AMISR the advanced modular incoherent scatter radar

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AMISR
The Advanced Modular Incoherent Scatter Radar

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***Abstract*—AMISR is a modular, mobile, UHF radar facility used by scientists and students from around the world to conduct studies of the upper atmosphere and to observe space weather events. SRI International, under a grant from the National Science Foundation, is leading the collaborative effort in the development and operation of AMISR. The novel modular configuration allows for relocating the radar to study upper atmospheric activity at different locations around the globe. Remote operation and electronic beam steering allow researchers to operate and position the radar beam on a pulse-to-pulse basis to accurately measure and glean new information from rapidly changing space weather events.**

I. Introduction

The scientific capabilities of an incoherent-scatter radar (ISR) result from a combination of its sensitivity, operational flexibility, spatial coverage and the geophysical environment in which it is deployed. The U.S. National Science Foundation's Upper Atmospheric Facilities program supports a chain of ISR facilities, spanning the globe from near the equator at Jicamarca, Peru, to the polar cap at Resolute Bay, Canada. The existing ISR facilities are technically very different from each other, having been designed at different periods of time and evolved to exploit specific characteristics of the geophysical environment within which they operate. The AMISR systems are the latest generation of radars in the program, and designed to be flexible, reliable, remotely operated and relocatable. These features allow AMISR to adapt to a wide variety of locations to best fit the needs of new geophysical conditions and to probe a variety of plasma environments.

II. System Description

An AMISR radar consists of a main phased array face along with the associated power management systems and the operations control center. Figure 1 shows one of the faces deployed at Resolute Bay, Canada.

The basic element of an AMISR system is the radar front-end Tx/Rx module, called an Antenna Element Unit (AEU), all components of which were designed and manufactured by SRI International. The AEU includes a 500-Watt solid state power amplifier (SSPA) and a cross-dipole antenna. The design of the AEU is conducive to plug-and-play upgrades, allowing for improved SSPA designs that takes advantage of technology improvements. Each AEU consists of low-level RF circuitry for phase control on transmit and receive, a low noise amplifier that sets the overall system receive sensitivity, the SSPA, a power supply and digital control and communications electronics.

Fig. 1. The northern AMISR face (RISR-N) at Resolute Bay, Canada.

The AEUs are arranged into groups of 32 onto an aluminum frame structure referred to as a panel. Each panel also contains a panel control unit (PCU) holding a single board computer running an embedded version of Linux. The PCU monitors the state of each AEU in real-time, recording the voltage, current, temperature, humidity and measurements of the forward and reflected power levels.

A panel serves as the fundamental building block from which a radar face is composed. A standard AMISR face contains 128 identical panels, arranged in a $\sim$30x30 meter roughly square configuration on a steel superstructure. That organization yields a total of 4096 AEUs, each transmitting at 500W, producing a total peak transmit power of approximately 2MW. The pulsed SSPAs are capable of transmitting a pulse length of up to 2 ms with a 10% duty cycle and operate in a frequency range of 430 to 450 MHz. A variety of different phase coding schemes can be applied to the pulse. The system specifications are listed in Table I.

The electronically formed beam has a narrowest 1.1 degree beam width (FWHM) and can be steered on a pulse-by-pulse basis to over 10,000 preset locations within the $\pm 25 - 35°$ field-of-view from boresight. The phasing is done via a physical path time delay board located within each AEU. The weights for each steering direction are preprogrammed and loaded on demand into the delay shifters at the start of each transmit pulse. The received RF signal is sampled by an array of digital receivers called RADACs. A master RADAC also generates the overall system timing and RF transmit pulse. The RF signals

TABLE I. AMISR SPECIFICATIONS

Transmit frequency range	430–450 MHz
Receive frequency range	418–464 MHz
Transmit power	2 MW (peak)
Transmit duty cycle	$\leq$10%
Transmit pulse length	1μs–2ms
Phase shift	6-bits, 5.625° LSB
System noise	1dB, nominal
T/R switching time	0.6μs
Inter-pulse period	1ms–20ms
Antenna elements	4096 (full face)
Beam width (FWHM)	1.1° (minimum)
Gain	+43 dBi
Beam positions	10,000
Grating-lobe-free steering range	$\sim \pm 25 - 35^\circ$
Beam switching speed	$\geq$1ms (A new position is loaded at each IPP)
Calibration	Noise Injection, Coherent Cal Pulse

are distributed to the AEUs using a corporate feed network on the face and the timing signals pass through a set of fiber optic cables.

