Microwave Propagation Over a Changing Snowcover

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ABSTRACT

A bistatic (separate transmit and receive units) microwave (10.5 GHz) radar is in continuous operation over a 120-m range at the CRREL research facility in South Royalton, Vermont. The transmitting and receiving antennas, mounted at a height of 60 cm over level, grass-covered ground, have E-plane vertical polarization and a 3.5-degree single-lobe pattern. The microwave carrier is modulated at 3 kHz. The microwave field at the receiver consists of directly transmitted, reflected, and scattered radiation. Variation in the received microwave field is monitored as a voltage proportional to field strength (automatic gain control, AGC). The instantaneous AGC voltage is reported to a recording system every half hour, together with automated snow depth and site meteorology data. The AGC is seen to increase during snowfall and to decrease as the depth of the snowcover decreases. During periods of approximately constant snow depth, the AGC flucuates with the (inferred) moisture content of the snow. For a given snow depth, the microwave field strength at the receiver is weaker, evident as a larger AGC, when the microwaves have propagated over a relatively wetter snow cover. The propagation loss over moist ground, as following snowmelt or thawing of the soil, is lower than than that over dry, frozen soil.

INTRODUCTION

A study of microwave propagation over a changing snowcover was conducted this past winter as part of a long-term project that investigates environmental effects on the performance of sensor systems used for detecting intrusion. The microwave system is a bistatic radar operating at a frequency of 10.5 GHz over a 120-m-long path of level ground (Fig. 1). The transmitting and receiving antennas are mounted at a height of 60 cm in order to provide good microwave

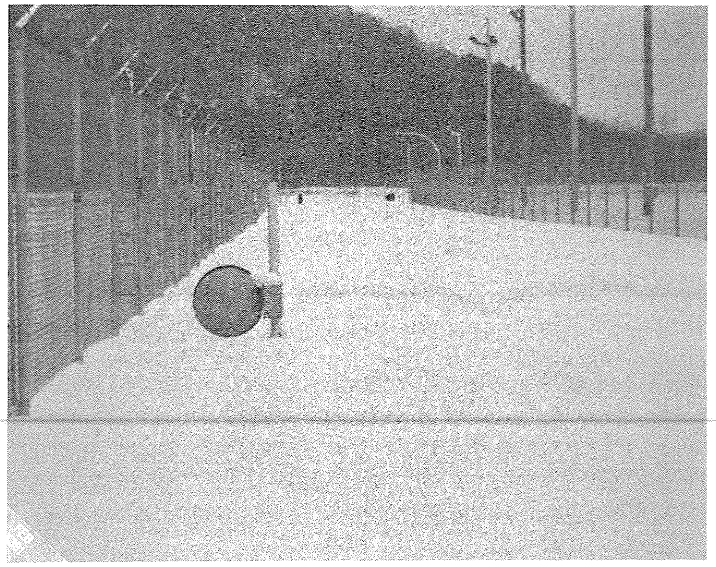

Figure 1. Microwave radar in place at CRREL field site in South Royalton, Vermont. The large round object in the foreground is the receiver, the small dark object in the background is the transmitter.

field coverage near the ground surface; consequently, the radiation is incident at the ground surface at large angles relative to the vertical. The antennas are located in the 9-m-wide clear zone between two straight sections of 2.4-m-high chain-link fence. The microwave field at the receiver consists of directly transmitted, reflected, and scattered radiation.

The microwave system has been in continuous operation at the same location since October 1990. Beginning in January 1991, the system's automatic gain control (AGC), which varies in proportion to fluctuations in the strength of the received microwave field, has been reported to a recording system every half hour. Automated measurements of snow depth, ground temperature, and site meteorology are recorded concurrently with the instantaneous AGC voltage.

This paper examines the differences in the AGC between situations of clear sky and snowfall and as the surface condition changes. In addition to indicating whether aspects of the winter environment render a microwave-based method of intrusion detection unreliable, the results provide an opportunity to assess microwave propagation over a changing snowcover on a daily basis.

AUTOMATIC GAIN CONTROL VOLTAGE

5–8 January 1991

During this period the area between the microwave transmitter and receiver was equally bare ground and patches of remnant snow or ice that were approximately 1–2 cm thick. A summary of selected site-characterization data is given in Table 1. The AGC voltage is shown in Figure 2. The time indicated is when the AGC voltage was sampled and recorded by the data logger. The notable features are a relatively constant value during the first 9 hours of 5 January, a steady increase in voltage during that afternoon that continued through the morning of 6 Jan, a period of relatively constant voltage beginning the afternoon of 6 Jan and continuing through the next morning, and an even less variable voltage during the latter half of 7 Jan and early 8 Jan. The AGC during the last 7 hours of this 4-day period is lower

