Radio Science, Volume 35, Number 5, Pages 1143–1153, September–October 2000

The effect of snow accumulation on imaging riometer performance

Mike C. Rose, Martin J. Jarvis, Mark A. Clilverd, and David J. Maxfield
Physical Sciences Division, British Antarctic Survey, Cambridge, England

Theodore J. Rosenberg
Institute for Physical Science and Technology, University of Maryland, College Park

Abstract. In January 1998 an imaging riometer system was deployed at Halley, Antarctica (76°S, 27°W), involving the construction of an array of 64 crossed-dipole antennas and a ground plane. Weather conditions at Halley mean that such an array will rapidly bury beneath the snow, so the system was tuned to operate efficiently when buried. Theoretical calculations indicate that because the distance between the ground plane and the array was scaled to be $1/4\lambda$ in the snow, as snow fills the gap the signal will increase by 0.6–2.5 dB. Similarly, the short antennas are resonant when operated in snow, not in air. Theoretical calculations show that the largest effect of this is the mismatch of their feed point impedance to the receiver network. As the signal for each riometer beam is composed of a contribution from all 64 antennas, for each antenna that buries the signal level will increase by 1/64 of ~9 dB. The measured response of the system to burial showed significant changes as snow accumulated in and over the array during 1998. The changes are consistent with the magnitude of the effects predicted by the theoretical calculations. The Halley imaging riometer system, having now been buried completely, is operating more efficiently than if a standard air-tuned configuration had been deployed. The results are of considerable relevance to the ever-increasing community of imaging riometer users regarding both deployment and the subsequent interpretation of scientific data. Some systems will experience similar permanent burial, while others will be subject to significant annual variability as a result of becoming snow-covered during winter and clear during summer.

1. Introduction

The riometer (relative ionospheric opacity meter) is conceptually one of the simplest instruments for observing the ionosphere. Developed from radio astronomy techniques, the riometer [*Little and Leinbach*, 1959] utilizes the absorption of incoming cosmic noise by the D region of the ionosphere as a way of measuring electron concentration variations in that region of the atmosphere. The basic design of the riometer has changed little over the years. It consists of a radio receiver operating well above the maximum plasma frequency of the ionospheric F region. A typical operating frequency is 30 MHz, and the antenna is usually of a simple broad-beam design (e.g., a Yagi). The current through a local noise source is continuously adjusted so that the noise power output matches the radio noise level received by the receiver from space. The current through the noise source is recorded for later analysis. It exhibits both a sidereal variation due to the antenna scanning the cosmos as the Earth rotates and variations on timescales ranging from seconds to seasons due to varying electron concentrations, and hence absorption levels, in the ionosphere. The sidereal variation is referred to as the quiet-day curve (QDC), and the instantaneous ionospheric absorption in decibels is derived from the ratio of the prevailing signal level to this curve [e.g., *Krishnaswamy et al.*, 1985].

Compared, for example, with absorption measurements using vertical radio sounding [e.g., *Mitra*, 1970],

Paper number 2000RS002314.
0048-6604/00/2000RS002314$11.00

the riometer has a high time resolution (typically 0.25 s) but a low sensitivity. This makes it ideal for the study of the intense and rapidly varying absorption which is induced primarily by high-energy electron precipitation in the auroral regions, and it is on this area of research that the majority of these instruments have been focused. Networks of riometers in the polar regions have enabled the general morphology of the auroral substorm to be defined [*Berkey et al.*, 1974], and multiple wide-beam riometers at single sites have enabled the motion of individual absorption features to be determined [e.g., *Ecklund and Hargreaves*, 1968].

More recently, the scientific community has turned its attention toward the smaller-scale structure and dynamics of absorption events, and this has resulted in a number of "imaging riometer" systems in the northern and southern polar regions [*Detrick and Rosenberg*, 1990; *Stauning*, 1996; *Browne et al.*, 1995]. These imaging riometers typically use a number of individual receivers multiplexed through a phased array of antennas to provide steerable narrow-beam scanning of the *D* region. At Halley (76°S, 27°W), Antarctica, an array of four wide-beam riometers, in the cardinal directions and each directed at 45° to the vertical, have been in operation for several years [*Hargreaves and Jarvis*, 1986]. In 1998 an imaging riometer system operating at a frequency of 38.2 MHz was deployed at Halley alongside this wide-beam array, necessitating the construction of an array of 64 crossed-dipole antennas and a ground plane. Weather conditions at Halley mean that such an array will rapidly bury beneath the snow.

This paper considers the theoretical implications of such burial, the practical steps taken to optimize the array based on these calculations, and the measured response of the system to burial. The results are of considerable relevance to the ever-increasing community of imaging riometer users regarding both deployment and the subsequent interpretation of scientific data. Some systems (e.g., South Pole) [*Detrick and Rosenberg*, 1990] will experience similar permanent burial, while others (e.g., Kilpisjärvi) [*Browne et al.*, 1995] will be subject to significant annual variability as a result of becoming snow-covered during winter and clear during summer.