A set of near-field sources and an RF propagation model are used to phase calibrate the system. The calibration is verified by listening to radio stars and other noise sources. During normal operations, a calibration signal is injected to measure the system noise. In addition, a telemetry stream is captured from each AEU consisting of measurements of voltage, current, temperature and estimates of forward and reflected power. These are stored for long term monitoring of the system health.

The AMISR concept entails the use of a large number of identical electronic subsystems, yielding a high degree of redundancy and a robust response to hardware failures. The systems as a whole have proved to be exceptionally reliable, as evidenced by the Poker Flat AMISR system operating 90-95% of the time over the past six years. Individual components have experienced the anticipated rate of failures. In a practical sense, this means that while failures do occur in the complex electronics, they can often be addressed during planned maintenance. This is in stark contrast to the situation at most other ISRs, where the failure of a single component must be addressed immediately before operations can resume. This redundancy is largely responsible for AMISRs amenability to unattended remote operations. We are not aware of any systems with similar capabilities that can be operated with so little on-site staffing.

The overall control of the system is driven from an Operations Control Center (OCC) that houses general-purpose computers as well as low-level RF signal conditioning modules that comprise the AMISR Control System (ACS). Physically, the OCC is an environmentally controlled shelter or building available for operator interaction with the system, though most interactions occur over the local area network whether the operator is in the OCC or not. The OCC also houses all of the data acquisition channels, and contains the source for the transmitted waveforms and RF receive signals from 16 equally sized portions of the array.

The prime power for the radar is routed through two Utility Distribution Unit (UDU) vans. The radar runs off of aircraft-standard 400 Hz power, which is generated by FMC JetPower units, one for every 16 AMISR panels, and up to 4 units in an UDU van. The 400 Hz power standard was chosen because the weight reduction in the cable and power supply magnetics across the face.

The flexibility of the AMISR systems opens a number of important possibilities for future expansion. An area that is especially ripe for improvement is spatial interferometry and post-experiment beamforming. Several initial interferometry experiments, mainly targeting meteor head echoes, have been performed but much more detailed imaging would be possible with some relatively modest improvements. This enhanced capability would be immediately applicable to research areas such as meteor head echo trajectory determination, naturally enhanced ion acoustic line characterization, and polar mesospheric summer echo spatial studies.

III. DEPLOYMENTS

AMISR consists of three separate radar faces, currently deployed at locations throughout the Arctic. The first face was installed at the Poker Flat Research Range near Fairbanks, Alaska, in 2006. The following two faces have been installed in Resolute Bay in the province of Nunavut, Canada in 2008. The system design allows for efficient dis-assembly, shipping, and re-assembly at a new location. Future AMISR locations are determined by a scientific advisory panel. Since each face of AMISR functions independently, AMISR can be deployed in multiple locations at the same time.

The Poker Flat Research Range is operated by the Geophysical Institute of the University of Alaska, Fairbanks, and hosts both launch facilities for scientific sounding rocket launches as well as a large cluster of scientific instruments to study the auroral and polar middle- and upper-atmosphere. The AMISR at Poker Flat (PFISR), shown in Figure 2, is located on a gravel pad near the launch pads. The antenna bore sight is tilted to the north, at an angle of 16° from the zenith and an azimuth of 15° geographic. The radar orientation was chosen to optimally support rocket experiments at Poker Flat while maintaining the ability to probe the ionosphere near the magnetic zenith.

PFISR finished engineering tests in December 2006, after which it began routine operations and became available for specific user-requested measurements by the scientific community. PFISR supported six sounding rocket campaigns during the winters of 2007 and 2009. Additionally, PFISR has been operating in a low-duty cycle mode whenever it is not running other experiments. This 24/7 coverage that began in support of the International Polar Years (2007–2008) continues and has provided a wealth of data to the ionospheric modeling community.

The second and third AMISR faces are installed at Resolute Bay, Canada. Located in the Territory of Nunavut on the south of Cornwallis Island at almost 75° geographic latitude, Resolute Bay is the gateway to the Canadian High Arctic. The location enables measurements in the region where coupling occurs between the solar wind and Earth's magnetosphere, ionosphere, and thermosphere. The first face (RISR-N) at Resolute was installed in 2008 and points north, deep into

Fig. 2. PFISR, the AMISR face at Poker Flat, Alaska.

the polar cap and near the magnetic pole. RISR-N completed tests in April 2009 and became operational in July 2009.