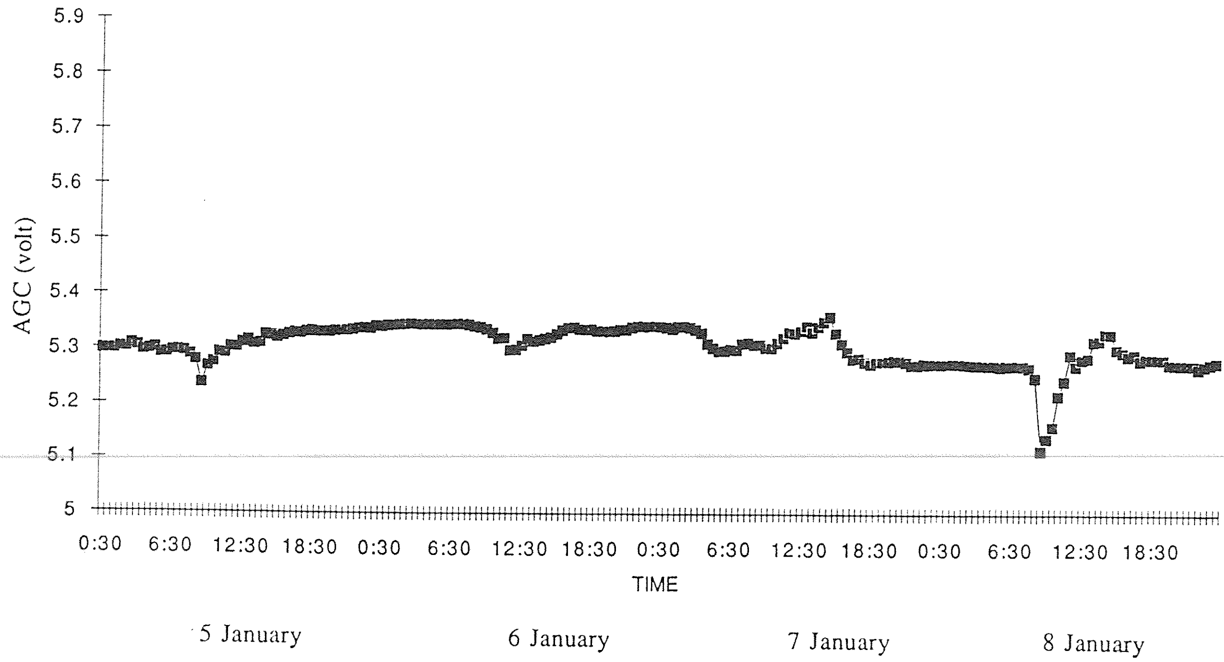

Figure 2. Time-series record of microwave radar AGC for period 5–8 Jan 1991.

Table 1. Selected site characterization data.

Date	*Snow depth*[1] *(cm)*	*Max.* air temp (°C)*	*Max.* wind speed (m/s)*	*Max. gust (m/s)*	*Max. incident radiation 0.3–3 μm (w/M²)*	*Snow observations*
5 Jan	0–2	−1.0	1.4	2.6	230	Equal amounts of bare ground or snow/ice
6 Jan	0–2	+0.8	2.6	4.3	180	Equal amounts of bare ground or snow/ice
7 Jan	0–2	−2.1	3.9	6.4	230	Equal amounts of bare ground or snow/ice
8 Jan	0–2	−9.3	2.3	3.6	345	Equal amounts of bare ground or snow/ice
9 Jan	0–8.3	−4.8	2.2	4.2	140	7–9 cm new snow
10 Jan	8–5	−0.7	5.2	10.0	385	
11 Jan	5–12	−11.0	3.9	4.7	195	Wind blown, 5–6 cm; 4–8 cm range
12 Jan	12–23	−5.7	2.4	3.6	(instrument snow-covered)	
23 Jan	15	−4.7	3.4	5.5	250	1-cm-thick crust on 14-cm-deep snow (0.24 g/cm^3)
24 Jan	15	−2.1	3.9	7.7	425	Blowing snow
25 Jan	16	−11.4	3.5	5.5	440	
26 Jan	16	−3.5	2.1	5.2	430	
29 Jan	17	+3.7	2.9	4.5	420	
30 Jan	17–15	+3.3	2.2	3.4	240	
31 Jan	18–26	−1.5	4.2	8.9	290	12-cm-thick layer new snow (0.1 g/cm^3); total depth 22–26 cm
1 Feb	25–23	−8.9	4.9	10.2	475	5–8 cm loose snow (0.15 g/cm^3); total depth 17–21 cm
2 Feb	23–22	+5.8	1.6	4.0	475	
13 Feb	9	−0.3	2.1	3.9	540	6-cm-deep snow cover on ice
14 Feb	9–21	+0.1	1.9	4.7	(instrument snow-covered)	11–12 cm new snow
15 Feb	21–19	+1.9	3.5	7.6	(instrument snow-covered)	
16 Feb	19	−9.8	4.2	9.2	(instrument snow-covered)	
17 Feb	19–18	+0.7	3.0	8.0	790	
18 Feb	18	+1.6	1.6	3.3	590	
19 Feb	18–23	+1.8	2.2	4.6	(instrument snow-covered)	13-cm-thick snow cover (0.10 g/cm^3) on ice
20 Feb	20–12	+6.8	4.4	10.9	605	
21 Feb	12–11	+4.5	3.2	6.6	260	
22 Feb	11–8	+10.3	6.1	14.6	435	0–3-cm-thick layer of ripening snow (0.35 g/cm^3) on ice
23 Mar	0–8	+0.7	4.4	9.2	100	
24 Mar	8–6	+2.4	1.9	3.5	175	
25 Mar	6–4	+3.6	1.5	2.5	315	
26 Mar	4–0	+7.8	2.1	3.1	810	Bare ground

1—Acoustic snow depth sensor.
*—30-minute average; measured at 2-m height.

than the initial value. The periods of steady or gradually increasing AGC are separated by episodes of abrupt drops in AGC. A drop in AGC voltage indicates that an increase in the strength of the net received radiation field has occurred.

The AGC drop on 5 Jan occurs midway in a trend of rising air temperature, from −14°C to within 1° of 0°C. This is 4.5 hours before the warmest portion of the day. The larger drop on 8 Jan coincides with a warming trend from −19°C to −5°C; the near-surface (within 5 mm) ground temperature reaches −2°C. The less pronounced dip during the morning of 6 Jan also occurs during the period of increasing air temperature; in this case, however, the total increase in temperature is on the order of 5°C. The subsequent rise in AGC continues through the warmest period of the day, when air and near-surface soil temperatures are above freezing. Because the drop in AGC occurs before the full effect of the warming trend on the temperatures of the exposed soil and the snow/ice patches is evident, it is unlikely that changes in the properties of the surface over which the microwaves are propagating are the cause of the abrupt drops in AGC. Instead, the abrupt drops in AGC upon initiation of periods of rising air temperature apparently are a consequence of instrument effects, i.e. the electronics of the transmitter and/or receiver respond to the positive temperature gradients in such a way that a stronger signal is transmitted and/or the received microwave field is more efficiently gathered. Either occurrence would produce the drop in AGC.

