A New Imaging Riometer based on Mills Cross Technique

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April 2003

Abstract

A new type of imaging riometer system based on a Mills Cross antenna array is currently under construction by the Ionosphere and Radio Propagation Group, Department of Communication Systems, Lancaster in collaboration with the Max-Planck-Institut für Aeronomie, Germany. The system will have an unprecedented spatial resolution in a viewing area of 300×300km. It is located at Ramfjordmoen, near Tromsø, Norway.

The riometer (relative ionospheric opacity meter) determines the radio-wave absorption in the ionosphere by measuring the received cosmic-noise power. The expected variation of background noise over a sidereal day is usually referred to as the quiet-day curve (QDC). The ionospheric opacity is deduced from the difference between the QDC and the received noise power. Absorption images may be produced by utilising a number of spatially-distributed narrow beams.

The Mills Cross system considered in this paper provides at least 4 times the resolution which can be achieved (with the same number of antennas) with a filled array antenna system. However, the cross correlation technique employed for producing narrow pencil beams requires information on both amplitude and phase of the signals to be cross correlated in contrast to other existing imaging riometer systems that record only signal power. This adds a considerable amount of complexity to the system which requires the use of state-of-the-art FPGA signal processing technology. The system design and specification will be presented.

While the application of correlation technique allows an increased spatial resolution — even for the same number of antennas used — it leads at the same time to an increased noise level in the measurements with adverse effect for the minimum integration time. For filled arrays the integration time can be as low as $\frac{1}{8}$s; for a correlation system the integration time will be at least some seconds to achieve comparable uncertainties. First experimental observations have confirmed this. The measurements also indicated that antenna sidelobes introduce phase delays that result in signal reduction/increase especially in the presence of a strong noise source (radio star). To what extent this has an adverse effect on the QDC is being investigated. Adaptive beam steering and tapering techniques are being analysed to minimise the effects of the sidelobes. The results of these investigations will also be presented.

Introduction

Existing riometers are either widebeam riometers consisting of a single antenna element above a conducting ground plane with resulting beam widths of the order of 60°, or imaging riometers made up of up to 256 equally spaced antenna elements that form a square additive phased filled array [3]. Lancaster University's Imaging Riometer for Ionospheric Studies (IRIS) is an example of such an imaging riometer as described in [6]. With its 8×8 antenna array IRIS achieves an angular resolution of 16° at the zenith which translates to an area of about 25×25 kilometers at 90km height. IRIS utilises a two-stage matrix of modified 8 port Butler matrices [5] to form a total of 49 simultaneous beams.

IRIS also has an additional widebeam antenna that is located at a distance of several wavelenghts from the phased array.

To observe small-scale structures in the ionosphere, a higher spatial resolution is often wished for [14]. In theory, it is possible to increase the angular resolution of a filled phased array to any required value. However, the required number of antenna elements increases with the inverse square of the required resolution. Practical limits are therefore imposed on the achievable resolution of such a system by spatial restrictions as well as high cost [12].

About 50 years ago, Mills [11] employed a technique to achieve high angular resolution with a relatively small number of antennas. He used this technique successfully to observe spatially small and well-defined strong radio sources in the sky, mainly the sun, with unprecedented detail.

A brief experiment employing an 8+8 Mills Cross type antenna array had been carried out in January 1990 by Yamagishi/Nishino [1]. Low signal levels from the antennas, limited dynamic range of the receivers and an analog cross correlator resulted in poor system performance that at the time seemed unsuitable for riometry application.

Plans for a new high-resolution riometer have been outlined in [13]. Advances in signal processing technology will enable the Mills Cross technique to be employed for riometry work for the first time. The goal is to observe small scale variations of absorption over the instrument's whole field of view. The fact that these weak changes have to be identified in presence of the continuous cosmic background noise imposes unprecedented challenges on this technique. In other words, for riometry, the signal to noise ratio that has to be dealt with is in fact the noise fluctuation over background noise.

