

# Active Microwave Remote Sensing of Road Surface Conditions

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An active microwave sensing system is investigated to provide real-time information about road surface conditions. Microwave radiation is very sensitive to the presence of water in the medium through which it passes. Thus, the amplitude and phase of a wave reflected from a road contains information about water, snow, and ice accumulation. Computer simulations of surface reflectivity based on the dielectric constant of various media were completed as a preliminary feasibility study. An experimental detection system was then constructed along with a liquid nitrogen-cooled asphalt test bed to simulate the road surface. Preliminary tests were conducted in the frequency range of 26.5 to 40 GHz. Microwave signals were directed to the asphalt surface by using a horn antenna, and the reflected signal was received by a microwave antenna feeding a diode detector. The resulting signal was then analyzed to extract the road surface information. Tests indicated that wet snow and ice can easily be distinguished, although it is difficult to discriminate among dry snow, dry ice, and dry pavement conditions. This problem is addressed by sensing the road with two separate transmitter frequencies. A simple maximum likelihood classifier algorithm was applied to the measured data to automatically identify the surface conditions.

**I**nformation about road surface conditions during winter is important for travelers as well as for highway patrol and maintenance personnel. Because accumulations of ice and snow create dangerous driving

conditions, obtaining timely and accurate data is an important task for highway departments and requires frequent patrolling (1). A more effective and less expensive alternative is the use of automatic sensors deployed along the road. The most prominent current technology involves the use of in-pavement sensors that measure pavement temperature, the presence of water, and the presence of deicing chemicals. The main disadvantage of such in-pavement sensors is their high installation and maintenance costs. Also, they are sensitive to only a small area of the surface, which may cause erroneous results when partial icing exists on the road.

Remote sensing approaches based on either active or passive microwave techniques have been investigated by several researchers. In an active system, a microwave transmitter generates a signal to probe the road surface (2–5), whereas in a passive microwave system only the black body radiation of the surface is detected (6).

In this paper, the technical feasibility of an active microwave sensing system using multiple frequencies is investigated. Microwaves in the range of 26.5 to 40 GHz are directed to the road surface, and the reflected microwaves are received and analyzed. Since the magnitude of the received signal for various surface conditions is measurably different because of moisture content, the received signal can be analyzed to provide an estimate of surface conditions.

Computer simulations based on various surface covers with different thicknesses were performed. The reflection coefficients were computed by using Fresnel's formulas of

reflection for plane waves. The results indicate that many conditions are distinguishable if multiple frequencies are used. Monte Carlo simulations were also completed to model real-world variations of the physical parameters such as temperature and surface cover thickness.

A prototype detection system covering the Ka-band of the microwave spectrum (26.5 to 40 GHz) and an artificial road test bed were constructed. Surface scans were made for different conditions including various thicknesses of water, snow, slush, and ice. For the analysis, specific frequencies were chosen for which distinctive features appeared in the received signal. The variations of surface conditions over time were also monitored. Typical data from this experiment are presented. Finally, a simple classification scheme was developed that could provide an automatic assessment of the surface cover.

## THEORY

The dielectric constant of a material determines the scattering characteristic of microwaves by the material. By observing the propagation of microwaves in the medium, one can derive information about the dielectric constant, which in turn gives insight into the physical properties of the material, such as its moisture content, density, and temperature. The following notation is used for the complex dielectric constant:

$$\epsilon = \epsilon' - j\epsilon''$$

where  $\epsilon'$  is the permittivity and  $\epsilon''$  is the dielectric loss factor.

The differences in the dielectric constant among the various media cause the wavefront to bend, reflect, or refract at an interface. Snell's law of refraction determines the angle or direction of transmitted and reflected electromagnetic waves, as shown in Figure 1.

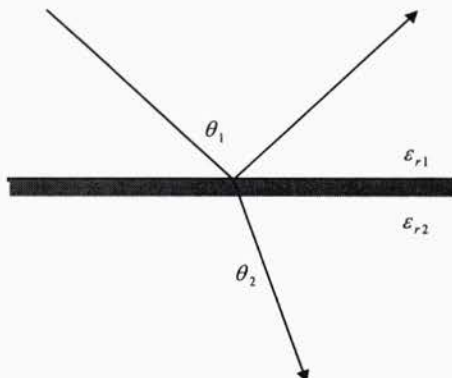


FIGURE 1 Refraction and reflection in a two-layer medium.