The way in which the characteristics of the ground surface influence the microwave radiation field is evident in the differences between the periods of steady or gradually increasing AGC. The relatively low "steady" AGC (5.27–5.3 V) corresponds to times when the temperature of the soil at the base of the snow/ ice patches is colder than –4°C; soil directly exposed to the low air temperatures is probably even colder during these periods, which are 0030–0800 on 5 Jan, 1900–2400 on 7 Jan, and 0030–0930 and 1600-2400 on 8 Jan. The high "steady" values of AGC (5.35 V) correspond to periods when the soil at the base of the snow/ice patches remains warmer than –2°C. The onset of periods of steadily rising AGC on 5 Jan (1100–1800), 7 Jan (1030–1500), and 8 Jan (1130–1500) coincides with the near-surface ground temperature transitioning from below –2°C to above –2°C.

The significance of –2°C is not in its absolute value, which is subject to the precision of the copper-constantan thermocouple used to obtain the temperature reading, but in the realization that thawing of frozen soil and melting of ice occur over a range of transition temperatures below 0°C. The periods when near-surface soil temperature is between –2 and 0°C would be periods of increasing liquid water content in the soil and snow/ice patches (Anderson et al., 1978). Whether or not it is windy (arbitrarily taken to be a wind speed of 3 m/s or greater) or calm has no noticeable influence on the magnitude of the AGC during steady-value periods.

9–12 January 1991

The AGC voltage during this time period is shown in Figure 3. The initial steady AGC is the continuation of the system response to microwave propagation over frozen ground and scattered patches of snow and ice. Beginning with the 0730 value there is a slight increase in AGC through 1030; from 1100 to 1430 the AGC increases by 0.11 V; and from 1430 to 0430 on 10 Jan the AGC is steady. Note that there is no abrupt drop in AGC during the morning of 9 Jan;