As we shall see from the following simulations, a cross of two perpendicular arms of 32 antennas each (totaling 63 antennas), see figure 1, will perform equally to a filled square antenna array of 16×16 antennas (totaling 256 antennas) in terms of both angular resolution and sidelobe levels. It seems inevitable that there has to be some aspect where this type of antenna system performs worse than its filled array equivalent, and this is the noise performance, something that has not been discussed to the full extent in the original plans [12]. New theoretical considerations [9] and first experimental observations (below) have shown that while for filled array type systems the integration time can be as low as $\frac{1}{8}$s, for a Mills Cross type system with improved spatial (=angular) resolution the integration time will have to be at least some seconds.

Experiment description

The Advanced Riometer Imaging Experiment in Scandinavia (ARIES) system at Ramfjordmoen consists of a cross of two perpendicular arms of 32 antennas each (figure 1). For the experiment results discussed in the following sections, a subset of only 16+16 antennas was used in an effort to reduce the complexity of the initial tests. The signals from the two arms of 16 antennas each are fed into a lossless combiner to produce two perpendicular fan-shaped beams pointing towards zenith. A set of phasing cables enabled swinging the beams to an alternate, predetermined 'worst-case' direction. This is the direction where strong signals are received by the sidelobes whereas the pencil beam created by the cross correlation stage looks at a quiet part of the sky.

The signals from the combiners were fed into two receivers. The receivers employed an in-phase/quadrature sampling technique. The receiver bandwidth was 1MHz, considerably wider than the bandwidths that are used with existing filled array riometers (IRIS: 250kHz). The resulting output was digitised using a high-speed A/D converter board that plugs into a standard PC. The board is capable of continuously and synchronously sampling 4 analogue channels at up to 10MHz sampling rate and 12 bit resolution. All experiments described below were carried out with a sampling rate of 2.2MHz.

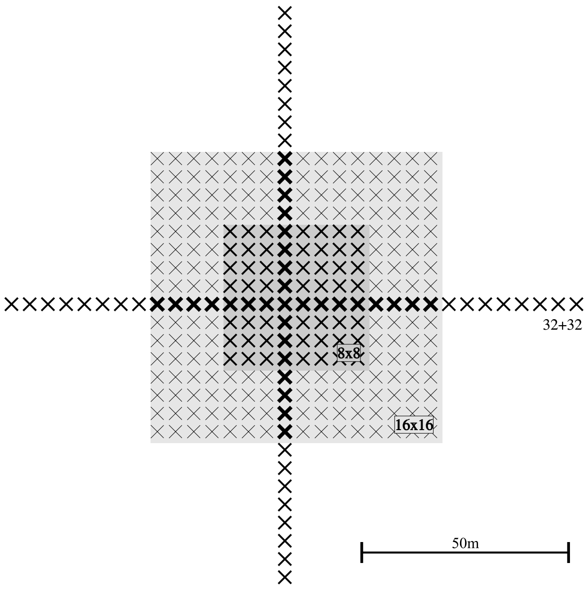

Figure 1: Physical layout of several Mills Cross and filled array antenna configurations

Cross correlation of the two resulting complex signals to find the signal from the area of sky common to both fan beams was carried out digitally. The integrated results of the cross correlation stage were stored for an inital integration time of 0.5s. Higher integration times could then be achieved when needed by means of post-integration.

Experimental results

A sample dataset for October 30th, 2002 can be found in figure 2. The top panel shows widebeam data. The middle two panels show data as recorded by the two fan beams. The bottom panel is the result of cross correlating the signals from the two fan beams to derive the signal common to both fan beams, referred to as pencil beam.