Snell's law in the case of nonmagnetic media is

$$\frac{\sin \theta_1}{\sin \theta_2} = \sqrt{\frac{\epsilon_{r2}}{\epsilon_{r1}}}$$

where  $\theta_1$  and  $\theta_2$  are the angles of the incident and transmitted waves, and  $\epsilon_{r1}$  and  $\epsilon_{r2}$  are the relative dielectric constant values of the corresponding media.

By employing Maxwell's equations and applying the boundary conditions at an interface, the Fresnel's reflection coefficients can be calculated (7). The change in the amplitude and phase of the reflected wave is given by the reflection coefficient.

For a wave polarized perpendicular to the scattering plane, the reflection coefficient is given by

$$R_{12}^{\perp} = \frac{\sqrt{\mu_{r2}/\epsilon_{r2}} \cos \theta_1 - \sqrt{\mu_{r1}/\epsilon_{r1}} \cos \theta_2}{\sqrt{\mu_{r2}/\epsilon_{r2}} \cos \theta_1 + \sqrt{\mu_{r1}/\epsilon_{r1}} \cos \theta_2}$$

and for a parallel polarized wave it is

$$R_{12}^{\parallel} = \frac{\sqrt{\mu_{r1}/\epsilon_{r1}} \cos \theta_1 - \sqrt{\mu_{r2}/\epsilon_{r2}} \cos \theta_2}{\sqrt{\mu_{r1}/\epsilon_{r1}} \cos \theta_1 + \sqrt{\mu_{r2}/\epsilon_{r2}} \cos \theta_2}$$

The medium is assumed to be nonmagnetic; therefore, the permeability values ( $\mu_r$ ) are unity (8,9).

For a three-layer medium, shown in Figure 2, the overall reflection coefficient is given by

$$R = \frac{R_{01} + R_{12} \exp(-j2k_{1z}d_1)}{1 + R_{01}R_{12} \exp(-j2k_{1z}d_1)}$$

where

$$\begin{aligned} k_{1z} &= (\omega^2 \mu_{r1} \epsilon_{r1} - \omega^2 \mu_{r0} \epsilon_{r0} \sin^2 \theta_0)^{1/2} \\ &= \omega \sqrt{\mu_{r1} \epsilon_{r1}} \cos \theta_1 \end{aligned}$$

is the propagation factor, and  $d_1$  is the thickness of the middle layer. The total reflectivity is given by  $\Gamma = |R|^2$ .

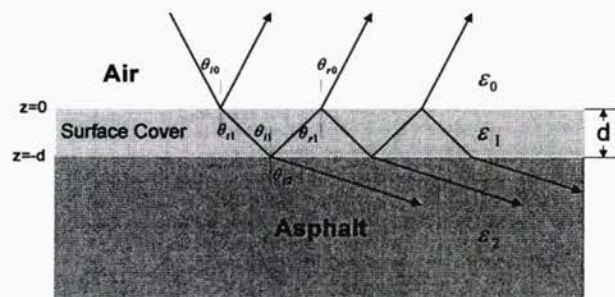


FIGURE 2 Three-layer surface model used in computer simulations.