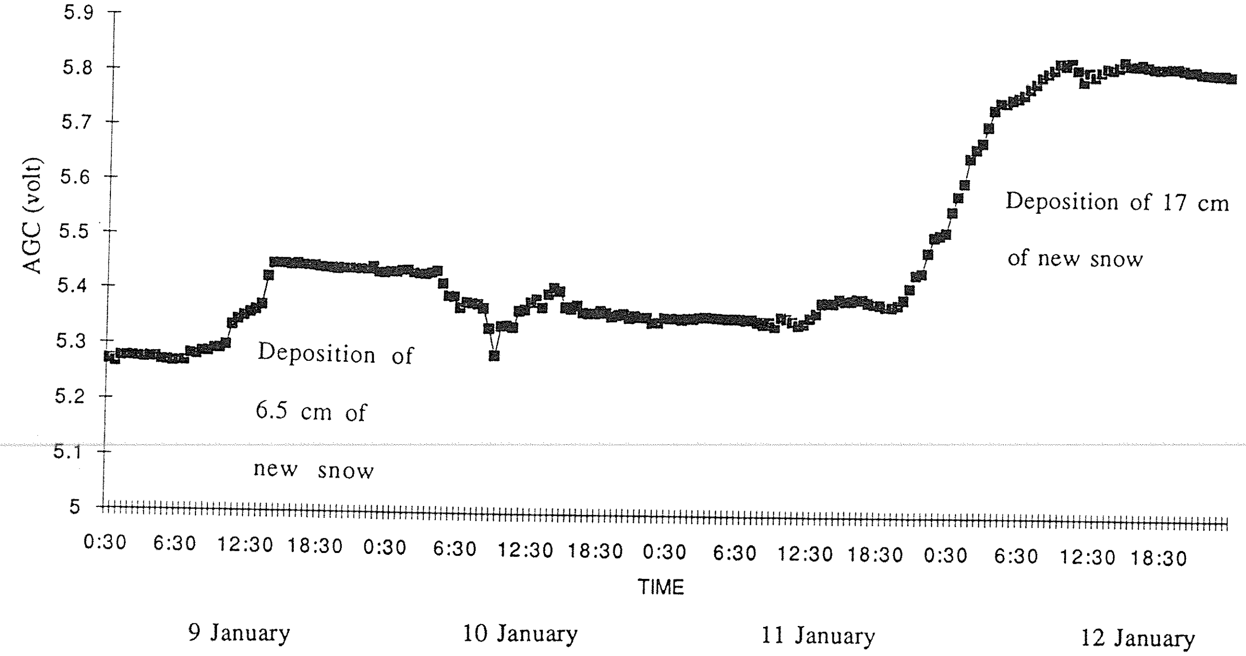

Figure 3. Time-series record of microwave radar AGC for period 9–12 Jan 1991

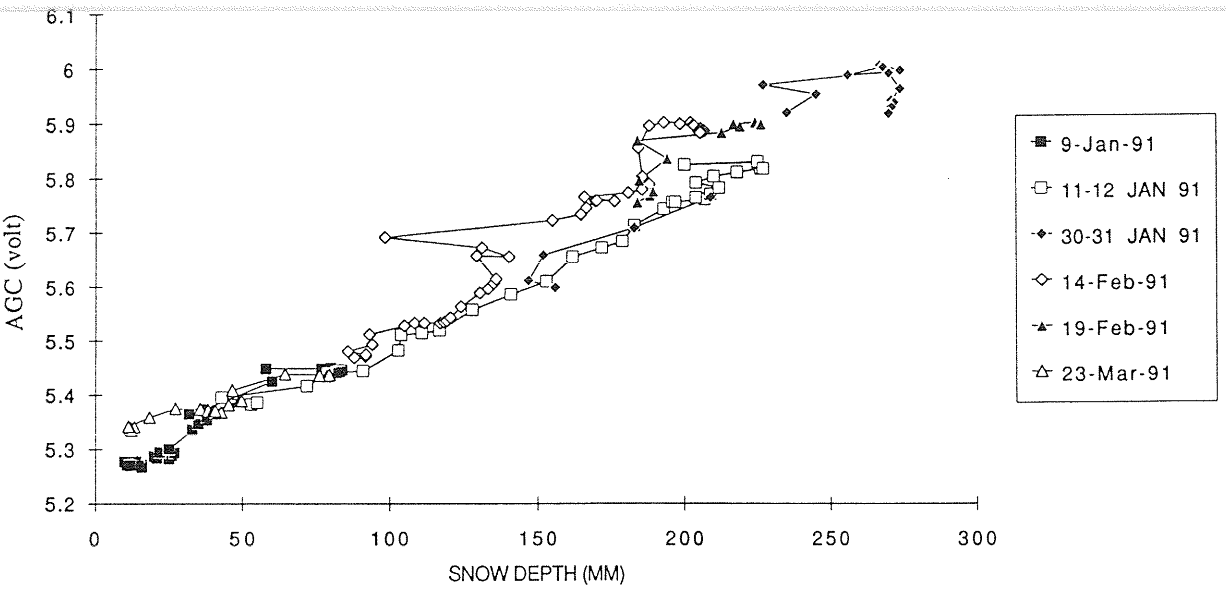

Figure 4. Microwave radar AGC as a function of snow depth during six snowstorms.

this is consistent with the absence of a steep positive temperature gradient. Instead of temperature, the site condition that is determining the response of the microwave system is the accumulating snow layer. The output of an acoustic snow depth sensor indicated an increase in snow depth between 0700 and 0730, and continuing snow accumulation through 1500, when the snow depth was 8 cm; this was an increase of approximately 6.5 cm in 8 hours. The AGC dropped off slightly during the remainder of the day and the next morning as the snow settled slightly. Between 0900 and 1600 on 10 Jan the depth of the snowcover varied, decreasing overall by approximately 2.5 cm, as strong winds (maximum gust 10 m/s) redistributed the loose snow and left windblown surface structures. Following this the AGC was relatively steady through noon of 11 Jan as the air during this period gradually warmed to –13°C. There was a slight increase in AGC over the next 2 hours, during which the air temperature was steady and the wind was calm. Beginning at 2030, however, the AGC rose rapidly until 0430 (12 Jan) and then more gradually through 0930. This 11-hr period of rising AGC corresponded to a snowfall of 17 cm. Figure 4 shows the increase in AGC with snow accumulation during this and the 9 Jan snowstorms.

A consistency between the two storms is that the increase in AGC that occurs during the storms persists after snowfall ceases. This indicates that the higher AGC is a consequence of microwave interaction with the snow on the ground, not interaction with airborne snow. The presence of the snow layer introduces additional pathways by which the radiation can reach the microwave receiver. The radiation may be reflected at the snow surface as well as refracted upon passage through the snow layer due to the difference in dielectric properties of snow and air. At 10.5 GHz, the wavelength of the microwaves in the snowcover is approximately 2 cm.

23–26 January 1991

The AGC during this period is shown in Figure 5. The fluctuations in AGC are similar to those during 5–8 Jan, and can be predicted from the temperature history for each day as that is an indication of whether the snow warmed to the extent that liquid water was released. The main difference in the AGCs is the overall magnitude, with the present AGC being 0.2 V higher due to the presence of the 15-cm-deep continuous snowcover. A snowpit on 23 Jan revealed a 1-cm thick crust overlying a 14-cm-thick layer of loose, rounded, elongate grains; snow in the lower layer had a density of 0.24 g/cm^3.

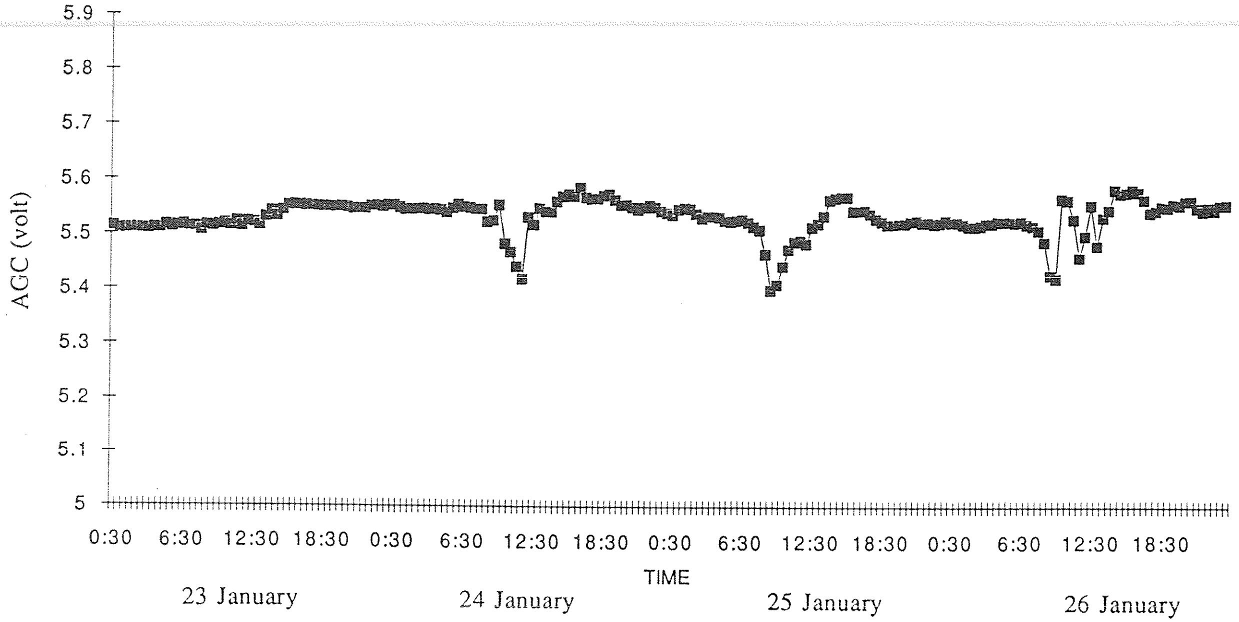

Figure 5. Time-series record of microwave radar AGC for period 23–26 Jan 1991.