Integration time

One aim of the October 2002 experiment was to find what time resolution could be achieved with the Mills Cross type riometer. Theoretical considerations suggest significantly increased integration times compared to filled array riometers [9], and so do simulations that

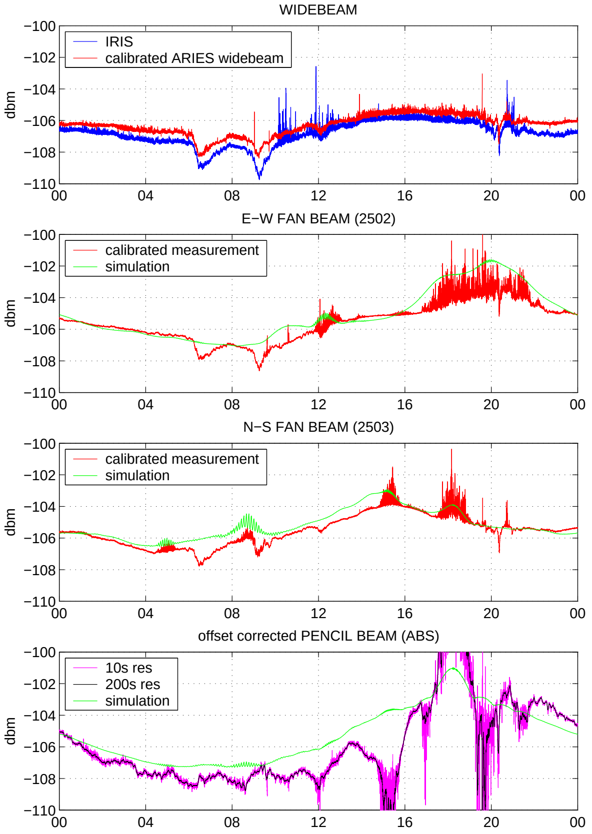

Figure 2: Recorded data for 2002-10-30

were carried out by the author. The October 2002 experiment was used to verify these theoretical predictions for a worst-case scenario. Figure 3 shows the precision that was achieved during the October 2002 experiment for several given integration times and compares these results to the existing IRIS riometer. The top two lines show how integration time relates to noise width for the ARIES worst-case beam for two different days during quiet periods (no scintillation due to radio stars). The bottom three lines show the same relationship for data recorded by IRIS beams looking at approximately the same area of the ionosphere (beams 9 and 10) and for the IRIS zenithal beam (beam 25), again during quiet conditions.

Notice the different slope of the two sets of curves. The reason for this difference in slope is not immediately obvious and has yet to be investigated in detail. The fact remains, however, that whereas resonable results are obtained from the IRIS filled array riometer with integration times of around one second, figure 3 reveals that data from the Mills Cross will have to be integrated for a longer period of time to achieve the same precision.

Phasing issues, comparison to simulation

Due to absence of suitable attenuators, the October 2002 Experiment was carried out with untapered antenna arrays, leading to very high sidelobe levels. On the plus side, the high sidelobes would help to verify the exact beam locations and shapes. Also, strong sidelobes will easily be identified in the resulting data and ways of eliminating their influence can therefore be investigated more easily. In addition, since this was the first experiment of its kind, it seems prudent to start with a system as simple as possible, thus eliminating some potential sources of error from the outset. It turned out that the high sidelobe levels allowed the observation of an effect that would not have been so prominent, had tapered arrays been used.

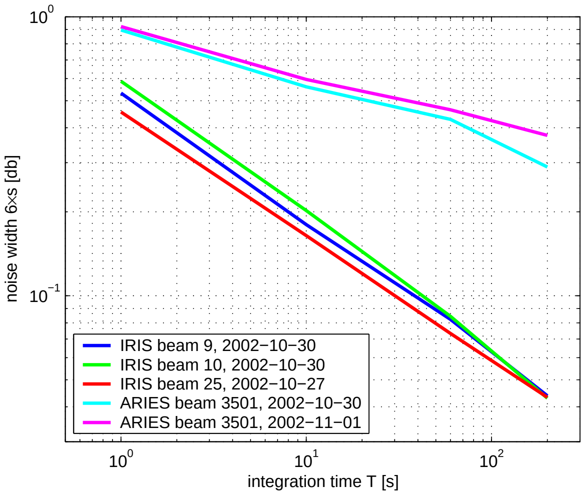

Figure 3: integration time vs. precision for ARIES/IRIS

One simplification that was used during the initial simulation phase of the project was the assumption that the characteristics of the antenna system were fully described by its power response. For existing riometers like IRIS this is certainly sufficient. However, due to the cross correlation process involved in a Mills Cross type riometer (a multiplication process that makes the system nonlinear and causes the principle of reciprocity to no longer apply [8]), such a system is also sensitive to phase differences between the signals to be cross correlated.

