emission of 427.8-nm auroral light at either South Pole Station or P2 in this event is consistent with these estimates of absorption height.

The analysis presented here and in Doolittle and Mende (*Antarctic Journal*, in this issue) of a Sun-aligned arc observed at two locations using different imaging techniques offers a glimpse of how the data from multiple, spaced instruments in the AGO/manned station framework will help to clarify the interpretation of polar upper atmosphere phenomena.

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The 16-beam phased-array radiowave imager for studies of cosmic noise absorption at U.S. AGO sites

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A significant improvement in the riometer technique for examining cosmic noise absorption was made with the installation of a 49-beam phased array riometer system at South Pole Station, Antarctica (invariant latitude –74°) in January 1988 (Detrick and Rosenberg 1988, 1990). Since this initial deployment, the University of Maryland has installed identical 49-beam systems at Sondre Stromfjord, Greenland (geographic 67°N 306.28°E, invariant latitude +74°), and Iqaluit, Northwest Territories, Canada (geographic 67°N 306.28°E, invariant latitude +74°). The use of antenna arrays producing multiple narrow beams is necessary to examine the spatial scale of regions of energetic electron precipitation that are coincident with cosmic radio noise absorption activity and to resolve time development from spatial motion.

This 64-element, phased-array system, however, requires considerable effort in the field installation and a large recorded data capacity—on the order of 1 megabyte per day. When the spatial and time resolutions can be compromised, a smaller array makes the construction and installation of the system much easier and imposes less burden on the data-acquisition facilities. We will discuss some of the general features of a 16-beam imaging riometer that differ from those of the larger system. Primary design constraints included the requirement for rapid and simple field installation, as well as low-power operation and low data-sampling rate.

Design features of the 16-beam IRIS (imaging riometer for ionospheric studies) system are shown in table 1. This system is used in conjunction with the network of automatic geophysical observatories (AGOs), which are being installed on the antarctic plateau (Rosenberg and Doolittle, *Antarctic Journal*, in this issue). The operating frequency and physical details of the antenna design are the same as the 64-element phased array. Like the 49-beam IRIS, the 16-beam system uses the Butler matrix for beamforming. As described by Detrick and Rosenberg (1990), the 49-beam phasing matrix produces beaming in two dimensions by physically orienting

Table 1. 16-beam PENGUIN IRIS features

- 38.2-megahertz operating frequency
- 16-antenna phased array
- Circularly polarized dipole (turnstile)
- 16-beam Butler matrix phasing
- 27-degree full –3-decibel beamwidth
- 200-square-kilometer ionospheric viewing area
- 45-kilometer beam projection dimension
- 12-second image scan, all 16 beams
- Dual riometers

perpendicular arrays of Butler matrices. The 16-beam system accomplishes the orthogonal connections between the matrices on a flat surface, since many fewer electrical paths exist between the matrices. As shown schematically in figure 1, the complete phasing matrix comprises eight identical 4-port Butler matrices. All eight matrices are contained on a single (multilayer) circuit board. Four of the matrices are used to connect the 16 antennas to the circuit; these are labeled "input ports" in figure 1. The same output port number from each of these four matrices is input to another 4-port matrix to provide the steering-phase increments in the perpendicular direction for that set of ports; for example, the left-most ports from all the matrices in the top row in figure 1 feed into the same matrix in the lower row. Successive sets of the remaining output ports from the antenna matrices provide the inputs for the other three 4-port matrices. The 16 final output ports are switched one at a time into one of two riometers; the switching is performed so that each riometer samples all the output ports, but one riometer samples the outputs eight ports ahead of the other. The switching is made every 750 milliseconds (msec), so all the ports are sampled by each riometer in 12 seconds. The sampling of the outputs by one riometer ahead of the other results in a complete scan of the radio sky by the pair of riometers at a 6-second rate, instead of 12. The Butler matrix is constructed on a 7-layer printed circuit board, using stripline circuitry for the traces interconnecting the hybrid components and measured lengths of microstrip transmission line for the 45-degree phase shifts (represented as circles in figure 1). Special care in the design ensures that no phase error is introduced through the stripline circuitry: the interconnection line lengths are matched at critical points in the matrix. The total signal loss through the matrix is less than about 2.5 decibels (dB). The use of circuit board stripline for the phasing elements of the matrix results in a system that requires no calibration or adjustments.