2. Theory of Antenna Design for Snow Burial

The imaging riometer for ionospheric studies (IRIS) developed by the University of Maryland, College Park [*Detrick and Rosenberg*, 1990], has been widely and successfully used for studies using cosmic radio noise absorption [*Hargreaves et al.*, 1991; *Ranta et al.*, 1997], but the deployment of a similar system at Halley presented a special challenge, as the station is built on a floating ice shelf and is subject to an annual snow accumulation of around 1.5 m. At Halley, structures built on the surface are rapidly buried by drifting snow, are subject to continual further burial at the annual accumulation rate, and experience considerable horizontal and vertical stress in the moving and densifying snow. Small structures, such as individual masts or antennas, can be easily maintained above the ever-accumulating surface by annual extension or by digging up and redeploying them. Large structures, such as buildings, are difficult and expensive to maintain above the surface and represent a considerable challenge to structural design and maintenance engineers.

The IRIS antenna array consists of 64 crossed-dipole antennas, which together with their supports cover an area of approximately 40×40 m. Each of the antennas is held 1/4λ (or approximately 2 m) above a ground plane [*Detrick and Lutz*, 1996]. It would not be practical to maintain a structure as large as the antenna array above the snow surface, and it must be expected that the array will be buried and will then get deeper by about 1.5 m per year.

If an antenna array is to operate buried within a dielectric medium such as snow then there are several effects that need to be considered.

1. The wavelength of the radio waves within the dielectric medium is shorter than that in free space:

$$\lambda_{\text{medium}} = \lambda_{\text{free-space}} / \sqrt{(\varepsilon_r)}, \qquad (1)$$

where ε_r is the relative permittivity of the dielectric medium. This means that the spacing between the individual antennas of the array and the spacing of the antennas from the ground plane as measured in wavelengths is different for the same array, depending upon whether it operates in air or snow. In addition, the length of an antenna as measured in wavelengths is also different for the same antenna operating in either air or snow.

2. The radio waves will be subject to both refraction and reflection loss as they pass from air into the snow. Refraction is simply defined by Snell's law:

$$\sin\theta_{\text{air}} / \sin\theta_{\text{ice}} = \sqrt{(\varepsilon_r)}. \qquad (2)$$

Reflection loss at a dielectric boundary is dependent upon polarization and is

$$\text{Reflection loss (dB)} = 10\log(1-(P_\perp^2+P_\parallel^2)/2) \quad (3)$$

for a circularly-polarised wave or for a wave composed from random sources (such as that from cosmic noise) [*Kraus*, 1988] where $P_\perp$ and $P \parallel$ are the reflection coefficients for the two mutually perpendicular polarization directions and are given by

$$P_\perp = \frac{\sin(a) - \sqrt{\varepsilon_r - \sin^2(a)}}{\sin(a) + \sqrt{\varepsilon_r - \sin^2(a)}} \quad (4)$$

$$P_\parallel = \frac{\varepsilon_r \sin(a) - \sqrt{\varepsilon_r - \sin^2(a)}}{\varepsilon_r \sin(a) + \sqrt{\varepsilon_r - \sin^2(a)}}, \quad (5)$$

where a = angle of incidence.

3. The radio waves will be attenuated as they pass through the snow. Snow is a lossy dielectric [*Glen and Paren*, 1975], whose permittivity at high frequencies can be expressed as

$$\varepsilon_r = \varepsilon_r' - \jmath\varepsilon_r''. \quad (6)$$

The attenuation constant is given by

$$\alpha = \frac{\pi\varepsilon_r''}{\lambda_{\text{free-space}}\sqrt{(\varepsilon_r')}} \quad \text{Np m}^{-1} \quad (7)$$

and the attenuation (A) is

$$A = 20\log(e^{-\alpha}) \quad \text{dB m}^{-1}. \quad (8)$$

The values of ε_r' and ε_r'' are dependent upon the density, temperature, and impurities in the ice.

The real part of ε_r can be estimated from the empirical relationship [*Robin et al.*, 1969]

$$\varepsilon_r' = (1+0.84\rho)^2, \quad (9)$$

where ρ is the density of the snow/ice.

The value of ρ linearly increases with depth from about 0.4×10^{-3} kg m^{-3} at the surface to about 0.55×10^{-3} kg m^{-3} at 10 m and then slowly increases after that [*Fujii*, 1983]. Taking 0.45×10^{-3} kg m^{-3} as an average density gives ε_r' of 1.9.

The value of ε_r' can also be measured by observing the change in resonant frequency of antennas as they are buried. This was done for several antennas, including a single IRIS type dipole, and gave a repeatable value for ε_r' of 1.74 ± 0.04 for an antenna buried at 2 m depth. Although the value obtained by this method is somewhat lower than that predicted by the density or by comparison with values quoted in the glaciology journals for example, by *Glen and Paren* [1975] and *Robin et al.* [1969]), it was decided that direct measurement of the scaling factor had the greatest validity in our determination of ε_r', as this was going to be used as a value to determine a scaling factor for antenna sizes, etc.

The parameter ε_r'' has been measured by determining the attenuation of radio waves bounced off the bottom of the ice shelf near Halley in glaciology studies [*Walford*, 1968]; ε_r'' varies with temperature but is close to 0.005 at the temperature of the snow within the first few meters of the surface.