The solid black line in figure 4 shows the actual recording from the 16+16 worst case beam, together with the simulated result based on a skymap at 34.5MHz [7] and power radiation patterns. The general trend of the two curves is essentially the same and the predicted times for when the main beam passes through the galactic plane match the readings. This means that our beam is indeed pointing in the direction we expected it to point. In addition to that, we can notice strong alternations in the recordings that do not show up in the simulation. Whilst the general shape suggests influences from the sidelobes, the explanation for the exact shape does not seem that simple. Based on the power pattern simulations we would expect these alternations to look quite differently:

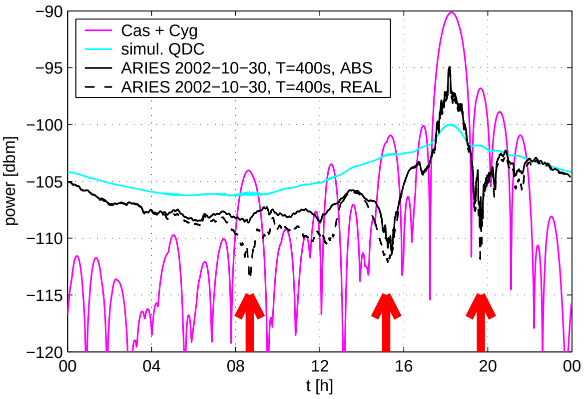

Figure 4: ARIES ‘worst case’ beam for 2002-10-30

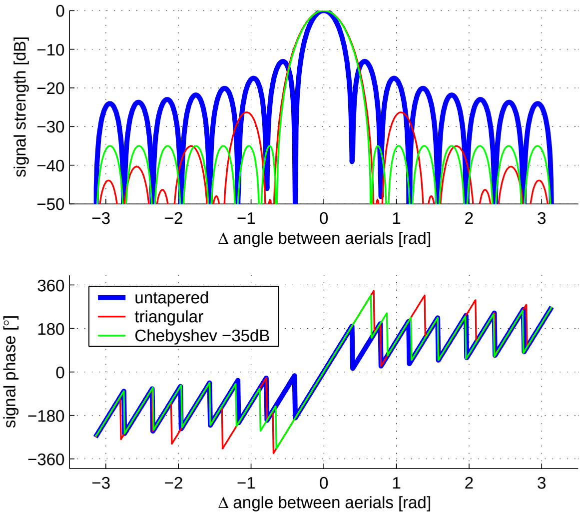

Figure 5: Amplitude and phase response for several tapered linear phased arrays

The red curve in figure in figure 4 shows the predicted combined influence of only the two strongest radio stars, Cassiopeia and Cygnus, on the beam in question. As we can see, we sometimes record minima when based on the power pattern we would really expect maxima, i.e. at times when we expect to see a very strong signal from Cassiopeia/Cygnus due to it being in the centre of some sidelobe, we really observe a considerable *reduction* in received signal. In the dataset in figure 4, this is most prominent for 8:40, 15:10, 19:40 UT (red arrows).

Upon further investigation, the cause of this observation was found to be the aforementioned sensitivity of the cross correlator to phase differences in the input signals that are to be cross correlated. The theoretical amplitude and phase response for a 16 element linear phased array, which is exactly the same as one arm of the Mills Cross antenna array, is plotted in Figure 5 (thick blue line). The top panel shows amplitude sensitivity and the bottom panel phase response.

In Figure 6, the two small panels on the left depict the relevant fan beams that form the recorded pencil beam (right panel) for the day of observation, together with the trace of the two strong radio stars (outer ellipse is Cygnus, inner ellipse is Cassiopeia). From figures 5 and 6 it becomes apparent that not only do we expect to receive a strong signal originating from the radio star whenever it passes through some sidelobe common to both beams, but we also expect a different phase offset between the signal that originates from the radio star and is received by the two beams individually, depending on the current exact position of the star. If we had only one single point source in the sky, this would give us a very accurate means of determining its position, even with relatively broad beams.