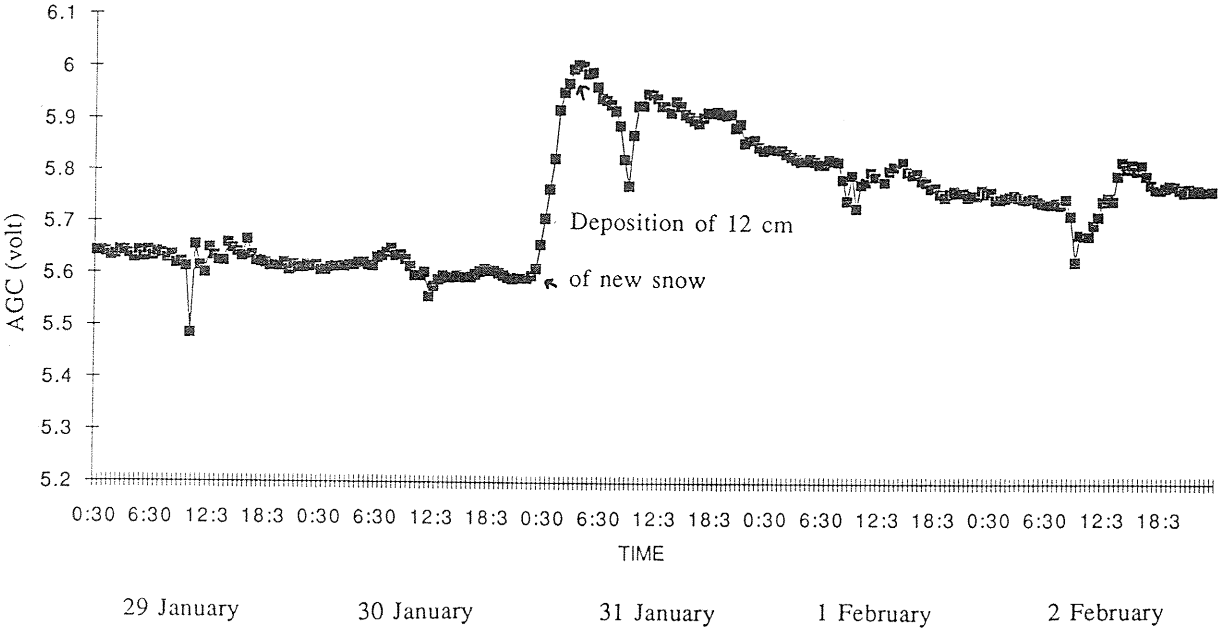

Figure 6. Time-series record of microwave radar AGC for period 29 Jan–2 Feb 1991.

Background

A snowstorm on 28 Jan left 3–3.5 cm of snow (density 0.08 g/cm^3) that began melting in the warm (5°C) air.

29 January–2 February 1991

The AGC during this period is shown in Figure 6. The AGC on 29 Jan is controlled by:the depth of the 17-cm-thick snowcover in the early morning when snowdepth is relatively constant, the instrument response to a steep positive temperature gradient (20°C in 4 hr) that results in the abrupt drop in AGC in mid-morning, the high liquid water content of the snow when the air temperature was above freezing (1100–1630), and again the depth of the snow layer for the remainder of the day and the next morning. A rise in AGC due to increasing liquid water content also occurs on the morning of 30 Jan; in this case, the snow becomes wet due initially to exposure to warm (0°C or above) air and subsequently to warm rain. The combined effect is to reduce the thickness of the snowcover but the net result is a short-term increase in AGC. Winds were moderate during this period so there was little drying action by circulating air.

The dominant event on 31 Jan was the continuation of a snowstorm that began around midnight. By the end of the storm at 0330, 12 cm of snow had been deposited. Although the snow depth decreased by only 1 cm during the day, the AGC began to decrease within 1 hour of the end of the storm. The new snow initially may have been relatively wet, as the air temperature was –2°C; later that day, however, the new snow was characterized as a loose, dry powder of 1-mm-size angular grains and a density of 0.1 g/cm^3· Immediately following the storm, the air temperature dropped and the wind became stronger (maximum gust 4–6 m/s), which probably had a drying action on the snowcover. Just as an increase in liquid water content has correlated with a higher AGC, the loss of moisture would explain the early morning drop in AGC.

The overall trend of decreasing AGC over the next 2 days again coincides with a reduction in snow depth, from 26 to 22 cm. The late morning fluctuations in AGC on 1 Feb correspond to a period when the temperature range within the deepest 10 cm of the snowcover increased to between –2° and 0°C, although the average air temperature was –10°C. Again, increased wetness of the snow could explain the fluctuations in AGC. The pronounced period of high AGC on 2 Feb coincides with the snow being at 0°C and the air being warmer. As this is an unquestionable occurrence of high liquid water content, the correlation between snow wetness and relatively high AGC is confirmed. Winds were moderate during this period so there was no related drying action.

13–17 February

The time-series AGC for this period is shown in Figure 7. Although the acoustic snow depth sensor indicated a 9-cm-deep snowcover on 13 Feb, it actually was an approximately 5.5-cm layer of aging snow on a 3.5-cm-thick basal ice layer. The prominent change in the AGC is the increase during 14 Feb. This coincided with 12 cm of snowfall