Once ε_r' and ε_r'' are known, then estimates can be made for the various effects previously discussed, and where necessary the antenna and array design can be modified. The length of the dipole antennas and the spacing of the antennas from the ground plane need to be scaled by $1/\sqrt{\varepsilon_r'}$, which, as ε_r' is taken as 1.74, gives a scaling factor of 0.76.

If the beam pattern of the antenna array was only to be considered within the snow, then the spacing of the antennas would also need to be scaled by the same factor; however, the beams are subject to refraction at the snow surface, and this refraction needs to be taken into account when determining the spacing of the antennas. For IRIS the spacing between antennas is $\lambda/2$, and phase delays are introduced between adjacent antennas to form the required pattern.

Waves from an angle θ reinforce (and form a beam) when the phase delay between adjacent antennas is

$$\Phi = \pi\sin\theta. \quad (10)$$

However, when the array is buried the spacing between the antennas becomes $\sqrt{\varepsilon_r} \times \lambda/2$, and as Φ is fixed by the receiver electronics, the angle of the beam is now defined by

$$\sin\theta_{\text{snow}} = \Phi/(\pi\sqrt{\varepsilon_r}). \quad (11)$$

This beam, however, is subject to refraction at the surface, where

$$\sin\theta_{\text{air}}/\sin\theta_{\text{snow}} = \sqrt{\varepsilon_r}. \quad (12)$$

Hence $\sin\theta_{\text{air}} = \Phi/\pi$, and the required phase delays between antennas are the same for an array buried in snow as they are for an array operated in air, and the spacing of the antennas stays the same. The situation of no change in the antenna beam pattern is only true if the angle that the beam makes with the snow-air interface is less than the critical angle for total internal reflection; this condition is met for all the IRIS array main beams, but many of the sidelobes are subject to total internal reflection.

The reflection loss at the dielectric boundary can be calculated from (3) and varies between 0.08 dB for the vertical beam and 0.12 dB for the edge beams. This amount of attenuation will not impact the operation of IRIS.

The attenuation in the bulk of the snow, from (8), is 0.013 dB m^{-1} and is negligible. It was mentioned above that the ε_r'' varies with temperature and hence the attenuation of the waves within the snow also varies with the temperature of the snowpack; however, this effect is small, and neither the daily or seasonal variations are large enough to be seen with the IRIS resolution of ~0.05 dB.

3. Experimental Setup

The array was constructed in a manner similar to a normal IRIS array except that the dipole elements were shortened and the distance between the antennas and the ground plane was reduced, both by a factor 0.76, as discussed above. Most items were built from stronger-grade material than that used for a conventional IRIS so that the stresses from being buried could be absorbed. Great attention was paid to routing of the antenna feed cables and their strain relief so that some movement could occur without failure. The IRIS vault electronics was placed within a wooden shaft at the center of the array; this shaft will be extended as the snow surface rises so that the electronics remains accessible.

IRIS was switched on on January 15, 1998, and an attempt to bury the array with a mechanical snowblower was made between February 1 and 3, 1998, but only 50 cm of snow was added onto the ground plane before the machine suffered mechanical failure.

The array continued to bury naturally by drifting snow, although snow fences were used to manage the drift in an attempt to bury the array as evenly as possible. By March 1998 an average of 100 cm of snow had accumulated on top of the ground plane, although in an uneven fashion, and the first of the antennas had become completely buried. By August 1998 all but 10 of the antennas had buried completely. The 10 remaining were located in the wind scoop formed near the central wooden shaft. These final antennas were very slow to bury and were finally covered by use of a snowblower in January 1999. During the whole burial process, great attention was paid to maintaining the antennas, as they experienced considerable stresses while in a partially buried state.

Because the array operated for some time in a partially buried state, it was possible to examine the signal power increase with time. This is primarily because of the following two effects:

1. The distance between the ground plane and the array was scaled to be $1/4\lambda$ in the snow; until this space filled with snow the distance was less than $1/4\lambda$, and hence the ground plane reflection was out of phase with the direct wave. With no snow between the ground and the antennas the phase mismatch will result in a signal reduction of about 0.6 dB for the center beams and 2.5 dB for the edge beams. As snow fills the gap the signal will increase by this amount.

2. The short antennas are not resonant when operated in air. They will have a small reduction in efficiency, but the larger effect is the mismatch of their feed point impedance to the receiver network. Numerical simulations using MINEC [*Logan and Rockway*, 1986] show a feed point mismatch that could result in 5 to 9 dB signal loss in comparison with a perfect match; in a practical situation the loss will be less than this maximum as the original match will not be perfect. As the signal for each riometer beam is composed of a contribution from all 64 antennas, for each antenna that buries the signal level will increase by 1/64 of ~5–9 dB.

4. Results

The primary aim of the IRIS is to study auroral radio absorption. To facilitate this, the diurnal background variation of the sky brightness, the quiet-day curve (QDC), must be subtracted. The data from January 1998 to January 1999 were processed a month at a time, giving 13 individual curves. For this analysis the choice of a month is somewhat arbitrary, being a compromise between getting a sufficient number of "quiet" days in each period in order to produce an accurate QDC and a period short enough to allow detailed analysis of any changes introduced as the IRIS was buried by snow. The QDCs were determined using all data for the month and smoothed by removal of all absorption spikes present. A time resolution of 120 s was used.