The second radar at Resolute Bay (RISR-C) was installed in 2011 by the University of Calgary and points southward. The two AMISR faces provide routine measurements of polar cap electrodynamics, generating the data needed to understand the coupling and its global effects. The chosen orientations of the antennas maximize the F-region convection coverage and extend the measurement latitudinal capability by using the other existing high-latitude ISR facilities. Figure 3 shows the coverage of RISR-N, RISR-C, PFISR, along with the ISRs at Sondrestrom, the European Incoherent Scatter radars (EISCAT), the EISCAT Svalbard Radar (ESR), and Millstone Hill, all at 400 km altitude. These RISR antenna orientations provide excellent polar cap convection coverage, especially considering the combination of the EISCAT, ESR, and Sondrestrom radars.

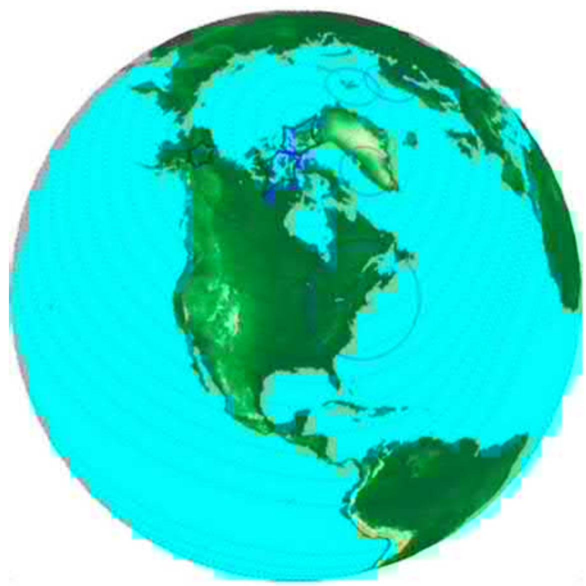

Fig. 3. Illustration of the antenna coverage at 400 km for the AMISR radars at Poker Flat and Resolute Bay. The circular patterns are the existing dish antennas ISR systems at Millstone Hill, Sondrestrom and EISCAT.

IV. Remote Operations

AMISR is designed to be remotely operated and runs autonomously for a majority of the time. The system software is based around a modular framework called the Data Transport Network. It orchestrates the large number of programs that are responsible for communicating with the various hardware subsystems, health and status monitoring, data collection, and experiment scheduling. A set of web-based displays allow for monitoring of the system performance and real-time data products. The autonomous operations are based on a set of prioritized schedules. Science experiments are scheduled on ahead of time on a monthly basis.

When discussing AMISR operations, there is very little distinction between running the system locally or remotely. In a sense, the system is always remotely operated, even when operators are on-site. The interfaces for the main system programs are web browser-based. This implementation allows for any number of authenticated users to access the applications simultaneously from multiple locations around the world.

A. Network Topology

Figure 1 shows the basic network layout for an AMISR site. Three separate internal networks reside behind a firewall server. Our external network presence is limited to a single IP address presented by the firewall. Access to the private internal networks is controlled by the firewall server. In general, the only network service exposed at this point is secure shell (SSH). Users are authenticated onto the internal networks using

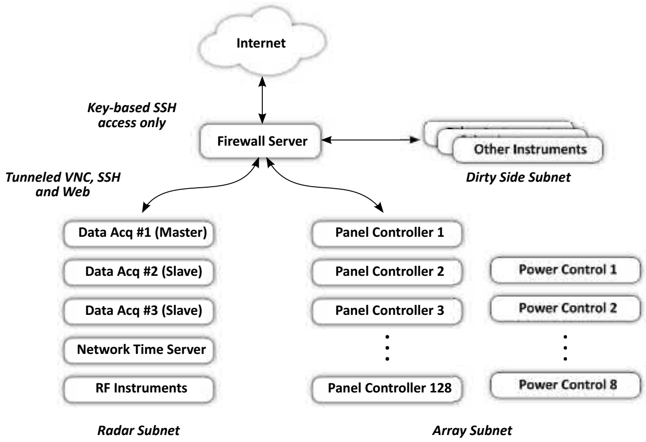

Fig. 4. AMISR system network topology.