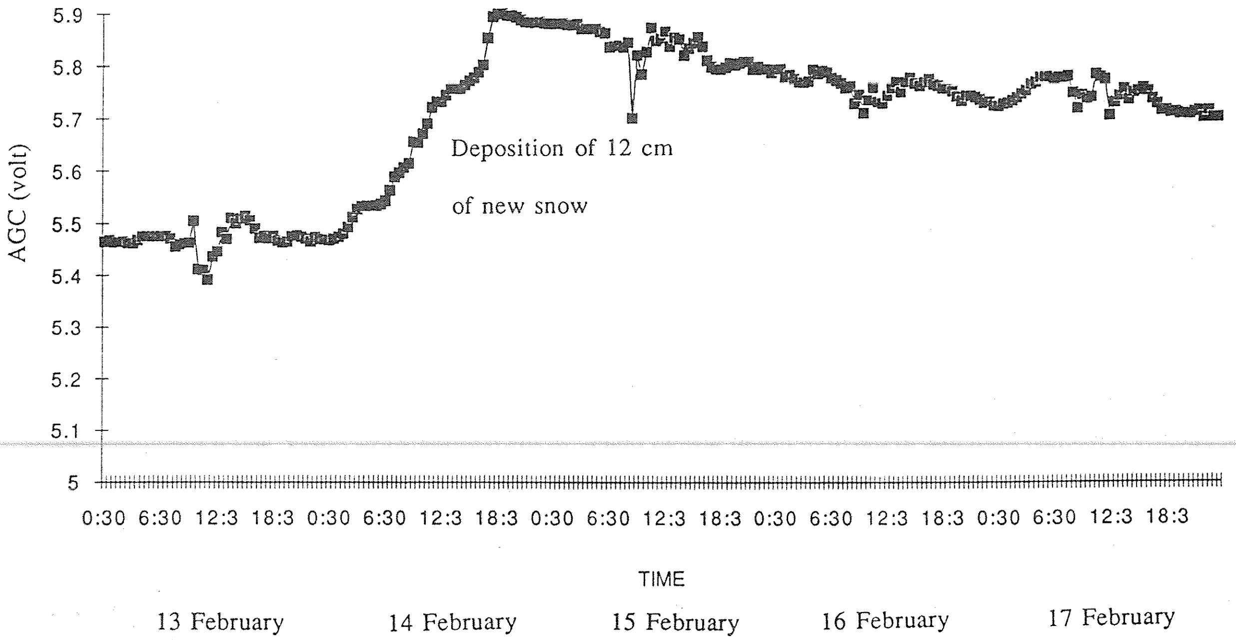

Figure 7. Time-series record of microwave radar AGC for period 13–17 Feb 1991.

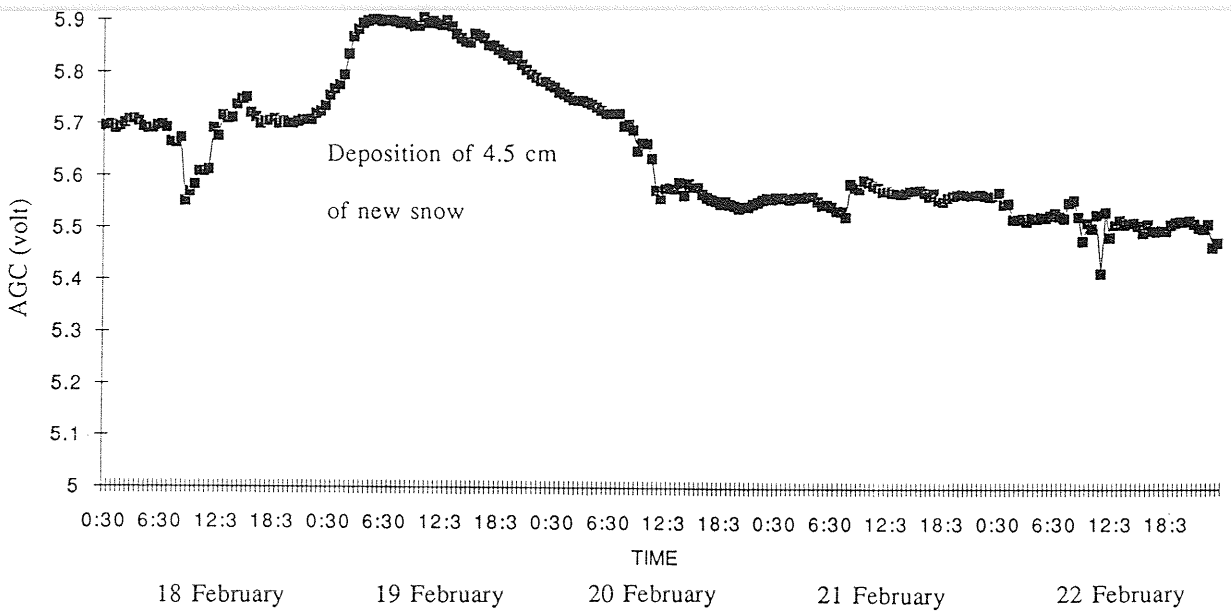

Figure 8. Time-series record of microwave radar AGC for period 18–22 Feb 1991.

between 0230 and 1830. By the end of 17 Feb, the snow depth had decreased to 18 cm as a consequence of settling and of melting during periods when the air temperature was above freezing (maximum 4°C) on 15 and 17 Feb.

18–22 February 1991

This period includes episodes of snowfall, rainfall, and melting. The corresponding AGC is shown in Figure 8. On 18 Feb the initial 18-cm snow depth decreased to 17 cm in the afternoon. The AGC was controlled sequentially by the snow depth, by the instrument response to a large positive temperature gradient, by the increase in liquid water content of the snow as it melted while the air temperature was above freezing (1130–1600), and by the snow depth during the remainder of the day. Snowfall began shortly after midnight; 4.5 cm of fresh snow deposited between 0030 and 0500 brought the depth of the snowcover to 22.5 cm as determined with the acoustic snow depth sensor. During the remainder of 19 Feb, two factors determined the AGC: a 1.5-cm decrease in snow depth caused the overall decrease in AGC, and the high liquid water content that was a consequence of contact with warm air caused short-term increases in AGC. Rain fell through 1030 on 20 Feb, which caused a rapid loss in snow depth (3.5 cm in 10 hr). Once the rain ceased, the air warmed from 1°C to 8°C and the snow depth decreased another 4.5 cm in 4 hr. The AGC dropped most rapidly in the hour following the cessation of the rain, which suggests that the AGC had been higher due to the raindrops in the air than it would have been for the same snow depth and liquid water content under clear-sky conditions.