The monthly QDCs for the center beam of the IRIS array are shown in Figure 1a. The values are given in ADC units and represent the output voltage of the riometer bridge, whose amplitude is proportional to cosmic radio noise level in the beam. Each month is plotted. The curves also show some variation in level during the day caused by the nonuniform intensity of the radiation arriving at the Earth from the sky. The

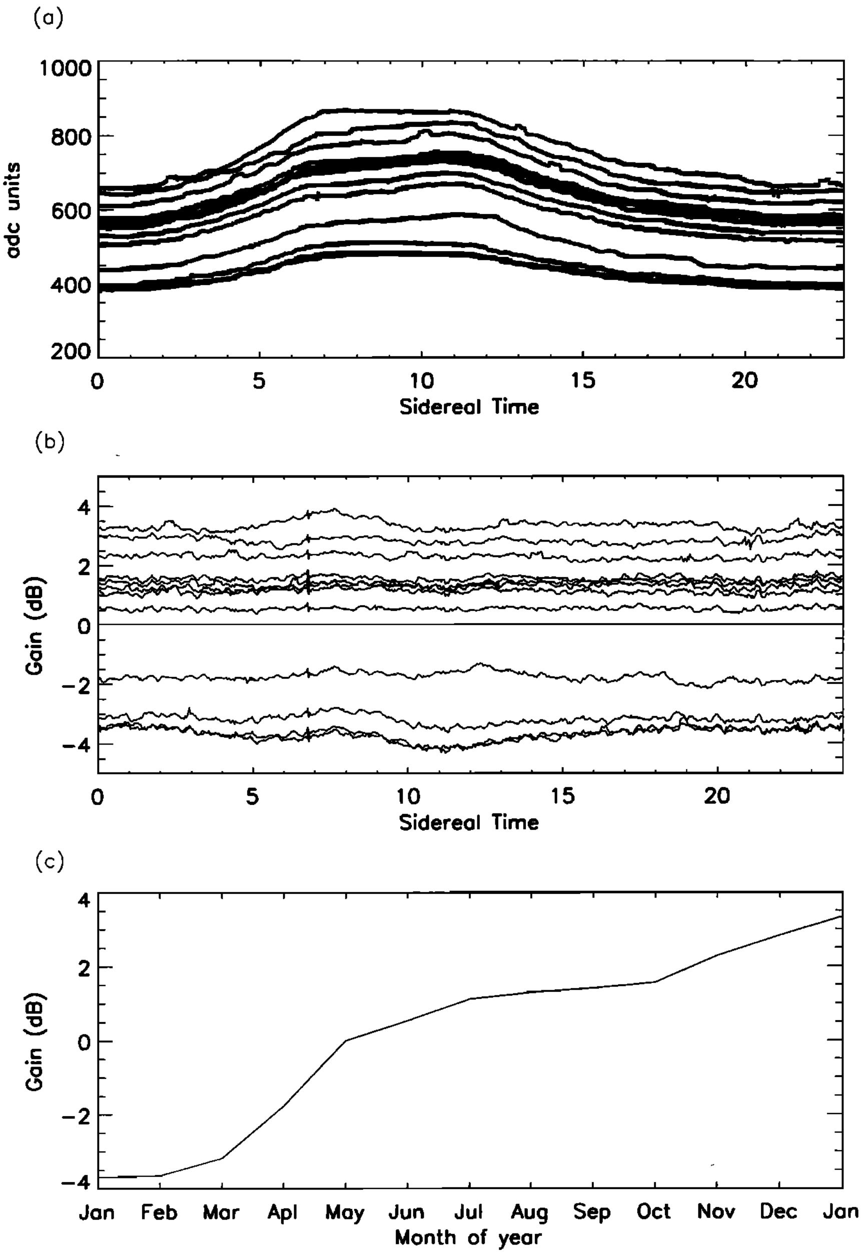

Figure 1. (a) The quiet-day curves from the central beam for the months from January 1998 to January 1999 inclusive. The lowest values are associated with January 1998, while the highest are from January 1999. The values increase sequentially throughout the year. (b) The change in gain of the quiet-day curves observed from month to month, relative to the values in May 1998. The order is as described above. (c) The average change in gain for each month.

peak around 08:00 sidereal time is due to the cosmic radio noise from the Milky Way, although the region of the Milky Way observed by the center beam is somewhat less well defined than in some other beams of the array. It can also be seen that the average level of the curves increases sequentially with time, although the difference between consecutive months varies considerably. The primary cause of this change is due to the changing snow conditions.

In Figure 1b the change in monthly QDC is shown as a change in gain (decibels) relative to the QDC for May 1998. The diurnal variations in background noise levels have been removed, and each month is represented by a straight line. The sequential increase in gain over time is clearly apparent, with gain values ranging from about -4 dB to about +4 dB relative to May 1998 levels. Periods where little change in gain occurs are readily identified, particularly January-February 1998 and August-October 1998.

Figure 1c shows the monthly variation of the mean gain, i.e., the mean of the 770 2-min QDC values from Figure 1b covering the whole day. The period between March and July, 1998, is one of significant changes in gain. Somewhat less dramatic changes were still occurring at the end of the period of study.