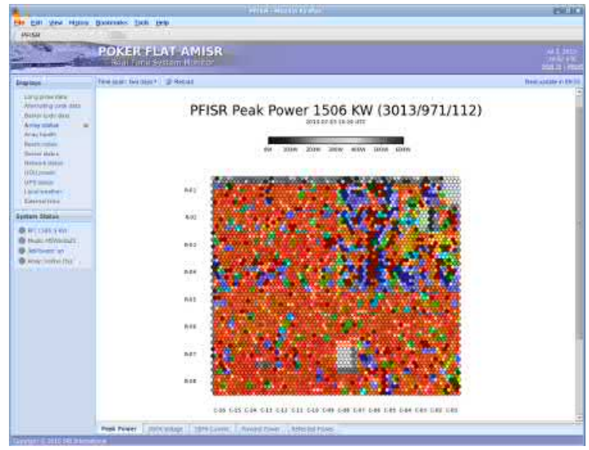

Fig. 5. Example of the health status monitoring web displays.

public keys (password authentication is disabled to prevent brute-force cracking attempts).

The main site server runs an enterprise-grade version of Linux, and in addition to the firewall, provides local services to the internal networks such as DNS, DHCP and file sharing.

The radar operations are conceptually divided into two groups. One controls the timing and data acquisition, the other is used to control and monitor the phased array. These are represented in the figure as the radar and array subnets.

The first operation group consists of the data acquisition computers and assorted RF instruments such as up and down converters, which reside on the radar subnet. The data acquisition computers each contain a RADAC digital receiver and timing board. The master data acquisition computer produces the fundamental timing pulses. These signals include the beam steering direction, transmit pulse window and the receive period. The timing signals are distributed to the array over a separate set of fiber cables.

The second major subnet in the system involves the computers that control and monitor the phased array. Each panel, holding 32 antenna transmit units, has an embedded Linux system for control and health monitoring. The panels are powered from a set of 400Hz JetPower frequency converters. The JetPowers, as well as power to any given panel, can be controlled through the Power Monitor and Control Units (PMCU).

The majority of the computers and racks in the system can have their power cycled through a series of network power switches. The interfaces for these units are available from the server and help tremendously in resolving abnormal situations.

The third subnet, referred to as the dirty side, is where non-radar related client computers and other instrumentation at the site reside. It is firewalled from the other subnets to prevent unauthorized access.

B. Software Services

The system software, running both on the server as well as the data acquisition computers, is designed around a client-server model. The core functionality is implemented in a set of long-running background processes. Each process presents a network accessible application programming interface (API) from which client programs can be built for control and display. One such client is a web-based interface for showing the current state of the digital receivers, modes and data collection. The main server also utilizes these APIs for remotely scripting operations.

To run an experiment on AMISR, an experiment description file is selected using the control service running on the master data acquisition computer. These experiment descriptions specify items such as the pulse coding schemes, antenna beam directions, pulse repetition interval, receive windows, and the frequencies for the up converters and down converters. A catalog of these experiment files resides on the master data acquisition computer. The control API allows the querying the catalog, starting or stopping an experiment, and determining the current status. A command API runs on each of the data computers, which the master uses to control their functions during an experiment. The RF instrumentation, which includes RF up and down converters as well as signal routing for calibration, has a similar command API that can be accessed from a set of network services exported by the server.

Each of the embedded panel control computers (128 in a fully built out face) have a network API that allows for individual AEUs to be enabled, queried for telemetry such as temperature, voltages and current draw from the amplifiers.

The firewall server presents software services for controlling the power state of the array and overall site status monitoring. Starting the array involves powering on the JetPower units, followed by the panel control computers and finally each antenna element unit. Each minute, the health and status of the array is sampled, down to the individual antenna level. These data are archived, monitored for fault conditions and presented via a series of real-time web displays. An example display illustrating the transmit power of each AEU is shown in Figure 5.

C. Operations

Operating AMISR can either be done manually or automatically. When designing new experiment modes, performing troubleshooting or running special experiments, the system can

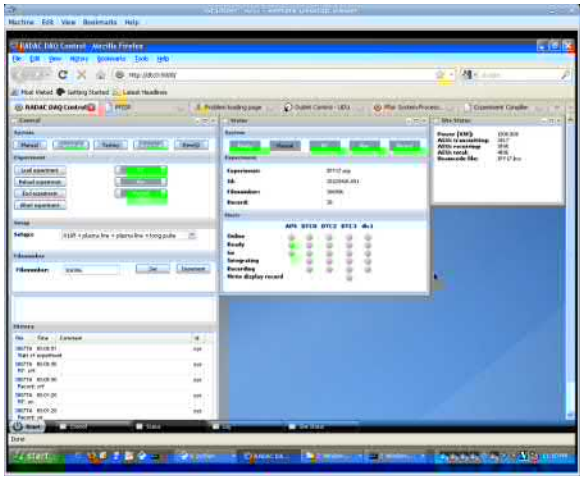

Fig. 6. Web-based interface for the master data acquisition computer.