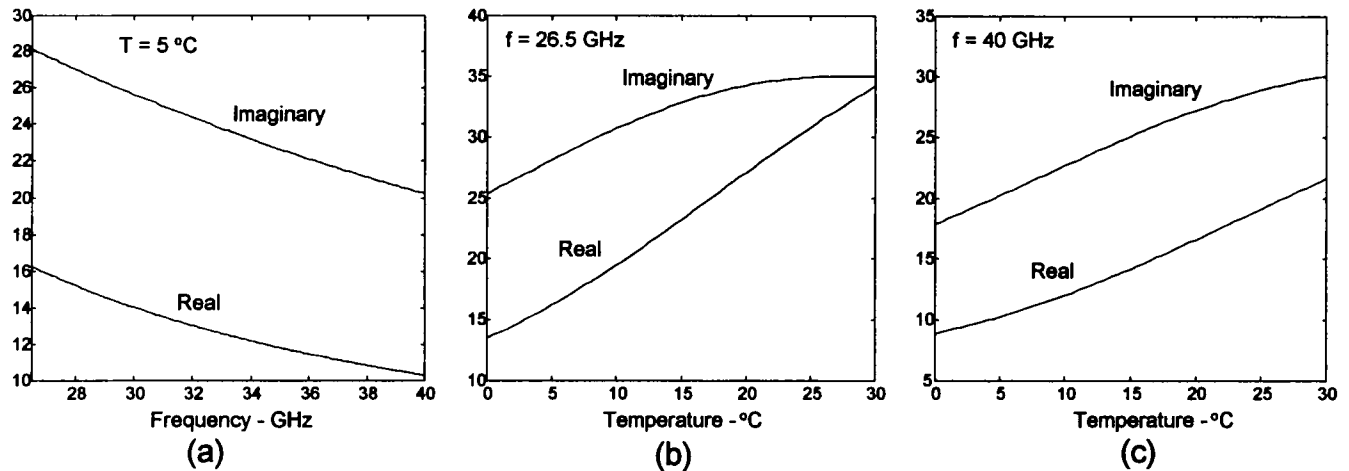


FIGURE 3 Dielectric constant of water as function of frequency and temperature, calculated with Debye formula.

### COMPUTER SIMULATIONS

By using these equations, the reflectivities of three-layer surfaces were computed as a function of frequency, thickness of the middle layer, polarization, and angle. The following values of relative material dielectric constants are used in the simulations (5,7).

The dielectric constant of water is both frequency and temperature dependent. As shown in Figure 3(a), at  $5^\circ\text{C}$  it varies monotonically from about  $16 \pm j28$  at 26.5 GHz to  $10 \pm j22$  at 40 GHz. The dependence on temperature is shown in Figures 3(b) and 3(c) for two representative frequencies. The permittivity of ice is independent of frequency with a value of 3.15, and the loss factor is three to four orders of magnitude smaller than that of liquid water. The dielectric constant of snow depends on its density and water content (7). For these calculations the values corresponding to a density of  $0.25\text{ g/cm}^3$  were used.

Figure 4 displays the general behavior of reflectivity versus frequency for an incident angle of  $60^\circ$  using plane waves polarized parallel to the scattering plane. The surfaces, with the exception of the dry surface condition, are assumed to have covers for 2 mm water, 1 cm ice, wet snow, and dry snow. Although the real situation is far more complex than this simplified theory, the results indicate that the surface conditions should be distinguishable at certain frequencies.

Monte Carlo simulations were conducted to model the full range of likely real-world variations in the parameters. In this approach, the values of dielectric constants and thicknesses for each condition were uniformly randomized over the range given in Table 1 (10). Utilizing reflectivities at two frequencies creates a variable space, as shown in Figure 5. Curved decision boundaries can be used to distinguish between wet snow and ice covers. Water is easily distinguished because its reflectivity values are around 0.7 for each frequency.

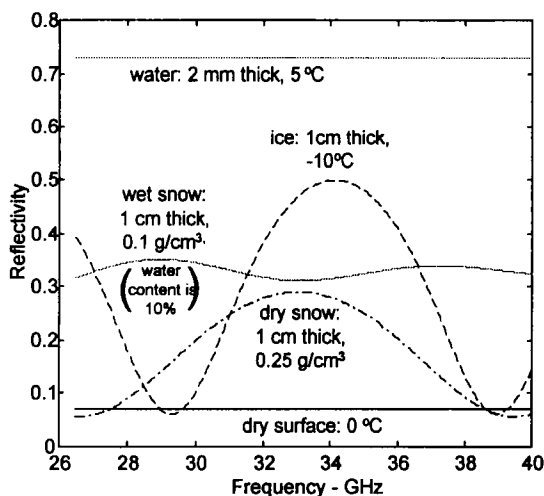


FIGURE 4 Reflectivity of surface conditions for plane wave parallel to scattering plane.

