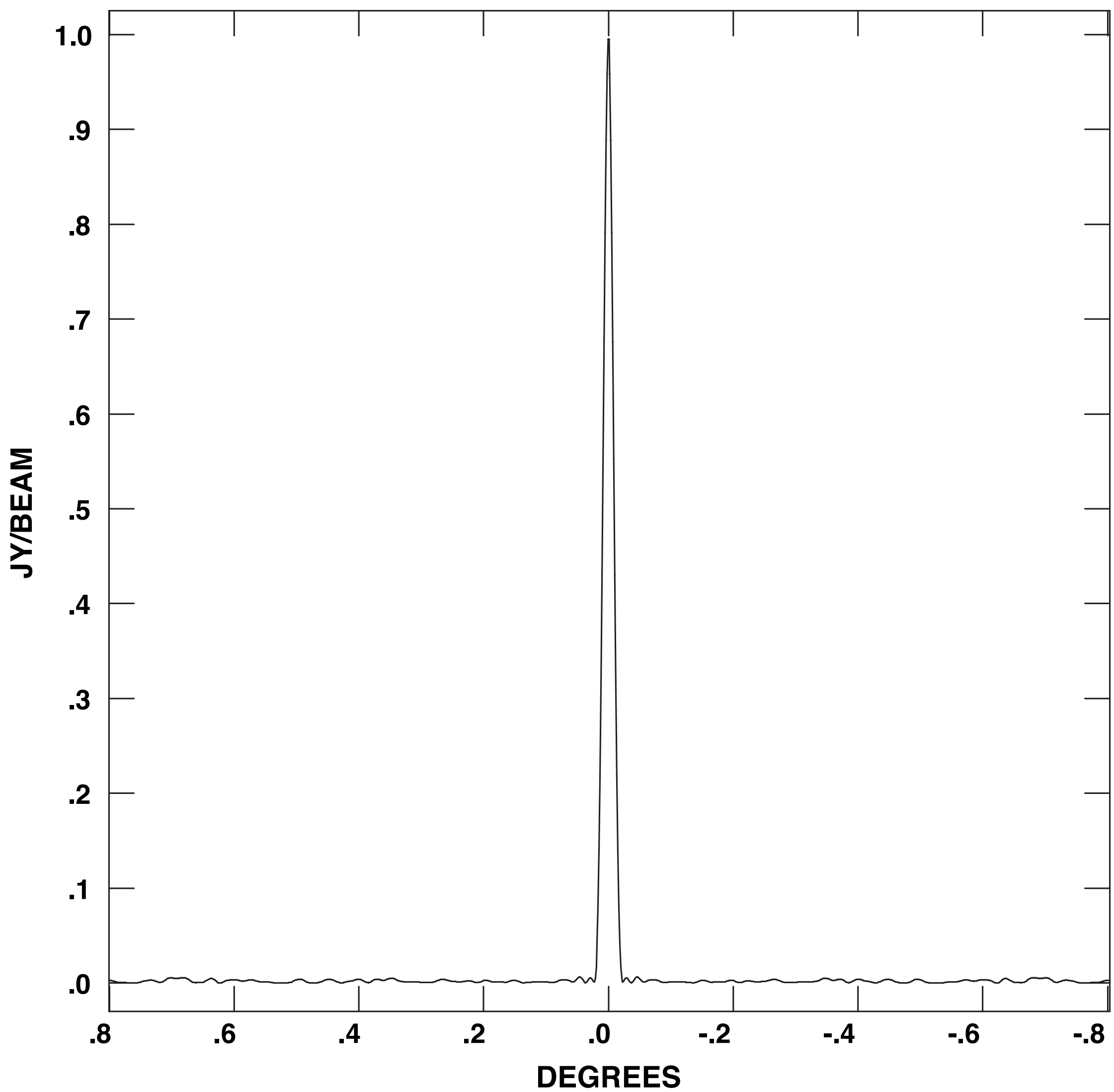

Fig. 12.— One dimensional slice of the beam pattern shown in Figure 11.