Hemispheric Imaging of Galactic Neutral Hydrogen with a Phased Array Antenna System

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Abstract

The thousand element array (THEA) system is a phased array system consisting of 1 m^2 tiles having 64 Vivaldi elements each arranged on a regular 8-by-8 grid, which has been developed as a demonstrator of technology and applicability for SKA. In this paper we present imaging results of galactic neutral hydrogen with THEA. Measurements have been taken using a dense 2-by-2 array of four tiles as a four tile adder. The results are compared with results from the Leiden-Dwingeloo Survey, showing qualitative agreement, but also indicating that further studies are needed on the instrumental characteristics.

1 Introduction

The international radio astronomy community is currently making detailed plans for the development of a new radio telescope: the Square Kilometer Array (SKA). This instrument will be a hundred times more sensitive than telescopes currently in use. ASTRON is developing one of the options for this new synthesis telescope, using antenna stations with phased array technology consisting of over one million receiving elements with a mixed RF/digital adaptive beam former. The thousand element array (THEA) [1] is one of the demonstrator systems that has been built during the SKA development program and is officially continued as the THEA experimental platform (THEP), but is usually still named THEA.

THEP is an out-door phased array system which was originally designed for 16 tiles, but currently consists of only four 1 m^2 tiles having 64 broadband Vivaldi elements arranged on a regular 8-by-8 grid each. Within each tile beam forming is done at RF level before the normal and quadrature components of the signal are each sampled as 12 bit signal. This system is implemented twice in each tile allowing THEA to make two beams over the sky simultaneously.

The complex signals from the beams from all tiles are fed into a powerful digital backend where beam forming at array level is done. This backend provides an FX correlator having 1024 frequency channels and 20 MHz bandwidth allowing to produce the power spectra of two signals or determine the cross correlated power of two signals. Both results can be integrated over time and stored on hard disk.

By scanning the beam of a single tile, a sky image can be formed at low resolution [2][3]. In this paper we will show that such a system in phased array technology can be used successfully for astronomical observations by presenting results from observations on galactic neutral

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hydrogen made with a four tile adder of 2-by-2 tiles. The results will be compared to results from the Leiden-Dwingeloo survey (LDS) [4][5].

2 Preparations on data from the Leiden-Dwingeloo Survey

The Leiden-Dwingeloo Survey has provided an all sky map of galactic neutral hydrogen visible from Dwingeloo. The Dwingeloo telescope is a 25 m single dish telescope having a half power beam width (HPBW) at 1420 MHz of 0.6°. The data is collected on a 0.5° grid or at 60% of the spatial Nyquist criterion to reduce the number of measurements. The RMS noise of the resulting maps is 0.07 K per frequency channel.
The LDS data cube is expressed in galactic longitude l and latitude b and the velocity with respect to the local standard of rest (LSR), while the THEA data cubes are expressed in the directional cosines l and m and the velocity along the line-of-sight (LOS). Furthermore the spatial as well as spectral resolution of the two instruments differ. The following steps were taken to convert the data to the same coordinate system for comparison.

1. The spectral resolution of the LDS data is 1.03 km/s, while THEA operates with a spectral resolution of 4.22 km/s at 1420 MHz. Therefore the LDS data was divided in consecutive series of 4 frequency planes and averaged over the frequency planes within each series. This step also reduced the number of data points by a factor 4.

2. It was concluded that the first and last frequency planes only contained some small high velocity clouds which would not be detectable by THEA. The relevant frequency planes were all found between the 70^{th} and the 150^{th} plane. Therefore the amount of data was reduced further by selecting only those planes for further processing.

3. The coordinate transformation between galactic coordinates and the (l, m)-plane poses the problem that a regular grid in one coordinate system is mapped on a distorted grid in the other. Since the phased array beam pattern has a constant shape in the (l, m)-plane, convolution with the phased array beam pattern in the (l, m)-plane is algorithmically less complex than in galactic coordinates. Therefore the convolution was done in the (l, m)-plane. Since a regular grid greatly simplifies the convolution operation, a regular (l, m) grid with a spacing of 0.01 was defined and mapped on the (l, b)-plane. A bilinear interpolation was used to obtain the intensity values at the desired positions. This produces a 0.57° spacing in the (l, b)-plane in the zenith direction. This step results in a data cube of $201 \times 201 \times 81$ points, which is padded with zeroes on positions where $\sqrt{l^2 + m^2} > 1$.

4. The points in the resulting (l, m, v_{LSR}) data cube were weighted with $\sqrt{\cos(\frac{1}{2}\pi\sqrt{l^2 + m^2})}$ to account for the sensitivity pattern of the individual receiving elements.

5. The array beam pattern was calculated on a grid with $-2 \leq l, m \leq 2$ and a spacing of 0.01 assuming an ideal THEA tile with omnidirectional receiving elements aimed at the zenith. This assumption can be made since the sensitivity pattern of the receiving elements is already taken into account in the previous step. The seemingly very large grid is needed to account for the full side lobe and grating lobe structure for every point on the map.

