Advanced Rio-Imaging Experiment in Scandinavia (ARIES): System Specification and Scientific Goals

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ABSTRACT

The Advanced Rio-Imaging Experiment in Scandinavia (ARIES) is a new type of imaging riometer (relative ionospheric opacity meter). It represents the first of a new generation of imaging riometers, based upon a Mills Cross system rather than a filled square phased-array. ARIES is located at Ramfjordmoen, near Tromsø, Norway, and is partly adjacent and partly overlapping with the field of view of Imaging Riometer for Ionospheric Studies (IRIS) system in Finland and a new Imaging Riometer to be installed at Alomar. In this paper both the scientific goals and system design of ARIES will be presented.

1. INTRODUCTION

The riometer (relative ionospheric opacity meter) determines the radio-wave absorption in the ionosphere by measuring the received cosmic-noise power. The 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. Thus measurement of absorption is conceptually very simple. The quiet-day curves are normally produced from the measured noise power by a heuristic algorithm. This method has the benefit that the long-term changes in sensitivity due to seasonal and solar-cycle variations in the background D-region absorption are automatically corrected. Absorption images may be produced by utilising a number of spatially-distributed narrow beams.

The imaging riometer is unique in that it provides information on the lowest regions of the ionosphere (D region). This enhances its value when used in conjunction with other instruments, which are more sensitive to higher regions of the ionosphere, since the entire height profile of geophysical events can thus be investigated.

The design of the new Advanced Rio-Imaging Experiment in Scandinavia (ARIES) system differs from all other imaging riometers so far constructed, as it is based upon a Mills Cross Antenna system providing an order of magnitude more beams than existing Imaging Riometer for Ionosphere Studies (IRIS) resulting in a factor of four improvement in spatial resolution, yet still only using the same number of antennas. However, the cross correlation technique employed for producing narrow 'pencil' beams will require the 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 digital signal processing complexity to the system which requires the use of state of the art FPGA technology. 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 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). 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, has been introduced in order to minimise the effects of the sidelobes.

2. THE ARIES SYSTEM

ARIES Beamformer: The crossed dipoles (Fig.1), which are combined with a 90° phase-shift, are arranged in two intersecting rows of 32 antennas. The antenna outputs are fed into 2 banks of Butler matrices, one producing a North-South fan pattern, the other an East-West fan. The outputs of the Butler matrix boards are connected to a total of 64 riometers. Therefore, ARIES has a 2-stage beamforming procedure. Stage 1 uses analogue Butler Matrices (BMs) to produce fan beams followed by Stage 2, when a digital cross-correlator utilises these fan beams to produce pencil beams allowing high resolution images to be formed. This 2nd stage is the most demanding from a signal processing viewpoint.

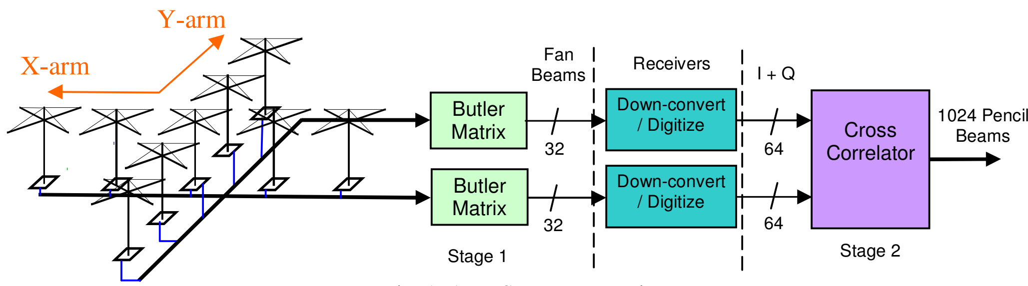

Fig. 1: ARIES system overview

Due to the fact that each antenna arm contains 32 antennas the output of the Butler Matrices are 2 orthogonal sets of 32 fan beams. Cross-correlating these fan beams requires 32 × 32 (1024) complex multiplications per input period. In addition to this, the outputs need to be integrated, which due to the complex nature of the down-converted signals required 2048 integrator operations per input period. The shear number and speed of these multiplications and integrations make the real-time signal processing a very demanding task. Given a sampling rate of 1.5MSPS and 1024 complex multiplication our system is required to be capable of performing 9×10^9 Multiplications/Sec. Additionally another system requirement is the ability to accept a large number of inputs from the 128 ADCs.