### METHODOLOGY

The prototype system comprises a 486-based computer with data acquisition board, a microwave oscillator, wave guides, microwave horn antennas, lock-in ampli-

TABLE 1 Approximate Dielectric Constant Values for Ka-Band of Microwave Spectrum

| Material   | Permittivity ( $\epsilon'$ ) | Dielectric loss factor ( $\epsilon''$ ) |
|------------|------------------------------|---|
| water      | $13 \pm 3$                   | $24 \pm 4$                              |
| wet snow   | $4 \pm 0.5$                  | $0.75 \pm 0.25$                         |
| ice        | $3.15 \pm 0.1$               | $2 \times 10^{-3} \pm 5 \times 10^{-4}$ |
| dry snow   | $2.1 \pm 0.2$                | $4 \times 10^{-4} \pm 5 \times 10^{-5}$ |
| road (dry) | 1.43                         | 0.21                                    |

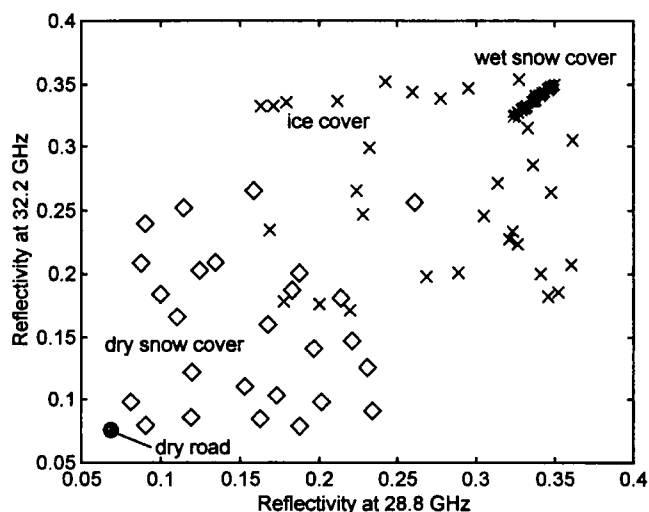


FIGURE 5 Reflectivities for important surface conditions at two frequencies as the dielectric constants and surface cover thickness (1 to 2 cm) are varied.

fiers, a reference oscillator, adjustable test stands to support the equipment, and a liquid nitrogen-cooled model road surface. A high-level diagram of the system is shown in Figure 6.

The data acquisition board generates an output voltage between 0 and 10 volts as set by software. This voltage controls the YIG-tuned GaAs microwave oscillator to produce microwaves in the range from 26.5 to 40 GHz. The microwaves travel through waveguides, an isolator, and two directional couplers. The first coupler is used for voltage-to-frequency calibration. The second coupler is used to monitor the source power, which was not leveled. Next, microwaves are modulated by the PIN diode attenuator, which is driven by the local oscillator's reference signal.

For most measurements, the modulated microwave signal is directed with a horn antenna onto the center of road surface at an incidence angle of  $60^\circ$  from a height of 40 cm. A second horn antenna receives the reflected microwave signal, and a crystal diode detector converts it to a direct current that is proportional to power. This current is dropped across a load resistor to provide an appropriate voltage input signal to the lock-in amplifier. The input voltage is mixed with the reference signal supplied from the local oscillator. The output voltages from the lock-in amplifiers are sent to input channels of the data acquisition board and recorded.

Road surface covers that were simulated include wet surfaces with various amounts of water, wet snow, dry snow, and ice with thicknesses varying from 0.1 to 2 cm. The road surface was covered with Styrofoam to maintain low surface temperatures over longer periods.

## RESULTS AND ANALYSIS

The first step in the procedure is to normalize the reflection data to account for variations in transmitter power and path attenuation as a function of frequency. A reference signal was created by measuring reflection from a copper sheet placed over the road surface to act as a near-perfect reflector. Subsequent scans of actual surface conditions were then normalized by dividing the received signal with the reference signal. Reflectivity of surface condition is then given by

$$R_i = \frac{V_i}{V_{\text{ref}}}$$

where  $V_{\text{ref}}$  is the corresponding reference signal.