The snow depth decreased only 1 cm during 21 Feb, a colder day (maximum air temperature 4°C vs 8°C) than 20 Feb. The abrupt increase in AGC between 0800 and 0830 coincided with the air warming from 0 to 1°C. The AGC subsequently remained high due to the high liquid water content of the melting snow cover, and it remained steady because the decrease in depth was insignificant relative to the effect of snow wetness on microwave interaction with the snowcover. The abrupt drop in AGC between 0030 and 0200 on 22 Feb coincided with the freezing of the wet snow as the air temperature decreased to –3°C. The AGC remained steady during the ensuing period of low temperature (minimum –5°C). Finally, the snow began to melt again as the air warmed to 11°C. The consequence was a loss of 3 cm of snow betwen 0900 and 1700; this left the basal ice layer, approximately 5 cm thick, with 0 to 3 cm of wet, ripening snow (density 0.35 g/cm^3) on top. The high-amplitude fluctuations in AGC coincided with the warmest part of the day, when water released by the snowmelt was perched on the ice layer. As this was also a period of high wind (maximum gust 14.6 m/s), windblown movement of the standing water probably caused the fluctuations as the microwaves reflected from the moving surface.

23–26 March 1991

The time-series record of AGC for this period is shown in Figure 9. The early portion of the record for 23 Mar represents microwave propagation over bare, frozen ground. In contrast with 5–8 Jan, when the soil was frozen to a depth between 22.5 and 30 cm, the soil is now frozen as deep as 45 cm. The increase in AGC beginning at 1400 coincides with a resolvable increase in snow depth, as indicated by the acoustic snow depth sensor. Approximately 3 cm of snow fell between 1400 and 1600 and between 2000 and 2200, with a more gradual increase in snow depth in between these periods of relatively high deposition. The AGC shows a similar step pattern of increases during the period of snowfall. Total acumulation was 8 cm. A combination of rainfall and above-freezing air temperature on 24 Mar caused a decrease in snow depth to approximately 6 cm. The abrupt increase in AGC on 24 Mar coincided with the air warming above 0°C. Although snow depth decreased steadily between 0600 and 1830, the AGC fluctuated about a steady value. This is another example of an increase in AGC due to rain offsetting the customary decrease in AGC that accompanies a decrease in snow depth. The AGC remains relatively steady through the evening of 24 Mar and morning of 25 Mar, which was also a period of unchanging snow depth. The AGC fluctuates during midday on 25 Mar, which was a period of warm air and later rain; the snow depth decreased by 2 cm in this period. The last snowcover of the season was lost on 26 Mar. The sharp drop in AGC coincides with a large temperature increase, which has been attributed to instrument response to high positive temperature gradients. The AGC during the evening is lower than that at the beginning of this time period although the microwaves were propagating over bare ground in both cases. The moisture content of the ground on 26 Mar would be higher than on 23 Mar (by an unknown amount) because the meltwater from the 4-cm-deep snow layer had been released during the day. Although the soil was still frozen at depth, the surface layer had warmed to 2°C during the day. Both thawing of the soil and infiltration of meltwater would have caused the soil to be

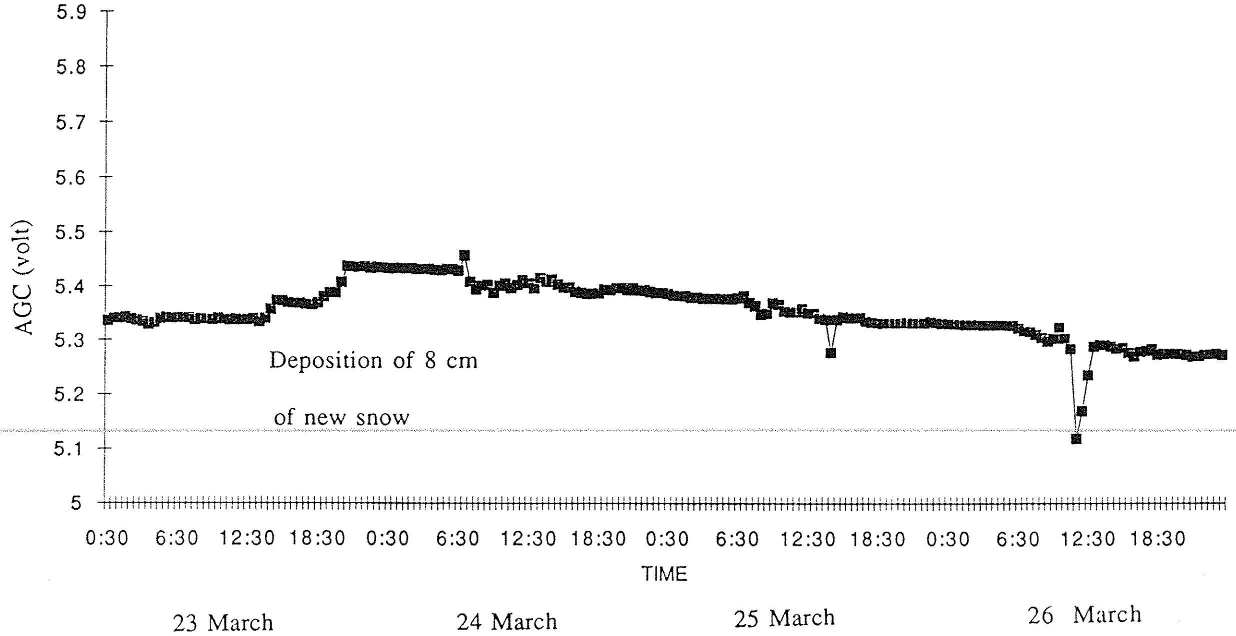

Figure 9. Time-series record of microwave radar AGC for period 23–26 Mar 1991.

quite damp. The lower AGC indicates that the strength of the received microwave field is stronger when the moisture content of the ground (no snowcover) is higher.