The monthly change in gain relative to May 1998 for each of the beams of the array is shown in Figure 2. The beams are labeled from 0 to 48, with beam 0 representing the southeast corner of the array and beam 48 representing the northwest; poleward is at the top. The center beam is labeled 24. Each beam is made up of equal contributions from every antenna in the array. However, there are only seven active riometers, each one being fed signals from all the antennas. Each individual riometer has a unique calibration. As a result, beams 0, 7, 14, 21, 28, 35, and 42 share the same calibration information, whereas beams 1, 8, 15, 22, 29, 36, and 43 share a separate set, and so on. The figure shows that the variations in gain of all of the beams are similar, with the largest changes occurring during March-July 1998. The typical total change in gain over the 13-month period of study is 7–8 dB throughout the whole array.

Information regarding the buildup of snow around the array is shown in Figure 3. In anticipation of the antennas ultimately being buried by snow, the design was such that the antennas were tuned for snow conditions. As a result, significant increases in gain occur when the antenna elements are actually covered in snow, not just when snow covers the ground plane. Therefore it is important to identify how many elements of the array have been fully covered at different times of the year. Figure 3a is such a plot. No antennas were completely covered until March 1998. Increasing numbers became buried until August, when only those elements around the central shaft were still exposed. These final few remained exposed until after January 1999 because of a consistent wind scoop around the central shaft.

Our calculations have shown that significant changes in gain could be caused by a steady buildup of snow in the 1.5 m gap between the ground plane and the antenna elements. Figure 3b shows the typical snow levels throughout the array at different times of the year. Obviously, the buildup of snow was variable across the array, with differences in level caused by being upwind or downwind or near or far from the central shaft. The figure shows a typical level for the array and should be considered approximate at best. The solid line is a log fit to the data and is used to try to remove some scatter from the actual measurements due to the impulsive nature of the snow deposition as a result of blizzards.

A simple model can be constructed which includes the contribution of both the number of antennas covered by snow as a fraction of the total number and the percentage depth of snow on the ground plane. Figure 3c shows the output of the model in comparison with the changes in gain observed on a side beam during 1998. We used the theoretical values of 2.5 dB for the contribution due to buildup of snow above the ground plane and determined the effect due to antenna burial by a least squares fit method to the observed changes. We found that 6.9 dB provided the best fit. We note the good agreement between the estimated effect due to antenna element burial and that predicted from the theoretical values calculated previously. Figure 3d shows similar output of the model in comparison with the changes in gain observed on the center beam during 1998. We used the theoretical values of 0.6 dB for the contribution due to buildup of snow above the ground plane and determined the effect due to antenna element burial by a least squares fit method. We found that 6.2 dB provided the best fit. Once again, we note the good agreement between the estimated effect due to antenna burial and that predicted from the calculated theoretical values. In this analysis we have held the contribution due to buildup of snow constant. This was because the theoretical variability of the value to small changes in estimated snow