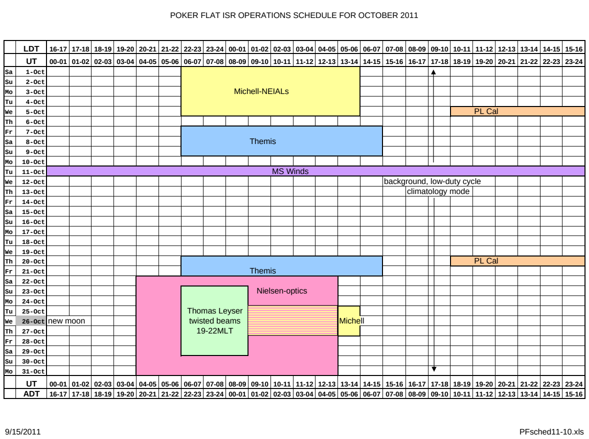

Fig. 7. Sample schedule showing multiple experiments at PFISR. During the periods when there is no scheduled experiment, the radar operates in a low-duty cycle patrol mode to continuously gather basic observations of the ionosphere.

be manually operated from the web interface for the master data acquisition computer, shown in Figure 6. Remote users can access the web interface if they are authenticated onto the server via an SSH tunnel.

The majority of the time, AMISR operates in an automated fashion. The experiments are scheduled on a monthly basis. Scheduling files describing which experiment to run and at what times are uploaded to the server's calendar service. Multiple overlapping schedules can exist and they are sorted based on a priority scheme. This stacking method lets us easily accommodate quick mode changes for satellite overpass tracking or slotting in a special experiment based on geophysical conditions. The server evaluates the schedules each minute and reconciles the system state match the desired mode. This reconciliation might involve turning on the array or communicating with the master data acquisition computer to switch the active experiment. If a user is manually running the system, the scheduler is paused. As soon as manual mode is released, the scheduler resumes and reconciles the system with the desired mode of operation. An example of a monthly schedule is shown in Figure 7.

V. Science Highlights

The system is routinely operated to probe geophysical targets from the troposphere to the upper thermosphere and ionosphere (ground to 1000 km altitude). These targets include atmospheric reflections in the troposphere and stratosphere, meteor head echoes in the mesosphere and lower thermosphere, coherent structures that occur both naturally and artificially in the ionospheric plasma, and most commonly and importantly ionospheric thermal backscatter (Thomson scatter) known as incoherent scatter. Incoherent scattering is the most comprehensive ground-based ionospheric diagnostic mechanism in existence, giving information on the electron density and ion concentrations, thermal structure (electron and ion temperature), motion (due to neutral winds and electric fields), and collisional properties of the medium. Because ionospheric backscatter correlation times (spectral widths) and ionospheric scale heights vary drastically depending on the altitude region being probed, a variety of pulse-coding methods are used depending on scientific goals. These may include (a) very high range resolution (up to hundreds of meter) probing of structures in the mesosphere and lower thermosphere making use of short, coherently phase-coded pulses to form pulse-to-pulse spectral products, (b) phase-coded pulses that make use of the random nature of incoherent backscatter (in particular, clutter from unwanted ranges) to make high resolution measurements of inter-pulse autocorrelation functions, and (c) long uncoded pulses designed to maximize sensitivity in low signal-to-noise ratio environments typically present at high ranges. The system can be flexibly programmed to alternate transmit frequencies within pulses or on a pulse-to-pulse basis to achieve maximum duty cycle while mitigating range and frequency aliasing issues.

Scientifically, AMISR systems have shed light on and led to breakthroughs in ionospheric and atmospheric research. PFISR, situated in the auroral zone, has imaged auroral structuring in the ionosphere, leading to new insights on the causal mechanisms behind auroral storms. The unattended and remote operations capability of PFISR has led to a nearly continuous data set of ionospheric conditions that have led to breakthroughs in understanding the sources of ionospheric variability and space weather events, which often originate deep in the lower atmosphere or within the solar corona, solar wind, and magnetosphere.

VI. Conclusion

AMISR makes strategic use of new technologies and innovative remote sensing capabilities that redefines the traditional approach to experimental solar-terrestrial physics. It provides scientists with a powerful new tool that can be easily positioned at the most beneficial spots on the globe for ground-based solar-terrestrial research.

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