Summary of AGC variation as snowcover changes

The variation in AGC voltage during a total of 31 days in January, February, and March 1991 demostrates that the AGC typically increases during snowfall, remains steady if snowmelt is not occurring, and decreases as the depth of the snowcover decreases. The increase in AGC during snowfall is the consequence of microwave interaction with snow on the ground, not airborne snow. Increased liquid water content of the snowcover results in higher AGC; the occurrence of these increases may be predicted from the daily temperature history. Rain causes an increase in AGC that offsets the decrease in AGC that customarily accompanies a reduction in snow depth. There is less propagation loss, and so lower AGC, when the microwaves propagate over moist, rather than dry, frozen ground.

DISCUSSION

The nature of the study reported here is unlike that of most microwave studies involving a snowcover, both in its duration and its configuration. The range of snowcover conditions represents both winter-long evolution and loss of a snowcover and also the changes occurring on a time scale of a few hours. The record of the microwave system's AGC indirectly monitors the daily variation in those properties of the snowcover that characterize the interaction between the microwaves and the snowpack. Although the AGC record is not continuous, the gaps in the record due to the sampling interval (30 min) are small relative to other long-term studies, such as airborne measurements, where the sampling interval may be on the order of days. This study does provide a qualitative indication of the daily and long-term changes in a northern New England snowcover.

The typical New England nature of the snowcover, however, makes it difficult to quantify the microwave interaction with the snowcover. The snowcover was shallow (maximum depth 26 cm) throughout the winter and, except for occasions of new snow on formerly bare ground, was stratified. When the snow was dry, the microwaves would have penetrated the entire snowcover, producing a net return that depended on the frozen/thawed status (moisture content) of the underlying soil and on the layering of the snowcover. Even the reduced penetration depth in wet snow may have been large relative to the thickness of the top snow layer. Reviews such as Dozier (1987) summarize the difficulty of characterizing a snowcover with regard to microwave remote sensing.

A common feature of the six snowstorms considered for this paper is that the AGC increased while snow was accumulating. The rise in AGC is now recognized as an indication that the snowcover is deepening, but can it indicate anything else about the new snow? Figure 4 suggests that the rate of change of AGC with snowdepth is dependent on the wetness of the snow. Two of the storms, 9 and 11–12 Jan, occurred on cold days (see Table 1) when the air did not warm above –5°C. During two snowstorms (19 Feb and 23 Mar) the air temperature was between –2° and 0°C throughout. For the remaining storms the air was initially warm and turned cold during the latter part of the storm (30–31 Jan), or the air warmed during the storm (14 Feb). Figure 4 indicates that the relationship between AGC and snow depth is characterized by two sets of curves. The lower set consists of the "cold" storms of 9 and 11–12 Jan and the early part of the 14 Feb snowfall. The upper set is the 19 Feb and 23 Mar storms and the latter portion of the 14 Feb storm, corresponding to the warm air period. The 30–31 Jan storm falls in each set of curves for a portion of its duration, but at the end, as the air temperature decreases, its trend is from the upper to the lower set of curves.

The storms accompanied by warm air would have deposited snow that was wet relative to that accumulating during the cold storms. A higher liquid water content means that the portion of microwave energy reflected at the snow/air interface would have been larger than in the case of dry snow and that the portion of the energy transmitted into the snowcover would have been more highly attenuated as it propagated through the snow. The net result would have been that the strength of the microwave field after interaction with the snowcover would be significantly less than that due to propagation over a dry snowcover, and the system AGC would be higher in compensation. The trend of increase in AGC per increment of snow deposition during "warm" snowstorms is consistent with this interpretation.

Two instances of rainfall have shown that the microwave system's AGC is high but steady during rainfall and lower once rainfall ceases. The high AGC is consequently identified with propagation loss, presumably through scattering by the rain droplets. Ulaby et al. (1981) note that the severity of microwave scattering by rain is determined by the density and drop-size distribution of the water droplets, but summarize that rain has a negligible effect on microwave transmission for frequencies less than 10 GHz. The present study, conducted with a system operating at 10.5 GHz, validates Ulaby et al.'s conclusion while demonstrating that there is little margin between no and some transmission loss during rainfall at frequencies close to 10 GHz.

FUTURE WORK

A difficulty in extracting a quantitative assessment of the changing snowcover from the AGC record is the lack of snow characterization data. Because the data acquisition process at the South Royalton site is automated, there is a winter-long record of the AGC voltage, but snow characterization measurements are made only when project personnel are at the site. To have a more complete representation of snow properties, such as grain size, density, and liquid water content, that influence the interaction of microwaves with the snowcover, the site conditions data (air temperature, wind speed, incident and reflected radiation, snow depth) will be input to a model (Jordan, 1991) that predicts the temperature profile in the snowcover and in the ground. If the model results agree with the measured snow and ground temperatures, then parameters that determine the dielectric properties of the snowcover will be extracted from the model. Once that information is available, the AGC data will be reassessed in terms of expected propagation gains and losses as the microwaves interact with a changing snowcover.

SUMMARY AND CONCLUSIONS

The factors affecting microwave (10.5 GHz) propagation over a changing snowcover are snow depth, the liquid water content of the snow, rainfall, and the moisture content of the soil. Only snow depth and rainfall were measured during the study; relative changes in the other factors were inferred from site weather data and from measured temperature profiles for the snow and soil. Snowfall causes a microwave propagation loss that is proportional to snow depth. This is attributed to multipath effects as the microwaves reflect and refract at the snow surface and at dielectric discontinuities within the snowpack. For a given snow depth, the propagation loss is higher when the snow is wet. More microwave energy is lost through scattering at the snow surface, because of the greater mismatch in dielectric properties between air and wet snow than between air and dry snow, and through greater attenuation within the snowcover. Although at 10 GHz it is marginal whether microwaves are scattered by rain, in this study rain did cause a propagation loss in addition to that due to microwave interaction with the snowcover. Finally, the microwave system's AGC was lower when the ground was damp from snowmelt and thawing than it was when the ground was dryer. This suggests that a strong return of microwave energy from thawed soil at the base of a snowcover may partially offset propagation losses from interaction with the snowcover.

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