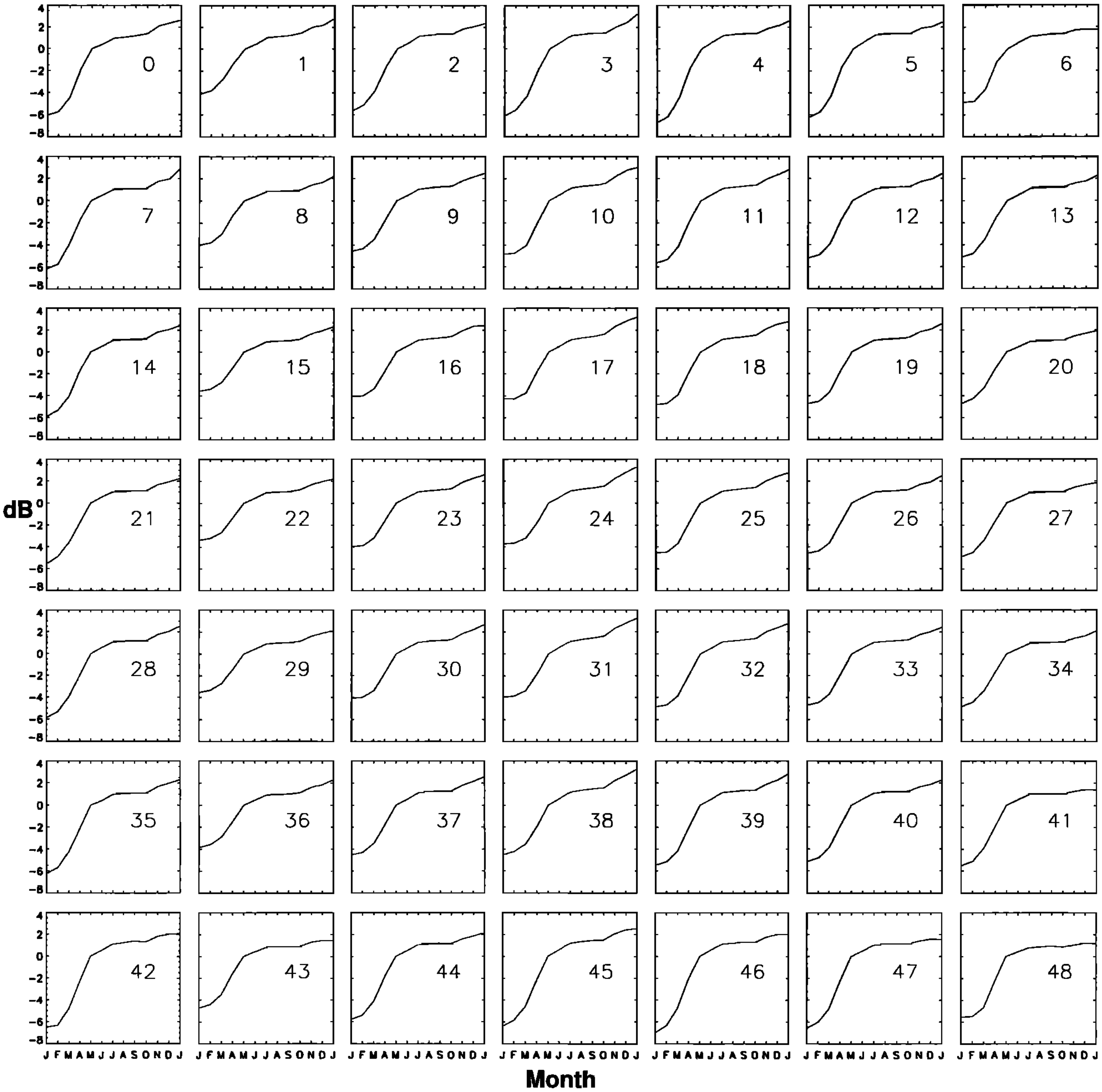

Figure 2. The change in gain associated with snow burial of the array for all beams. Beam 0 represents the southeast direction, beam 48 represents the northwest direction, and beam 24 represents the center.

conditions was much less than for that for the effect due to antenna element burial. The difference in the two snow buildup values (i.e., 2.5-0.6=1.9 dB) is at least consistent with the difference in the final gain values seen in Figures 3c and 3d once the whole array has been buried (i.e., ~2 dB), giving us some confidence in our approach. A further effect, due to the annual variation in ionospheric contribution of the absorption measured [*Krishnaswamy et al.*, 1985], would decrease the estimates of 6.9 and 6.2 dB by about 0.2 dB. This is based on an estimate on changing ionospheric conditions throughout