A number of possible real-time signal processing platforms exist and were evaluated for this project but ultimately Field Programmable Gate Array (FPGA) devices were selected as the implementation platform. The main justification for using FPGA technology is the fact that the cross-correlation and integration requirements of the system are well suited to a highly parallel implementation for which these programmable logic devices excel.

A suitable FPGA is the Xilinx Virtex-II XC2V8000 with a 146-pin *Mictor* connector. This allows us to easily accommodate the 64 multiplexed I and Q receiver channels from the ADCs and the auxiliary I/O such as the GPS data, pulse per second and noise source control and meet our signal processing requirements.

<u>ARIES Receiver</u>: The purpose of the receiver is to simultaneously digitise the incoming 64 radio frequency channels (centred on 38.2MHz) for digital signal processing in an FPGA.

The simplified block diagram of a single receiver channel is shown in Fig. 2 and the PCB on which two receiver channels are constructed is shown in Fig. 3. The incoming RF signal is down converted to its baseband in-phase (I) and quadrature (Q) components. This architecture was employed in order to retain both the phase and amplitude information of the incoming RF signal, necessary for digital beam forming and other applications. The down converter and baseband stage employ analogue electronics, currently found to be the most cost effective solution for the required number of simultaneously sampled channels. Active filtering, along with close tolerance components, provides excellent phase and amplitude matching between all channels. The I and Q channels are simultaneously digitised using a dual channel, 14-bit resolution, analogue-to-digital converter. Each converter produces a single multiplexed serial data stream; this helps simplify the cabling between the 64-channel receiver and FPGA. Modular construction is used throughout and the 64 receiver channels, along with the local oscillator, A-to-D clock generators, calibration noise source, power supplies and other peripheral electronics, are all housed in a standard 18U 19” sub-rack. The receiver design can easily be adapted for use on different frequency bands and bandwidths.

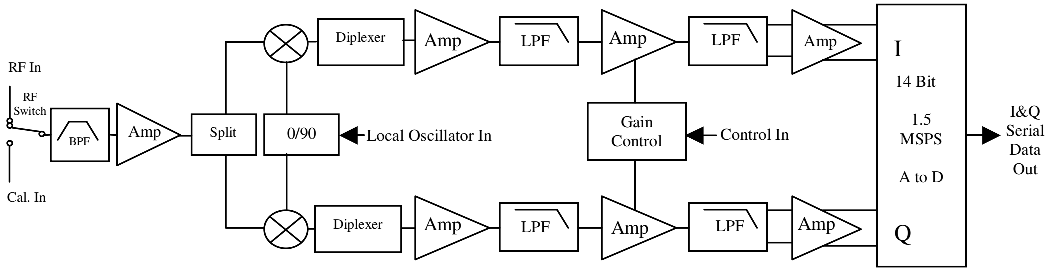

Fig. 2: Simplified block diagram showing a single channel of the 64 channel receiver

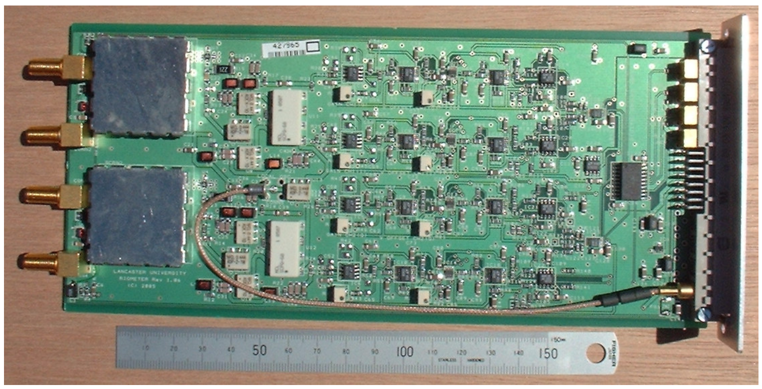

Fig. 3: Receiver PCB – two channels are constructed on a standard 220mm x 100mm Eurocard