It is this phase difference that explains the occurence of minima where we would expect to find maxima. One example is the minimum at around 15:10 UT. At that time we have Cygnus passing through the main lobe of the NS fan beam, and through the second sidelobe of the EW fan beam. Whilst the common cosmic noise background still results in a basic signal level, the reading is much reduced due to the strong *anti*correlation between the signal received from Cygnus by the two fan beams. Similar explanations can be found for other times.

This realisation provoked the implementation of a more detailed simulation package that no longer describes the antennas by their power response, but by two phasors in space quadrature for each direction of interest, thus fully describing the radiation characteristics of any possible antenna [10]. Not only will this enable the simulation of aforementioned phasing issues, it will also enable the study of influences of antenna and signal polarisation on the system performance.

Remedy

As explained in the introductory section, a riometer employs a differential method to determine absorption as the difference between the quiet day power level (quiet day curve, QDC) and the current power reading. This automatically filters out all influences common to both signals which is of great benefit, because in this context the nonuniform cosmic noise background is simply regarded as another unwanted signal and gets filtered out automatically.

Whereas this differential method of determining absorption as the difference between quiet day recording and current recording works very well for filled array riometers, it is clear from the previous discussions that this will not work as expected for the phasing-related effects observed with cross correlating riometers. Scenarios can be imagined where absorption that partly masks, for example, one of the radio stars might actually lead to an *increase* in the recorded signal whereas we would traditionally expect to see a decrease.

Moreover, even though it is possible to predict how the actual reading is influenced by all possible noise sources

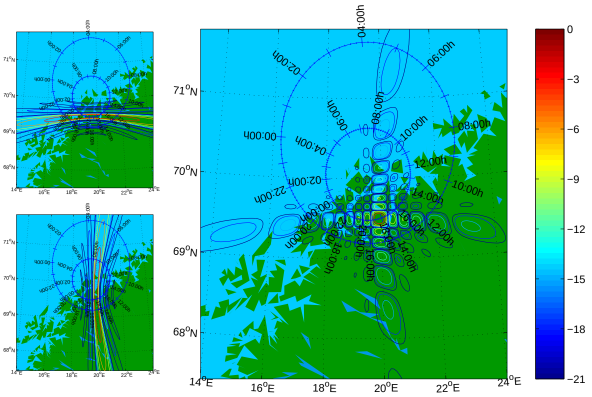

Figure 6: Beam contours for the two fan beams and the resulting pencil beam for 2002-10-30, influence of the radio stars. Colours represent signal power in dB below maximum.

at any given time, it is still not possible to determine where potentially observed deviations from that prediction originate from, i.e. the location and intensity of the absorbing region cannot be identified unambiguously. It can therefore be concluded that in order to attain high quality data, the sidelobes will have to be reduced to a level far below the one that was used during the initial experiment and in fact far below the sidelobe levels that are commonly achieved with today's filled array riometers. Currently, two techniques are primarily being investigated to accomplish this: tapering and adaptive beam steering.

Tapering

Tapering, i.e. attenuating the signals from the individual antenna elements of the phased array according to a given 'windowing function', prior to combining them in the beamformer, can in theory reduce the level of the sidelobes to any extent [4]. Tapering is straightforward to implement, and the exact tapering function can even be modified on-the-fly if a digital beamforming system is used. Apart from triangular tapering which originally promised to enable the 32+32 Mills Cross array to achieve the same results in terms of spatial resolution and sensitivity as a 16×16 filled array, other tapering functions can be used. The goal in this case is to find the optimum solution that sufficiently suppresses the sidelobes while maintaining a main beam narrow enough to achieve the wanted spatial resolution.