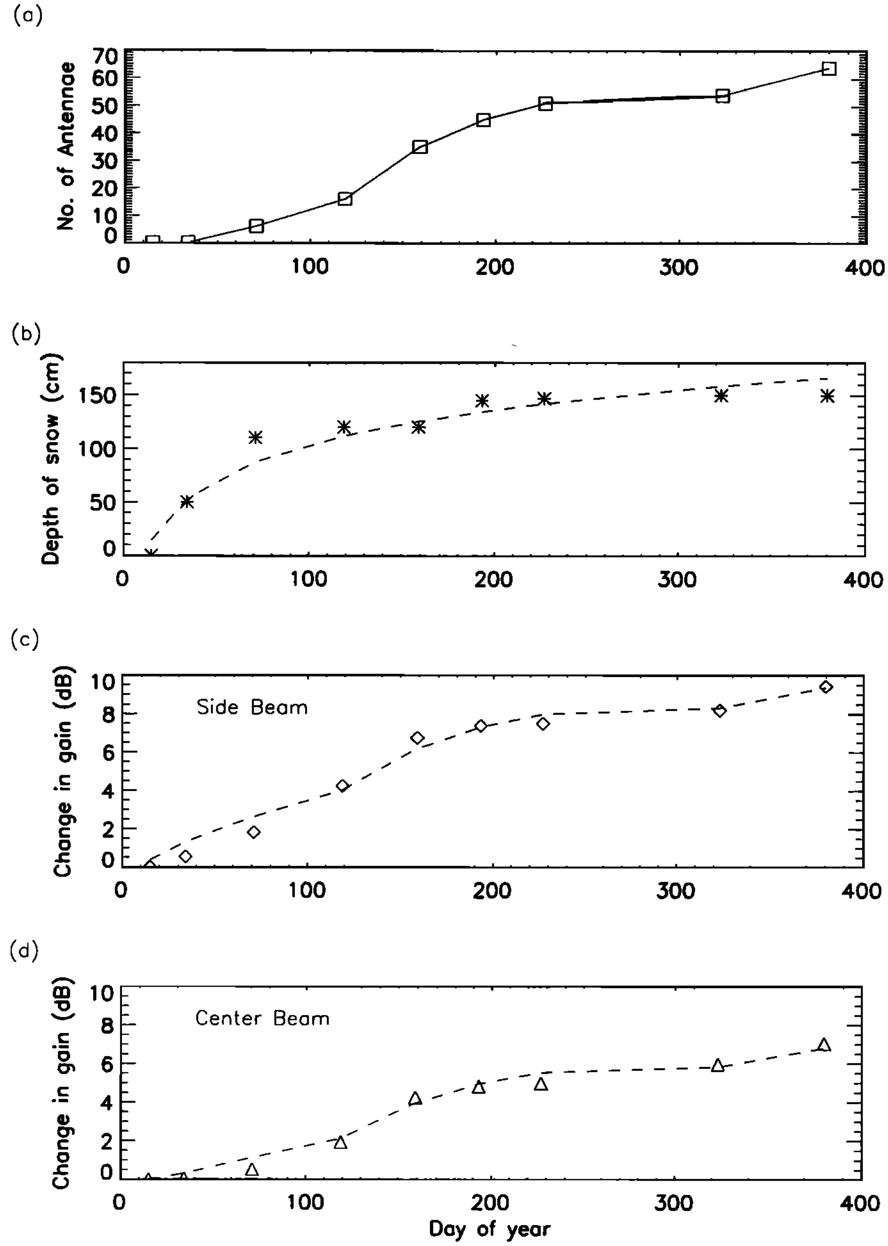

Figure 3. (a) The variation in the number of antennas completely buried by snow (□) during January 1998 to January 1999. (b) The variation in average snow depth (∗) over the whole array during the same period. (c) The observed change in gain of the side beam 3 (◇) compared with a simple model of snow cover on the array (dashed line). (d) The observed change in gain of the central beam 24 (△) compared with the same simple model (but with different effects due to snow cover from that for the side beam in Figure 3(c)). See text for more details.

the year made at Siple, Antarctica, which is at the same geomagnetic and geographic latitude as Halley. Corner beams are predicted to have an even greater response to snow levels than edge or side beams. We do not attempt to compare observed changes with theoretical calculations here because of large uncertainties in many of the parameters used.

5. Discussion

The models of the electrical properties of snow have been used to modify the IRIS antenna array and to allow it to successfully operate while buried in the snow at Halley. The continual accumulation at Halley means that the antenna array will be covered by an additional 1.5 m (on average) of snow every year, which will result in approx 0.02 dB of extra signal attenuation every year now that it is completely buried. Hence it can be anticipated that further signal attenuation will not limit the lifetime of the system. It is expected that the ever-increasing stresses on the individual antennas in the array will eventually cause failures, but this is unlikely to be a problem for the next 5–10 years.

Our original intention had been to bury the array immediately after construction, but machine failure meant that the burial process took place more naturally and over a period of time, thus allowing us to observe the gradual signal improvement and verify our model.

If we had built a standard air-tuned IRIS antenna array at Halley, we would have observed the opposite effect; the signal level would have declined as the array buried, probably making the system unusable within 2 years. The signal level changes for an unmodified antenna burying are opposite to, but not the inverse of, those discussed in this paper. If an unmodified antenna was built at Halley, then it would be expected that the central beam would lose about 1 dB as the gap between the ground plane and the antenna filled with snow and would then lose a further 5–8 dB as the antenna elements buried and became nonresonant.

Other IRIS antenna arrays in both Antarctic and Arctic locations will suffer signal loss from partial or complete burial. At some sites, such as the South Pole, the burial rate is very low. For newly installed systems in these conditions the initial signal loss per year is small as the space between the ground plane and antenna fills with snow. Once the snow reaches the antenna elements, rebuilding or modification of the array should be considered to avoid the more serious signal loss associated with nonresonance of the antennas. At some sites, such as Kilpisjärvi, the burial will be seasonal and may result in signal degradation for short periods. It should be remembered that the snow conditions vary considerably from site to site; the accumulation rate and temperature history effect ε_r' and the loss parameter ε_r'' are dependent upon impurity levels and temperature. Quantified predictions of signal loss at a particular site would require measured values of these snow parameters. However, the snow conditions at Halley are likely to cause less impact on an array than in some other areas, Northern Hemisphere regions in particular, where biological impurity levels are anticipated to be significantly higher. In the list of existing and planned imaging riometer installations given by *Stauning* [1996], 19 out of the 20 arrays would be influenced by either seasonal snow levels or eventual burial.

In addition to being the only practical way of maintaining an IRIS antenna at Halley, burying the antenna array does offer one potential operational benefit. Riometers are susceptible to interference from other electronic and electrical equipment, and often this interference is picked up on sidelobes of the antennas. In the case of a buried array, many of the major sidelobes are subject to total internal reflection at the snow-air interface and hence cannot pick up interference from a source above the snow surface such as that generated in nearby buildings.

6. Summary

In 1998 an imaging riometer system was deployed at Halley (76°S, 27°W) involving the construction of an array of 64 crossed-dipole antennas and a ground plane. Weather conditions at Halley mean that such an array will rapidly bury beneath the snow, so the system was tuned to operate efficiently when buried. This principally involved reducing the length of each antenna by a few centimeters and reducing the spacing between the ground plane and the antennas.

Theoretical calculations indicate that because the distance between the ground plane and the array was scaled to be $1/4\lambda$ in the snow, as snow fills the gap the signal will increase by about 0.6–2.5 dB. This effect is predicted to vary with beam orientation. For the central, vertical beam the impact of snow levels is at a minimum, i.e., 0.6 dB. However, the edge or side beams experience significantly more effects due to snow levels, i.e., 2.5 dB. This is due to the angle of arrival of the beam pattern and the oblique path through the snow.

Similarly, the short antennas are resonant when operated in snow, not in air. Theoretical calculations show that the largest effect of this is the mismatch of their feed point impedance to the receiver network. As the signal for each riometer beam is composed of a contribution from all 64 antennas, for each antenna that buries the signal level will increase by 1/64 of up to ~9 dB.