The calculation of the antenna directivity, or voltage reception pattern, for an array of antenna elements is a straightforward superposition of the field amplitudes in the radiation zone. The calculation of the directivity of the IRIS phased-array antenna is described by Detrick and Rosenberg (1990). The phasing increments formed in a Butler matrix are multiples of $2\pi/N$, where N is the number of input ports; for the 4-port Butler matrix, the steering-phase increment numbers [ß$_i$ in equation 3 of Detrick and Rosenberg (1990) are then $-\frac{3}{4}$, $-\frac{1}{4}$, $\frac{1}{4}$, and $\frac{3}{4}$].

The directivity patterns corresponding to the four output ports of one 4-port Butler matrix are distributed symmetrically about the zenith, with approximately 30° separation between beam peaks and beamwidth on the order of 27°. The largest sidelobe is about 11 dB below the peak of the zenithal beam; the sidelobe azimuthal beamwidth is approximately equal to that of the main beam but only about half that in zenith angle. The attenuation of the beam peaks away from zenith is due to the directivity pattern of the horizontal turnstile antenna. The ionospheric projection of the –3-dB locus of all 16 beams from the 2-dimensional Butler matrix array, to 90 kilometers altitude, is shown in figure 2. The dashed circle in the center of the pattern is the projected beam pattern of a broadbeam antenna. This projection takes into account the curvature of the ionosphere. The angular width of all the beams is nearly the same, although some widening

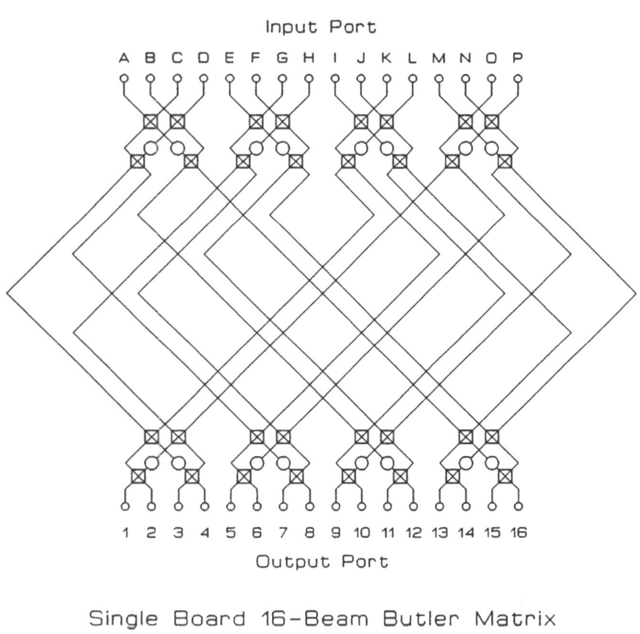

Figure 1. Schematic diagram of the eight 4-port Butler matrices that form the phasing system for the 16-beam imaging riometer. The antenna connect to the input ports, and the output ports are switched into the dual riometers. The square components represent quadrature hybrid couplers, and the larger cycles represent 45° phase shifters.