The top panel in figure 5 shows two examples of how different tapering functions will affect the radiation pattern of the 16+16 Mills Cross system compared to the untapered array, and these results can be scaled to the final 32+32 array and beyond. The red line depicts triangular tapering as suggested in the initial system design. The green line shows tapering according to a Chebyshev window for -35dB sidelobe suppression. As can be seen, Chebyshev tapering is capable of achieving the same narrow main beam width as linear tapering while suppressing the adjacent sidelobes below the level that can be achieved by triangular tapering. Chebyshev tapering is therefore a candidate for the final Mills Cross system. Note that the flexible FPGA-based design as outlined below will enable on-the-fly switching between tapering functions. Even though it is most likely not a good idea to dynamically adjust the tapering during operation, this can be done during the setup phase to experimentally verify the simulation results and hence choose the most suitable tapering function.

Adaptive beam steering

Beam steering is heavily used in radio and sonar direction finding [15]. In a digital system as outlined below, one is no longer stuck to the n beam directions that are produced by an n-port Butler matrix, instead the beam direction can be changed freely, subject to the capabilites of the respective beamformer. Whereas beam steering is often used for pointing the main beam in the direction of the signal source of interest, in our case this technique can be used to steer the beams so that the positions of strong interfering noise sources (radio stars) coincide with directions of minimum antenna sensitivity (nulls). This enables one to mask at least one strong interfering source and will in turn allow to make slightly higher sidelobe levels acceptable, thus maintaining a narrower main beam. Again, for a completely digital system, it is feasible to track these interfering sources very accurately, and the system can also refine its tracking instantaneously through a closed loop feedback control system.

Of course, flexible beam steering adds considerable complexity to the system. Due to the flexible FPGA-based hardware approach for the final system (outlined below), all the necessary components will be implemented in the FPGA, therefore not adding any further structural complexity to the system in terms of additional hardware.

Another important issue is that, since beam positions will be changing constantly and a given 'beam number' will therefore no longer always refer to the same position in the sky, the so-far commonly used way of describing riometer data in terms of time series for each beam will have to be revised. This will make 2D 'power images' the primary output of such a riometer system, i.e. the underlying beam data will no longer be of direct interest to the user.

Final System design (FPGA)

The structural design of the final 32+32 Mills Cross riometer recording hardware is outlined in figure 7. The system will feature digitally controlled receiver/downconverter stages connected to a

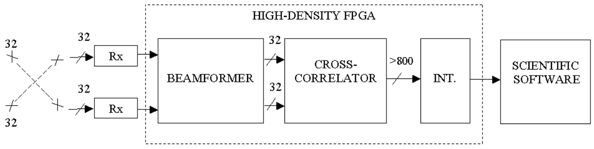

Figure 7: FPGA-based system design

bank of high-resolution A/D converters capable of synchronously sampling all input signals. The option of upgrading to fully digital receivers exists. As opposed to the configuration that was used during the October 2002 experiment, the digitised raw signals are then fed into an FPGA (Field Programmable Gate Array). Tapering, beamforming, cross correlation and integration will take place inside the FPGA. This will result in a low-bandwidth output signal (the integrated time series of the signals from each beam) that can easily be transferred to the control PC through the standard PCI (Peripheral Components Interconnect) interface [2, 16]. The PC will then perform further scientific processing such as image interpolation, quiet day curve generation and absorption computation.

Summary

For the first time, meaningful pencil beams have been obtained from a Mills Cross type riometer system. A Mills Cross antenna array connected to low-noise, high-gain receivers with a wide dynamic range and a fully digital beamformer and cross correlator is capable of achieving the same resolution as a filled phased array antenna whilst requiring a much smaller number of antennas (factor 4 in the case of a 32+32 cross). The experiment showed the need to suppress the sidelobes of such a system to a level even below the one determined by simulations and previous theoretical calculations due to the sensitivity of the Mills Cross to phasing differences in the signals coming from the two arms of the cross. This is achievable with appropriate tapering functions. In addition, adaptive beam steering will be able to mask the influence of the strongest sources of interference, the radio stars. Together with new high-level processing software, a riometer based on the Mills Cross technique will be able to image absorption with sufficient temporal and unprecedented spatial resolution.

Acknowledgements

The authors would like to thank the NCSA Astronomy Digital Image Library (ADIL) for providing the digital version of the sky survey at 34.5 MHz [7].

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