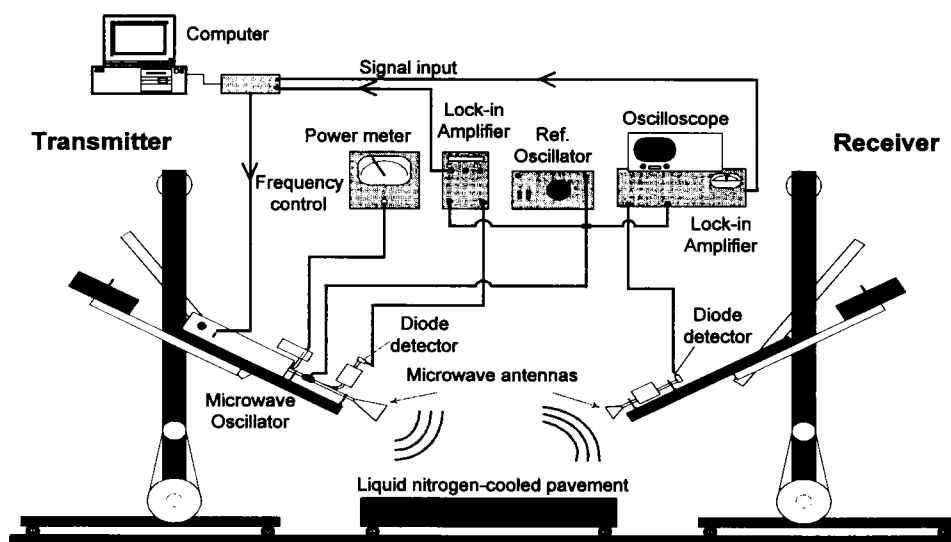


FIGURE 6 High-level diagram of active microwave remote sensing system.

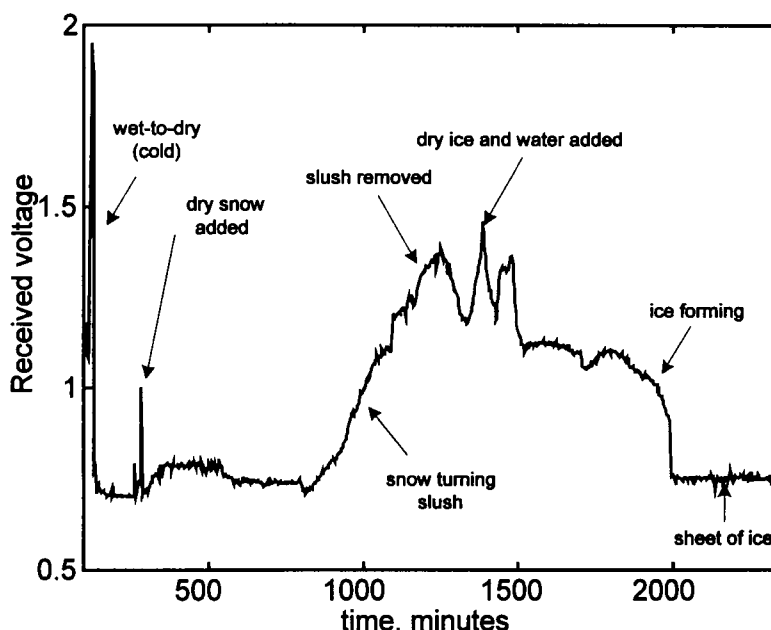


FIGURE 7 Reflectivity versus time for changing surface covers at 32.2 GHz.

Typical data are shown in Figure 7. The thicknesses of water, slush, ice, and dry snow covers were 0.2 cm, 0.5 cm, 1 cm, and 0.5 cm, respectively. The large peaks are caused by mismatches in the microwave apparatus and peculiarities of the source whose power is unleveled.

The results indicate that the ability to distinguish various surface covers on the basis of reflectivity data is dependent on the frequency used. For example, all conditions appear to be distinguishable for frequencies centered at 33.2 GHz, whereas at 32.9 GHz dry snow, ice, and dry surface reflection overlap each other.

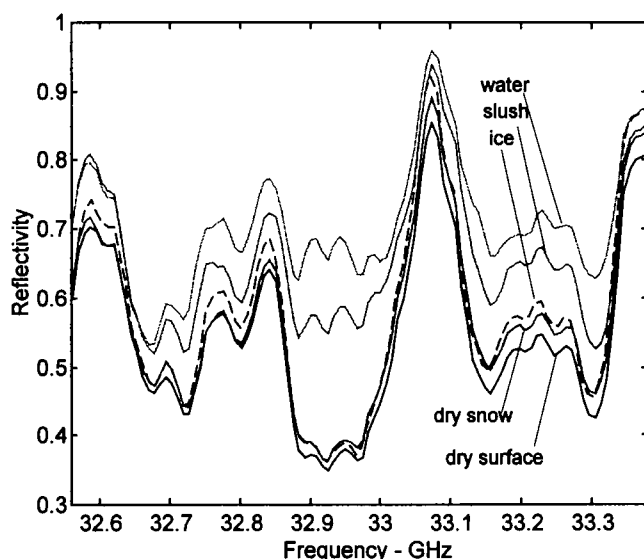


FIGURE 8 Normalized reflected signal from various surfaces.