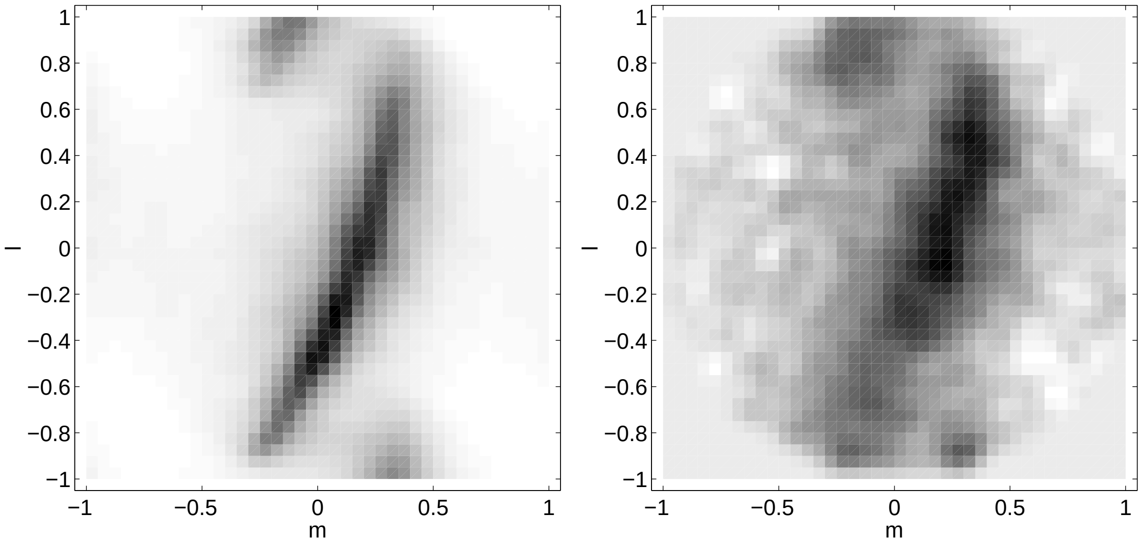

Figure 1: The left panel shows a total HI map based on LDS measurements after projection on the (l, m)-plane for April 8, 2003, 9:46.40 (GMT). The image is convolved with the array beam predicted for a 2-by-2 array of THEA tiles (see text for details). The right panel shows the total HI map actually measured with a 2-by-2 array of THEA tiles at the specified time. The image consists of 1246 points and was produced with one second integration per point.

6. The frequency planes of the (l, m, v_{LSR}) data cube were convolved with the array beam power pattern calculated in the previous step using the standard Matlab routine for two dimensional convolution of two matrices. The resulting product of the element beam pattern and the array beam pattern serves a first order approximation to the actual beam pattern of the instrument.

7. The final result was obtained by down sampling the convolved cube by keeping only the spectra at (l, m) coordinates at which the actual measurement were done. An example is shown in the left panel of figure 1.

3 Measurements with a 4 tile adder

For the observation of galactic neutral hydrogen four THEA tiles were placed in a dense 2-by-2 configuration oriented parallel to the quarters of the compass. Beam steering was done by adjusting the phases of all 256 elements such that the array of THEA tiles acted as a single larger tile. Phase deviations of the tiles not due to the geometrical delay, for example phase differences caused by slightly different lengths of the LO cables, were corrected by calibration on Afristar at 1480 MHz. This calibration was also used to find the gain differences between the tiles. These phase and amplitude differences were corrected by multiplication of the signals from the individual tiles by appropriate factors in the digital backend before the adder stage. Using this setup a full sky scan was made on April 8, 2003, 9:46.40 (GMT) on a regular (l, m) grid with spacings of 0.05. Only the points above the horizon were actually measured, the spectra of the other points were set to zero. The scan consisted of 1246 points which were measured with one second integration. The complete scan was made in 23 minutes. Since the