The measured response of the system to burial shows significant changes as snow accumulated in and over the array during 1998. The changes are consistent with the magnitude of the effects predicted by the theoretical calculations. In particular, the central and edge beams do show significant differences in their response to snow levels, consistent with the theoretical calculations.

The Halley imaging riometer system, having now been buried completely, is operating more efficiently than if a standard air-tuned configuration had been deployed. Any air-tuned array system that became completely buried by snow would suffer essentially the opposite, but not the exact inverse, of the effects discussed in this paper.

The results presented here are of considerable relevance to the ever-increasing community of imaging riometer users regarding both deployment and the subsequent interpretation of scientific data. Some systems will experience similar permanent burial, while others will be subject to significant annual variability as a result of becoming snow-covered during winter and clear during summer. Snow conditions vary considerably from site to site due to differences in the accumulation rate and temperature history effect (ε'_r) and the loss parameter (ε''_r), which are dependent upon impurity levels and temperature. Quantified predictions of signal loss at any given site could only be based on measured values of these snow parameters.

Acknowledgments. We would like to thank Helen Johns for her initial analysis of the quiet-day curves. We also thank André Phillips for testing antenna configurations at Halley and useful discussions in the design stage. Also, we would like to acknowledge the Halley field engineers for their contributions in deploying the system.

References

Berkey, F. T., V. M. Draitskiy, K. Henriksen, B. Hultqvist, D. H. Jelly, T. I. Shchuka, A. Theander, and J. Yliniemi, A synoptic investigation of particle precipitation dynamics for 60 substorms in IQSY (1964-1965) and IASY (1969), *Planet. Space Sci.*, *22*, 255–307, 1974.

Browne, S., J.K. Hargreaves, and B. Honary, An imaging riometer for ionospheric studies, *J. Electron. Commun.*, *5*, 209–217, 1995.

Detrick, D.L., and L.F. Lutz, *System Manual for the Imaging Riometer for Ionospheric Studies,*. Inst. for Phys. Sci. and Technol., Univ. of Md., College Park, Sept. 1996.

Detrick, D. L., and T. J. Rosenberg, A phased-array radio wave imager for studies of cosmic noise absorption, *Radio Sci.*, *25*, 325–338, 1990.

Ecklund, W. L., and J. K. Hargreaves, Some measurements of auroral absorption structure over distances of about 300km and of absorption correlation between conjugate regions, *J. Atmos. Terr. Phys.*, *30*, 265–283, 1968.

Fujii, Y., Preliminary report of glaciology study at Brunt Ice Shelf near Halley Base, Antarctica, in January 1982, *Antarct. Rec.*, *77*, 144–152, 1983.

Glen, J.W., and J.G. Paren, The electrical properties of snow and ice, *J. Glaciol.*, *15*, 15–38, 1975.

Hargreaves, J. K., and M. J. Jarvis, The multiple riometer system at Halley, Antarctica, *Brit. Antarct. Surv. Bull.*, *72*, 13–23, 1986.

Hargreaves, J.K., D.L. Detrick, and T. J. Rosenberg, Space-time structure of auroral radio absorption events observed with the imaging riometer at South Pole, *Radio Sci.*, *26*, 925–930, 1991.

Kraus, J.D., *Antennas*, McGraw-Hill, New York, 1988.

Krishnaswamy, S., D. L. Detrick, and T. J. Rosenberg, The inflection point method of determining riometer quiet day curves, *Radio Sci.*, *20*, 123–136 , 1985.

Little, C.G., and H. Leinbach, The riometer - A device for the continuous measurement of ionospheric absorption, *Proc. IRE*, *47*, 315–320, 1959.

Logan, J.C., and J.W. Rockway, The new Mininec - A mini-numerical electromagnetics code, *Tech. Doc. 938*, Nav. Oceans Syst. Cent., San Diego, Calif., Sept. 1986.

Mitra, A.P., HF and VHF absorption techniques in radio wave probing of the ionosphere, *J. Atmos. Terr. Phys.*, *32*, 623–646, 1970.

Ranta, H., A. Ranta, J. K. Hargreaves and S. Browne, Localized absorption events in the afternoon sector, *J. Atmos. Sol. Terr. Phys., 59*, 891–902, 1997.

Robin, G. De Q., S. Evans, and J.T. Bailey, Interpretation of radio echo sounding in polar ice sheets, *Philos. Trans. R. Soc. London, Ser. A., 256*, 437–505, 1969.

Stauning, P., Investigations of ionospheric radio wave absorption processes using imaging riometer techniques, *J. Atmos. Terr. Phys., 58*, 753–764, 1996.

Walford, M.E.R., Field measurements of dielectric absorption in Antarctic ice and snow at very high frequencies, *J. Glaciol., 7*, 89–94, 1968.

M.A. Clilverd, M.J. Jarvis, D.J. Maxfield, and M.C. Rose, Physical Sciences Division, British Antarctic Survey, Madingley Road, Cambridge, CB3 0ET, England, UK. (m.clilverd@bas.ac.uk)

T. J. Rosenberg, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742-2431.

(Received January 6, 2000; revised April 24, 2000; accepted May 10, 2000.)