The time to acquire the surface scans as a function of frequency was about 3 min. Because conditions on the road surface change very slowly, these scans can be viewed as snapshots of the surface reflectivity at a given instant of time. In contrast, monitoring the surface as a function of time indicates how reflectivity changes as the surface undergoes a transition from one condition to the next. Figure 8 shows a continuous record of reflectivity for changing road surface cover over a 2-day period, with transmitter frequency fixed at 32.2 GHz. Water, dry snow, and dry ice were added and liquid nitrogen was used for cooling to achieve various surface states. Details of the experiment are given in Table 2.

It is interesting to note that the reflectivity of the dry surface changes with temperature. Figure 9 shows a significant increase in reflectivity as the surface temperature increases from 15°C to 22°C. Figure 9 also shows results for snow cover superimposed on the same graph. As can be seen, the reflection amplitudes for snow and warm, dry surfaces overlap significantly, making it difficult to differentiate the surface states on the basis of reflectivity alone. However, if surface temperatures were known, the surface condition could be classified correctly.

#### SIMPLE MAXIMUM LIKELIHOOD CLASSIFIER

The results indicate that unambiguous estimates of the surface cover will require multiple measurements including reflectivity at two or more frequencies, surface temperatures, and perhaps phase information. Combin-

TABLE 2 Details of Experiment

| Time         | Action  | Comments   |
|--------------|---|--|
| 3 minutes    | 1 liter of water added while surface is cooled by liquid nitrogen.                              | absorbed quickly due to porosity of asphalt.                             |
| 210 minutes  | 2 buckets of dry snow is added to the chilled surface and leveled by hand using a metal shovel. | spikes in the reflectivity are caused by the presence of metal shovel.   |
| 700 minutes  | None  | snow is becoming slushy due to relatively warm temperatures.             |
| 1250 minutes | Slush is removed with the metal pan.  | surface is being cooled by circulating liquid nitrogen through the coil. |
| 1500 minutes | 3 kilograms of dry snow and 0.5 liters of water are added.                                      | wet and icy surface when temperature plunges below zero (°C).            |
| 1900 minutes | None  | ice is forming.  |

ing this information to form an optimal estimate can be done most efficiently by using pattern recognition, neural networks, or other adaptive strategies. These autonomous schemes would eliminate dependence on human interpretation and increase decision speed significantly. A simple experiment was conducted to see how a rudimentary pattern recognition scheme could be implemented. The input parameters comprise reflectivity values at only two frequencies to make it simple and easy to visualize. Other parameters can be added to improve system accuracy.

The surface detection scheme was based on a maximum likelihood classifier. Several simplifying assumptions were required. First, the data for each condition (class) were assumed to have a Gaussian distribution. This assumption did not turn out to be valid for all classes, but it allowed a simple classifier to be built and studied. Second, the road conditions were assumed to belong to a finite number of discrete classes. This is not physically correct, because gradual transitions can be expected from one condition to another. This problem could be addressed by using a more sophisticated algorithm such as a fuzzy classification approach.

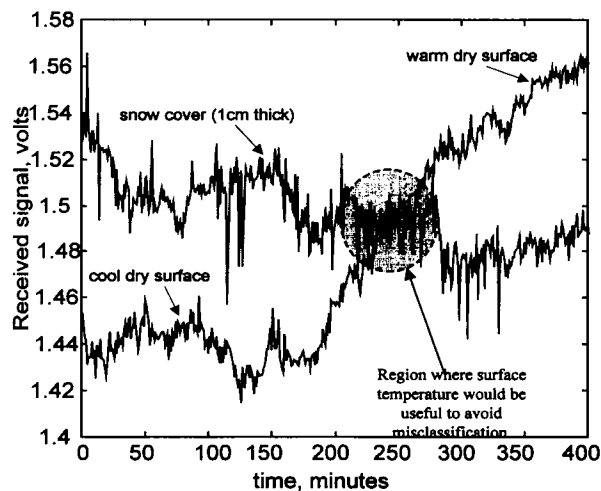


FIGURE 9 Ambiguity in surface detection, emphasizing the need for surface temperature.

