A backfire helix as prime focus feed for a radioastronomical parabolic antenna

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Abstract— **A backfire helical antenna has been built as a prime focus feed for a 5.5m diameter radioastronomical parabola. The antenna requirements of low sidelobes, narrow beam and 10% bandwidth have been met. Details of the construction technique and the measured beam pattern performance of the parabolic antenna are presented.**

Keywords— **radioastronomy, helix, backfire.**

I. Introduction

SYSTEMATIC studies of Galactic radio emission allow the direct estimate of some of the basic parameters affecting the dynamics of the galaxy, including the temperature and density of interstellar clouds, the spectral index of the energy spectrum of cosmic ray electrons, and the mean intensity of the Galactic magnetic field. In addition, studies of the Cosmic Microwave Background (CMB) anisotropy require accurate knowledge of the spatial and spectral characteristics of continuum Galactic radio emission (Banday and Wolfendale 1991; De Bernardis, Masi, and Vittorio 1991) [1,2]. Uncertainty in the level of Galactic microwave emission is also a limiting factor in the measurement of the CMB spectrum at frequencies below 3 GHz (Bensadoun et al. 1993) [3]. Improved measurements of the absolute sky temperature would also provide better baseline levels for source surveys with higher angular resolution.

The Galactic emission is composed of the superposition of signals of different origin and spectral index, which can, in principle, be disentangled from each others, given a sufficient number of measurements at different frequencies. Each component is also randomly polarized, and observations of the total power of the incoming radiation can advantageously be done when the antenna collect and transfer to the receiver the circularly polarized component of the signal.

To address the need for better-calibrated maps of Galactic emission, our research group has initiated the Galactic Emission Mapping (GEM) program to make well-calibrated, full-sky surveys at a number of frequencies between 408 and 10000 MHz (De Amici et al. 1994) [4]. At the core of this project is a small, portable radiotelescope, which has been designed and optimized for the GEM observations.

Several optical schemes have been adapted from visible-light- to radio- telescopes to reach the desired beam characteristics. Traditional solutions (such as prime focus, cassegrain, or gregorian) require the installation of a device (either a feeder antenna or a secondary mirror) with a typical size of one wavelength or more, at or near the prime focus point of the main reflector. These devices, and the mechanical structure that supports them, introduce distortions and scattering of the incoming radiation, reducing the effective collecting surface of the primary mirror, degrading the beam pattern of the antenna, and introducing unwanted off-axis response (Christiansen and Hogbom, 1987) [5]. This degradation is tolerable for large telescopes, but unacceptable in our configuration of small diameter of the reflector and long wavelength of observation.

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Both dipole and horn antennas, which constitute the most commonly used varieties of feeders for large reflectors, are sensitive only to one linearly polarized component of the e.m. radiation. The dipoles are limited by their mechanical structure, while the horns are limited by the waveguide-to-coax adapters at their throat. Typically, an orthomode transducer, mixing the signal from two orthogonal dipoles or waveguide probes, is employed when sensitivity to circularly polarized radiation is desired. This adds one more component to the radio chain, and becomes a source of additional noise in the receiver. It is therefore desirable that a device capable of collecting and transferring circularly- polarized radiation, with minimal or no obstruction of the collecting mirror, and without need for a support structure be used.

The concept of the backfire helix antenna (a monofilar helix constructed so that the main lobe of radiation is in the backward [toward the ground plane] direction) appears to be ideally suited for this task and we decided to use such an antenna as the prime focus feed for the low-frequency measurement below 2 GHz.

II. description

The helix has long been recognized as an effective way to transfer electromagnetic energy from a coax cable to free space, and its properties have been exploited for communication and radioastronomy in several occasions (e.g. Kraus, 1988 and references therein) [7] with good success. Its intrinsic mechanical construction makes it sensitive to circularly polarized radiation, and the backfire concept, with its small ground plane, seems to satisfy all the requisites.

The backfire helix antenna is mechanically very similar to the standard endfire helix (Kraus, 1988; King and Wong, 1984) [[6, 7]; the only physical difference between the two is the size of the ground plane, where the endfire antenna has a ground plane with diameter (typically) greater or equal to twice the helix diameter ($D \geq 0.7\ \lambda$), while the backfire antenna has diameter equal or smaller than the helix diameter ($D \leq 0.3\ \lambda$). The radiometric properties of the two helices are quite different; the main lobe of radiation is in the backward direction (along the helix axis, but from the open end toward the feed point of the helix) for the backfire unit. The limited experimental results also seem to indicate that the HPBW of the backfire helix cannot be made arbitrarily small by increasing the number of turns of the helix; a rather welcome characteristics, if the backfire helix is to be used as a feeder for a relatively short-focus ($f/D \cong 0.35$) parabola.