beam of the array of THEA tiles has a HPBW of 6°, the result may be slightly distorted due to sky rotation. However this will hardly be visible since neighboring points are measured within one minute after each other.
RFI spikes were removed from the resulting data cube by comparing the value in each frequency channel to the median of the surrounding frequency channels and replacing its value by this median value if it deviated more than 20%. This procedure removes spikes very efficiently without modifying the more continuous features such as the shape of the pass band and HI profiles.
Baseline subtraction was done between 1420.1 MHz and 1420.7 MHz by a linear interpolation between the lower reference band between 1419.9 MHz and 1420.2 MHz and the higher reference band between 1420.6 MHz and 1420.9 MHz. The choice for a simple linear interpolation was made based on a first visual inspection of the raw data. The resulting total HI map shown in figure 1 was obtained by simply adding the intensity values between 1420.1 MHz and 1420.7 MHz after baseline subtraction. The gray scale of the LDS image ranges from 0 K to the maximum in the map, while the gray scale of the THEA image ranges from the minimum of the fluctuations in the map to its maximum.
Comparison of the THEA result with the corresponding result from the LDS shown in the left panel of figure 1 shows qualitative agreement, although there are some significant differences which require further explanation.
These fluctuations are about four times larger than expected based on the system temperature, bandwidth and integration time. This can be explained by imperfect baseline subtraction due to ripples in the baseline of the instrument on frequency scales smaller than the scale on which the linear interpolation is applied. This causes a slight over- or underestimation of the intensity along specific lines of sight. These errors are relatively large for low intensity values. This effect may also vary over the sky, since the baseline is also affected by low power intermodulation products from radio stations. Unfortunately we found that there are many of these intermodulation products around 1420 MHz and have not found an effective mitigation strategy yet.
An important aspect of a phased array system is mutual coupling between individual elements of the array. The mutual coupling impedances express the coupled voltages to other elements as a function of the actual current in an element. The latter depends on the actual loading condition of the array. If the sum of all coupled voltages differs 180 degrees from the Thevenin voltage of an element, nothing is detected by that element. Since a THEA tile forms a regular array, this situation may occur simultaneously for a large number of elements, causing a sharp decrease in sensitivity for a few specific directions which are called blind angles. This could explain some of the white spots in the THEA image, but this needs further quantitative study.
The last noticeable difference between the LDS and the THEA image is the shift in maximum intensity along the galactic plane itself. This may be due to an asymmetric element beam caused by the asymmetry in the electromagnetic surroundings of the array and the fact that the tiles were not identical. Some simulation studies on the element beam have been done at ASTRON, but experimental verification has not been successful yet.
As a result of these difficulties and especially those concerning baseline subtraction, velocity profiles can differ strongly from the corresponding LDS results as shown in figure 2. It has already been concluded that the noise is about four times as large as expected based on bandwidth and integration time, thus leading to a noise level of about 6 K per channel. There is however agreement in the sense that along lines of sight where the LDS velocity profile shows only a single peak, the THEA velocity profile also shows a single peak and when

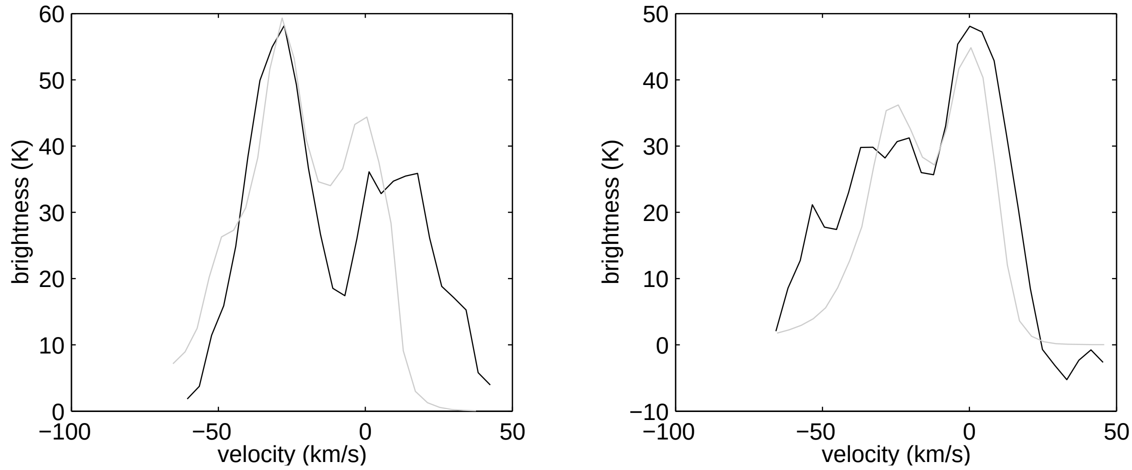

Figure 2: Comparison of velocity profiles from LDS (light gray) and THEA (black). The THEA profiles are scaled and shifted to match the LDS profiles.

the LDS profile is more complicated, this holds for the THEA profile as well.
Therefore a sample of profiles can be compared to find the scaling factor relating the number of counts from the A/D converter to brightness temperature. This scaling factor was used to derive the noise temperature from the number of counts in the noise floor before the baseline subtraction. With this approach a system temperature of 186$\pm$10 K was derived, consistent with independent tile system temperature measurements.

4 Conclusions

With the successful detection of galactic neutral hydrogen we have demonstrated that astronomical observations are possible with telescopes in phased array technology. However, our measurements do indicate that further research is needed to deal with instrument properties typical for phased array antenna, such as blind angles and the fact that RFI from all directions is detected by the instrument. Since these issues have an effect on instrument calibration as well the calibration routines used should also be reconsidered.
On a qualitative level we have been able to explain the differences between measurements from the Leiden-Dwingeloo Survey and THEA. This demonstrates that we already have a considerable level of understanding of the operation of phased array telescopes and particularly the THEA system. On a quantitative level we have been able to use a sample of velocity profiles to derive the system temperature of the THEA system which was found to be 186$\pm$10 K. It has become clear however that the aforementioned further research is needed if reliable astronomical measurements are to be done without using statistics, i.e. in a single measurement.

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