The probability density function (pdf) for reflectivity vector  $\mathbf{x}$  given that the signal belongs to surface class  $s_i$  is

$$p(\mathbf{x}/s_i) = \frac{1}{(2\pi)^n |\mathbf{C}|^{1/2}} \exp \left[ -\frac{1}{2} (\mathbf{x} - \mathbf{m}_i)' \mathbf{C}_i^{-1} (\mathbf{x} - \mathbf{m}_i) \right]$$

where  $\mathbf{C}_i$  is the covariance matrix and  $\mathbf{m}_i$  is the mean vector of surface class  $s_i$  (11).

To test the road surface when the condition state is concealed, the unknown reflectivity vector  $\mathbf{x}$  is input into the density function. The class with the largest pdf value is chosen as the assigned class for that particular input.

The maximum likelihood decision surface is shown in Figure 10. Note that the graph was generated by using a contour-type plot, which unfortunately results in multiple lines for each boundary. More properly, a single line would be used to represent the boundary. Figure 10 shows that the classifier works well for separating slush cover from dry surface and ice cover. Water reflectivity (not shown) would be very high (around 4), and thus

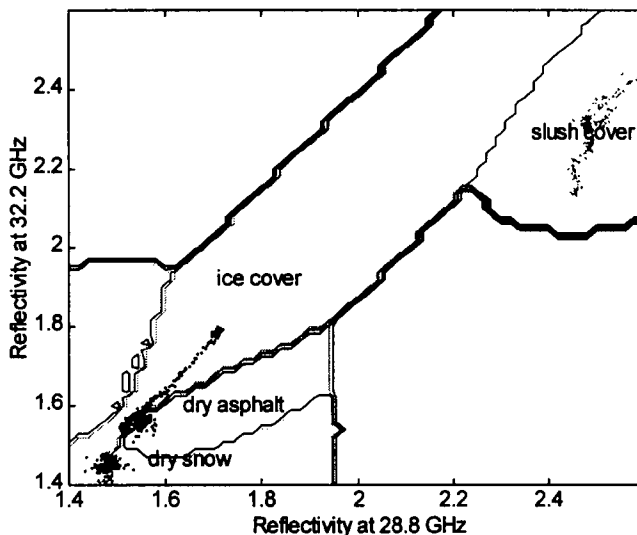


FIGURE 10 Decision boundaries and measured data points at two frequencies.

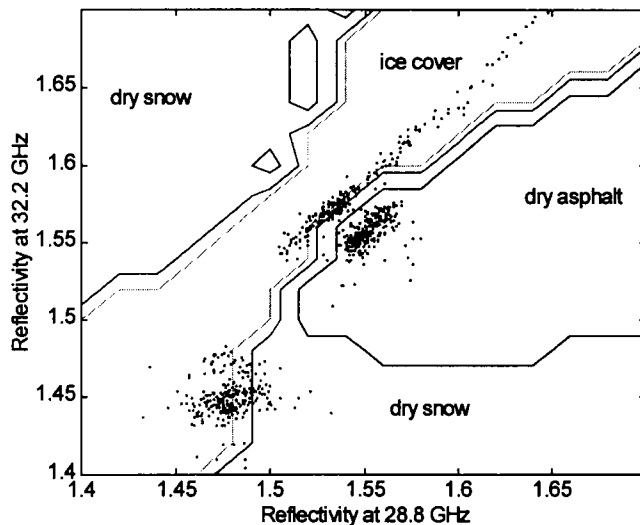


FIGURE 11 Zoomed decision boundaries with measured data points for several surface conditions.

would be easily distinguishable from the other surfaces. A zoomed plot of Figure 10 is given in Figure 11 to emphasize the region containing the snow cover, ice cover, and dry surface data points.