Theoretical solutions to the impedance and radiation pattern characteristics of the backfire helix have been worked out analytically by Sexson (1965) [8] and numerically by Nakano et al. (1988) [9], under slightly different boundary conditions: Sexson analyzes a single conductor helix, where the conductor consists of an infinitesimally thin tape. He concludes that the backfire characteristic of the helix antenna can be explained by a wave with purely complex propagation constant; the presence of a large ground plane excites a wave of real propagation constant, and traveling forward. Nakano et al. base their analysis on a single conductor helix, fed by an axially located coax, with a ground plane of variable diameter; after showing that the transition from forward- to back-fire beam pattern occurs when the ground plane diameter approaches the diameter of the helix, they calculate that the antenna exhibits characteristics of backfire pattern and circular polarization over a 30% bandwidth. Notwithstanding its potential and characteristics, experimental reports on the backfire helix have been published only by Johnson and Cotton (1984) [10], in association with a paraboloidal reflector for radar applications at 1.5 GHz. They used a mechanical design (with the helix wound around the outer conductor of the coax feed cable and grounded at the open end) quite different from the one analyzed by Sexson or Nakano.

We constructed a backfire helical antenna by winding copper tubing (diameter 0.95 cm, wall thickness 0.16 cm) around a cylinder of plexiglas (diameter 20.2, cm wall thickness 0.6 cm) which acted as the supporting structure. Allowing for the dielectric constant of the plexiglas, the electrical diameter of the helix was ≤ 1.05 wavelengths. The helix was held in place with non-conductive screws and clamps. The pitch of the helix was 14°, for a total length of 145 cm on 9.5 turns. A copper plate, of diameter 13 cm ($0.2\ \lambda$ at 408 MHz) acted as ground plane. The helix was brought to feed a low-loss coaxial cable (Andrew LDF4-50); the impedance of the helix was matched to the transmission line via a microstrip balun transformer and matching fins (Kraus 1988) [6]. Figure 1 shows a schematic view of the helix antenna installed on the parabola. We used a network analyzer to measure the VSWR of the antenna and transformer: it was $\geq$ 15dB across the frequency band of interest (385-425 MHz).

III. Expected performance

The beam pattern performance of the backfire helix and parabolic reflector combination was predicted both on theoretical principles, and from measurements of a 1:10 scale model. These figures provide an upper and lower limit to the expected performance of the final assembly.

From a rough beam pattern measurement of the backfire helix alone (lack of a suitable test range prevented accurate measurements at 408 MHz before final installation in the field), I expected a -10dB illumination taper at the edge of the 5.5m parabola. The assumption of a negligibly small feed antenna (Rahmat-Samii, 1988) [11] leads to the prediction of an 8.75° HPBW for the feed-parabola assembly, with a first sidelobe at -22 dB.

A scale model was constructed and tested at 4.02 GHz, yielding a 15° HPBW beam pattern; due to construction limitations, the support element and the feed cable of the model are poor approximations of the full-scale assembly.

IV. Results

The backfire helix was mounted on the 5.5m parabolic antenna, to measure the beam pattern of the GEM 408 MHz optical system. Each data run consisted of correlating the output signal of the radiotelescope with its angular distance from the position of the Sun, a powerful and (for the frequency and diameter of the antenna under consideration) small- angular-scale source. The Sun is well know to be a variable radio source, especially at low frequencies. The solar radio flux correlates well with the number of observed sunspots (Kraus 1986) [12]. During the days of the measurements described here (day 87-94, March 27 to April 5, 1994), the sunspot number was very low: NGDC-NOAA recorded an average of just 9 sunspots per day, close to the solar cycle's monthly average minimum, excluding variations in the Sun's radio emission as a possible source of uncertainties in these measurements.

The measurement could not be conducted with a stationary antenna, set to the Sun altitude at meridian, because such a measurement would be susceptible to local weather variations and drifts in receiver performance. Instead the telescope was swept along an arc in the sky at 30° from zenith with period of 1 minute. Each revolution of the antenna measured solar angles ranging from 0 ° (Sun on axis) to 60 °. By starting and stopping the tests well before or after the Sun passes the meridian, the antenna sidelobe response to the solar emission was measured up to 80 ° away from the beam axis.