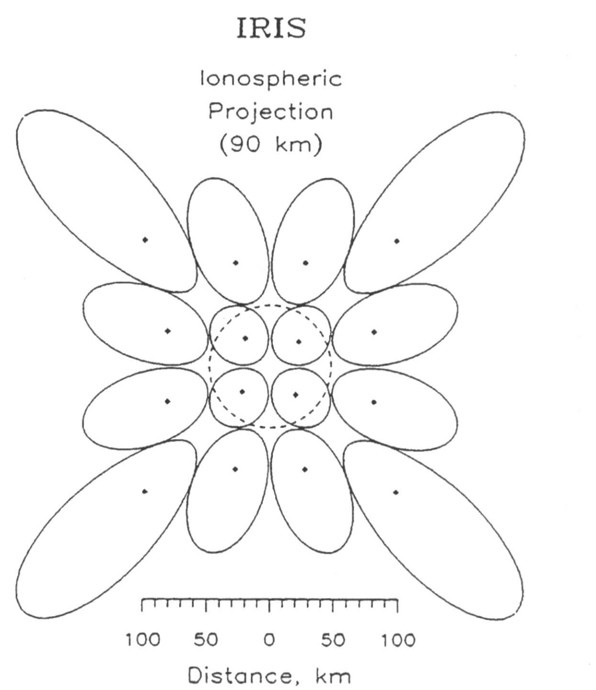

Figure 2. The projection of the –3-dB contours of the 16 IRIS beams onto the ionosphere at 90 kilometers altitude. The dashed circle in the center of the image represents the viewing area of a conventional broadbeam antenna. (km denotes kilometers.)

away from the zenith occurs; the ionospheric length of the projection is dependent on the zenith angle of the beam, as described in Detrick and Rosenberg (1990, equation 4).

The receiver's integration time constant is 20 msec; after a 100-msec delay for settling, the signal is integrated for 550 msec. The receiver intermediate frequency bandwidth of 200 kilohertz (KHz) then limits the sensitivity of the IRIS riometer to approximately 0.02 dB. The 12-bit analog-to-digital-converter (ADC) produces 24 bytes of storage for one complete scan of the 16 beams for each riometer. Including both the riometer data and four housekeeping samples, data are recorded at a 5-Hz rate, so that 432,000 bytes of mass storage are required per day; the capacity required for 1 year is about 158 megabytes.

The power requirements for the antenna/phasing system are minimal. The designed total electrical power budget for the system is shown in table 2. In operation, the system typically consumes about 4.8 watts, with occasional increases to 6.7 watts when the internal heaters activate to bring the interior temperature to the designed operating temperature of −10°C.

The initial results from the first AGO deployment are shown in an accompanying paper (Detrick and Rosenberg, *Antarctic Journal,* in this issue).

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Table 2. 16-Beam PENGUIN IRIS power budget

Component	Quantity	Voltage	Current (each)	Power
Riometers	2	12 volts	80 milliamperes	2.0
PIN diodes[a]	16 (on)	5 volts, −12 volts	3 milliamperes (on)	0.25
Altera EPLD[b]	1	5 volts	50 milliamperes	0.25
Microcontroller	1	5 volts	100 milliamperes	0.5
			Total electrical power:	3.0
			DC-DC converter loss @ 76% efficiency:	1.0
			Supplementary heaters:	3.0
			Total power consumption:	7.0 watts

[a]PIN denotes a special type of diode.
[b]EPLD denotes erasable programmable logic device, manufactured by Altera corporation.

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Initial results from the PENGUIN imaging riometer at AGO-P2

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PENGUIN (the polar experiment network for geophysical upper-atmosphere investigations) represents the science programs associated with the automatic geophysical observatories (AGOs) deployed on the antarctic plateau by the Lockheed Palo Alto Research Laboratory for the National Science Foundation (Rosenberg and Doolittle, *Antarctic Journal of the U.S.*, in this issue). The first AGO was installed in December 1992 at geographic (invariant geomagnetic) coordinates 85.7°S 46.4°W (70.0°S 18.6°E, McIlwain L-value approximately 8.5); this site, which has been designated P2, was the first of six planned AGO installations to be deployed.

The PENGUIN program studies the upper atmosphere using a variety of instruments that provide information for the analysis and interpretation of phenomena that affect the Earth's near-space environment. The PENGUIN upper atmosphere observatory includes a 3-axis search-coil magnetometer (Tohoko University of Sendai, Japan), a 3-axis fluxgate magnetometer (AT&T Bell Laboratories), a very-low-frequency (VLF) radiowave receiver (Stanford University), a low-frequency to high-frequency (LF-HF) radiowave scanner (Dartmouth College), a 630/427.8-nanometer (nm) dual-channel all-sky-camera (Lockheed), and a 16-beam imaging riometer (University of Maryland).

The riometer (relative ionospheric opacity meter) is an instrument that measures the opacity of the Earth's atmosphere to cosmic radio noise, which is used as a constant background against which small changes in the electron density of the ionosphere can be examined. The ionospheric plasma