Figure 11 indicates that the distinctly non-Gaussian distribution of ice cover reflectivity causes approximately half of the snow cover data points to be misclassified into the ice class. This is caused by the non-Gaussian distribution of ice cover. It should be noted that these data points are not separable if either frequency is used alone but are distinct when two of them are combined.

For visualization and simplicity, this classification was limited to two input parameters, but it could easily be extended to more than two input parameters, such as additional frequencies, phase information, or surface temperature. Also, better pdf estimates could be used to provide better performance for non-Gaussian conditions.

## PRACTICAL CONSIDERATIONS

### System Implementation

The complexity, size, and cost (about \$5,000) of a fully implemented system would be comparable to that of a police radar gun. The sensor could be implemented as a small pole-mounted transceiver unit installed adjacent to the roadway, with passive reflectors located on the opposite side of the road. At the receiver, a microprocessor would process the received signals to estimate signature values. A second set of algorithms would provide real-time estimates of surface moisture, snow, ice, slush, and multiple-layer conditions such as a thin sheet of water overlying an ice layer. On the basis of the preced-

ing analyses, a dual-frequency system, which would operate at two well-separated microwave frequencies to provide independent information about surface conditions, is proposed. Additionally, the proposed system would employ both a reflected path, in which the principal radio beam would reflect off the road surface, and a direct path, in which the beam would travel directly from transmitter to receiver antennas without intercepting the road surface. Unwanted variations common to both signals, such as antenna icing, atmospheric effects, and power supply fluctuations, could be eliminated by comparing the direct and reflected signals. This system design is being investigated as an NCHRP Innovations Deserving Exploratory Analysis (IDEA) Program project (NCHRP 31).

The proposed active microwave sensing technique offers many technical advantages over embedded sensors and passive microwave systems:

- The active microwave system should provide a more representative measure of actual pavement conditions than do point estimates of moisture from embedded sensors. Microwave measurements are based on reflections from the entire surface illuminated by the transmitter antenna.
- Unlike embedded sensors that detect moisture accumulations indirectly, the microwave system directly senses road ice and snow conditions, and trained personnel are not needed to interpret the data. The estimates are made by computer and are available to the public and maintenance personnel in real time.
- Use of both a direct signal and a reflected signal provides immunity to antenna icing and other time-varying effects, making this system much more robust and reliable than a passive system.
- The proposed microwave system would cost a small fraction of an embedded sensor installation while providing accurate condition reports and more detailed information about ice and snow accumulation. Moreover, as compared with embedded sensors, microwave systems can be relocated easily to new positions as required by highway managers, and are not damaged by snowplowing operations.

### Application

Increasingly, state and local highway departments must maintain more roads with fewer personnel, older equipment, and declining budgets. Low-cost winter road condition sensors would provide a means to leverage limited human resources by concentrating maintenance efforts where they are most needed. High-resolution real-time road information removes much of the guesswork and



allows optimum assignment of personnel and equipment to developing trouble spots.

Because of low unit cost and small size, the proposed system sensors could be installed at regular intervals along less-traveled rural highways, on bridges and mountain passes, along hazardous curves, and along highway stretches prone to icing or drifting snow. Microwave sensors would instantly detect worsening road conditions caused by rapidly evolving weather systems and thus eliminate inherent delays associated with eyewitness reporting methods. This detailed road information could be delivered to users by way of telephone and radio broadcasts, as well as other formats such as a World Wide Web page.

## CONCLUSIONS

The feasibility of active microwave remote sensing of road surface conditions was investigated. A prototype system was constructed and tested. Microwave reflectivity data were collected for a variety of conditions including accumulations of ice, snow, and slush produced in the laboratory. Two types of surface reflectivity scans were done, reflectivity versus frequency and reflectivity versus time. The following conclusions were drawn:

- Differing surface conditions generate distinguishable signatures in the microwave reflection data, establishing the feasibility of an active microwave system.
- Reflection characteristics vary as a function of frequency. Radiation at more than one frequency could be used to identify the road surface condition.
- Computer simulations were consistent with the actual measurements.
- Knowledge of surface temperature would be a desirable parameter for a detection system to help avoid misclassification of the road surface for dry snow cover, hard-frozen ice cover, or warmer, dry surface conditions.

## ACKNOWLEDGMENT

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