Several observing runs were done; the high brightness temperature of the Sun saturated the limited dynamic range of the receiver when the solar angle was less than 7°. In order to accurately map the center part of the antenna beam, the receiver gain was reduced by 4 dB during one of the observing runs and this systematic difference was accounted for during the analysis.

Data were taken during clear, calm days; in presence of high wind and/or clouds the system was turned off. There are about 34 hours of observations usable for beam pattern characterization.

The data were corrected for localized radio-frequency interference and data acquisition glitches. Changes in receiver gain and offset, induced by changes in its temperature, were modeled and removed, so that data taken during different days could be reliably added together. The Galactic plane was always more than 40° away from the position of the Sun during these tests; however, its presence in the daytime sky affects the accuracy of all measurements at large beam angles. This effect was modeled by convolving an existing map of radio sky at 408 MHz (Haslam et al. 1982) [13] to the expected (taken as the average between the modeled and scale-measured values) resolution of this antenna, and subtracting the model from the data. The analysis was then conducted and a best-fit beam pattern derived from the data; repeating the modeling and analysis process with the new beam pattern yielded no significant deviation in the final results.

After the corrections, the pointing of the beam was converted to RA-dec coordinates and the position of the Sun was computed. The data were binned by radial distance from the Sun.

The final, best fit beam pattern is shown in figure 2, together with the raw data for each of the scans and the combined scan. The antenna beam is well approximated by a gaussian shape, with HPBW of $10.1+0.1^\circ$, out to $18\text{-}20^\circ$ from center. The chi-squared is 45.6 for 25 d.o.f.

The data were combed for and purged of thermal drift in the receiver though modeling and reduction of all runs to a reference receiver temperature. RFI spikes were effectively removed from the data through binning, averaging and outliers-removing software. Ground contribution (if present) should manifest itself as an increase in the level of the baseline as the telescope is tipped toward the horizon; a limit on the amplitude of this effect can be given by comparing the data taken at a given solar angle, but at different zenith angles. The comparison was limited to data bins between 20° and 40° of solar elongation, both to the E and W, to avoid contamination from un-subtracted Galactic signal and/or atmospheric variations. There is no systematic gradient of signal between 20 and 40° from zenith and the results are consistent with a null effect to 95% confidence (2 sigma). Statistical uncertainty corresponds to less than 0.1% of the signal.

Residual asymmetries in the measured beam pattern could be caused by local horizon effects (at a level ≤ 0.2 K) or inaccuracies in the Galactic model. The possibilities of a 'memory' effect in the receiver output or of a strongly asymmetric beam pattern are not supported by data taken near the peak of solar signal.

V. Conclusions

The beam pattern of the GEM antenna at 408 MHz has been measured in the field out to 75° from axis. The results are in good agreement with the measurements conducted earlier on a rough scale model and with the theoretically predicted best achievable beam, and support the use of a backfire helical antenna as the prime focus feed for a radioastronomical parabolic reflector. The advantages of this configuration are the built-in sensitivity to circular polarization of the feed, the convenient location of the receiver just behind the parabolic mirror (minimizing the length of cables between the feed and the receiver, and making it easily accessible for inspection and servicing), and the reduction of beam degradation caused by diffraction.

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References

[1] Banday, A.J., and Wolfendale, A. W. 1991, M.N.R.A.S., 248, 705
[2] De Bernardis, P., Masi, S., and Vittorio, N., 1991, Ap.J., 382, 515
[3] Bensadoun, M. et al., 1993, Ap.J., 409, 1
[4] De Amici, G. et al. 1994, Ap. Space Sci. 214, 151
[5] Christiansen, W.N., and Hogbom, J.A., 1987, "Radiotelescopes', 2nd edition, Cambridge University Press
[6] Kraus, J.D., 1988, 'Antennas', 2nd edition, McGraw-Hill
[7] King, H.E. and Wong, J.L., in Johnson, R and Jasik, H. (edts): 'Antenna Engineering Handbook', 2nd edition, McGraw-Hill, 1984
[8] Sexson, T.L., 1965, Sylvania Electronics Systems Report, ASTIA AD 626088
[9] Nakano, H., Yamauchi, J., and Mimaki, H., 1988, IEEE, AP-36, 1359
[10] Johnson, R.C., and Cotton, R.B., 1984, IEEE, AP-32, 1126
[11] Rahmat-Samii, ... 198?, ????
[12] Kraus, J.D., 1986, 'Radio Astronomy', 2nd edition, Cygnus-Quasar Books
[13] Haslam, C.G.T. et al., 1982, A.A.Suppl. , 47, 1

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