3. SCIENTIFIC OBJECTIVES

Modern imaging riometers such as ARIES are not only used for traditional radio absorption measurements, but due to their imaging capability and receiving sensitivity they can be employed for a variety of studies in solar terrestrial physics. A significant part of the energy flow in the solar system is transferred via energetic charged particles. The precipitation of charged particles from the magnetosphere into the ionosphere is an important energy input to the high-latitude ionosphere and mesosphere. Strong precipitation events have been linked to destruction of ozone in the upper stratosphere and mesosphere and affect other chemical reactions, particularly the negative ion chemistry. Satellites can monitor the energy spectrum and pitch angle distribution of energetic electrons in space but their coverage is limited; riometers such as the IRIS and ARIES systems monitor precipitation constantly.

Riometers respond to changes in the electron density across a range of altitudes, mostly in the D-region, though during certain energetic events the measurements come from as low as 30-50 km altitude. Thus riometers are sensitive to the precipitation of high energy electrons (>30 keV) and solar protons (>10 MeV) and to the ionising effects of intense X-rays that accompany solar flares, leading to sudden ionospheric disturbances (SID).

Studies of auroral dynamics are important in understanding the coupling between the solar wind, magnetosphere and the ionosphere. Moreover, knowledge of the energy spectrum of the particles precipitating into the atmosphere is important in understanding the acceleration processes that are occurring in the magnetosphere. The spatial and temporal variations in the energy spectrum are key factors in identifying the magnetospheric acceleration processes. The ARIES system will provide an unique insight into the spatial and temporal morphology of magnetospheric particle acceleration processes within an appreciable region of the auroral zone.

The ARIES facility being located close to EISCAT HF transmitter (Heater) is ideally placed to record heater-induced absorption and scintillation in many beams thus enabling controlled 'laboratory type' aeronomical studies. This provides an excellent opportunity to employ ARIES as a diagnostic for D-region modification experiments.

Therefore, the data from the proposed instrument will provide a unique insight into the coupling between the solar-wind, magnetosphere and the lowest regions in the ionosphere. In addition one of the current significant omissions in the prediction of the performance of a HF communication channel is the ability to accurately predict the received signal strength required to avoid losing a connection. Measurement of D-region absorption is thus critical for producing accurate HF propagation models.

4. SUMMARY

We have addressed some of the technical issues related to sidelobes, and beamforming in a Mills Cross antenna configuration riometer. The most demanding part, from a signal processing viewpoint, is the cross-correlation of the fan beams as this requires 1024 complex multiplications (i.e. 4096 real multiplications) and 2048 integrations per input period. This task is carried out using the parallel processing capability of the FPGA and the implementation described here produces 1024 simultaneous beams with integration times covering more than 99% of a second for all beams. This is a considerable improvement on existing analogue imaging riometers, many of which produce 49 or 64 beams with each beam being integrated for less than 1/8 of a second. This customised beamforming design, operating close to the limit of a single FPGAs capability, was required and resulted in a low cost solution to the ARIES signal processing requirements.

Furthermore, we have detailed a state-of-the-art customised receiver with small form factor and excellent performance. This cost effective receiver is a key part of the design as 64 simultaneously sampled receiver channels are required in order to implement the FPGA beamforming technique employed by ARIES.

ARIES will become fully operational by September 2005 providing an excellent opportunity to study the role of energetic particle precipitation in the Sun-Earth connection. The increased resolution of ARIES will enable auroral structures of the same scale sizes as currently achievable with other types of instruments e.g. EISCAT, and optical imagers to be studied by riometry technique. Hence allowing the high-energy precipitation measured by the Riometer to be compared directly with other auroral processes for the first time. In addition, the ARIES field of view partly overlaps with the field of view of the IRIS system in Finland. This is particularly useful as it will extend the imaging riometer coverage of the auroral oval and also provides the ability to estimate the height of the maximum absorption and a 3D profile of the electron precipitation, by virtue of intersecting beams.