Terahertz and millimeter wave transmission of soils

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ABSTRACT

Transmission spectra were measured over the range 90-140 GHz and 300-4200 GHz for 20 soil samples that span a number of soil orders that have extensive worldwide distribution. A vector network analyzer equipped with 16 degree horn antennas covered the spectral range 90-140 GHz. Transmission measurements were also taken for some organic materials in the 90-140 GHz range. A Fourier spectrometer equipped with Hg arc lamp, pellicle beamsplitter, and Si bolometer collected transmission spectra over the range 300 to 4200 GHz. Transmittance ranged from 10^{-7} to almost 1. In all cases, transmission drops to zero for wavelengths shorter than the characteristic particle size of the sample as a consequence of scattering. In samples of mixed particle size, low transmittance in the 90-140 GHz range was found to be caused by the coarse component. This work is relevant to mine detection using THz and millimeter wave (mmW) radiation.

Keywords: terahertz, millimeter waves, landmine detection, soils, transmission

1. INTRODUCTION

There are an estimated 100 million land mines placed throughout the world,[1] as the unfortunate byproduct of various armed conflicts. The threat to civilians persists long after these conflicts cease, which greatly impedes economic and social recovery of the affected regions for many years. Land mines kill or injure an average of 70 people daily.[2] Anti-personnel mines can be buried just beneath the surface, whereas anti-tank mines are usually buried as deep as 40 cm. The landmines can be any shape and be made of many different materials including metal, plastic, or wood. There are a number of detection technologies applied for the remediation of minefields, such as inductance coils (metal detectors), magnetometers, ground-penetrating radar, infrared imaging, and explosives vapor sensors.[2] A THz/mmW system[3] is potentially attractive in that, in an imaging mode, it can achieve good discrimination between anti-personnel mines that are primarily though not exclusively non-metallic, and the small metallic debris (shrapnel, cartridge cases, etc.) typical of minefield conditions. Physical properties in favor of THz/mmW-based imaging are that the soil can have high emissivity and low reflectivity, whereas metallic objects are just the opposite, with high reflectivity and low emissivity. The THz/mmW emission by the soil depends mainly upon its temperature, whereas the effective temperature of the metallic objects depends on a cold-sky reflection. Because of the shape and size discrimination inherent in an imaging system, the tradeoff between false alarm rate and miss rate is favorable for THz/mmW wavelengths.[4] Ability to detect and image buried objects will depend on soil transmission and scattering, which may depend on soil type and morphology. This paper reports the transmission of different soils in the THz and mmW ranges.

2. EXPERIMENTAL METHODS

Transmission spectra were measured for various soils in the 90-4200 GHz range. A Bomem DA8 Fourier spectrometer equipped with Hg arc lamp, pellicle beamsplitter, and Infrared Labs 4 K Si bolometer (Figure 1) collected transmission spectra from 300 to 4200 GHz. The 300-1500 GHz range was taken using a 50 μm mylar beamsplitter at 240 GHz resolution with the 4 K Si bolometer. Additional measurements were taken in the 450-1650 GHz range using a 25 μm

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beamsplitter at 60 GHz resolution with the 4 K Si bolometer. Spectra were also collected in the range 1200-4200 GHz using a 12 μm mylar beamsplitter and the 4 K Si bolometer, however the transmission above 1500 GHz was found to be very low for all samples studied.

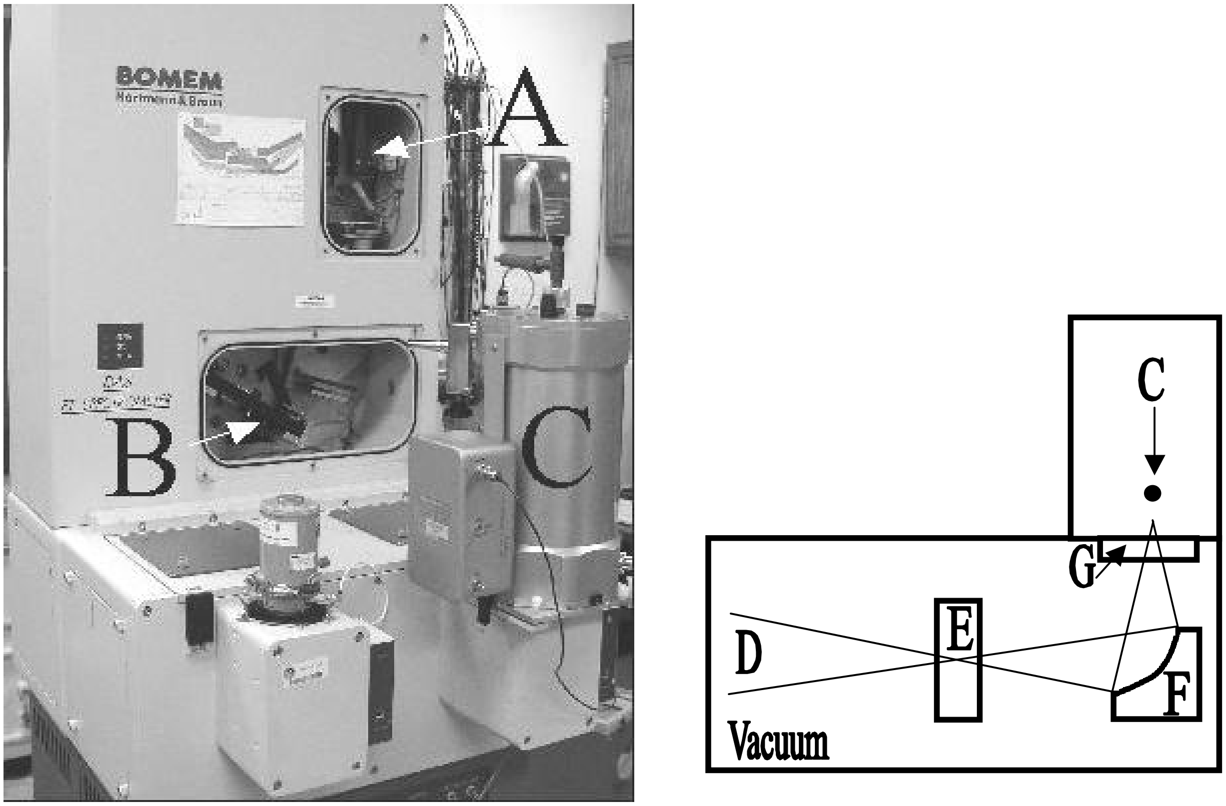

Figure 1: (left) A Fourier transform spectrometer equipped with Hg arc lamp (A), pellicle beamsplitter (B) and cryogenic Si bolometer (C) and (right) sample compartment with modulated beam (D), sample cell (E), off-axis ellipsodal mirror (F), and Polyethylene window (G).

An Anritsu ME7808A vector network analyzer equipped with 16 degree hom antennas (Figure 2) collected transmission spectra from 90-140 GHz at 0.125 GHz resolution. This high resolution data was smoothed using adjacent point averaging to reduce oscillations in the baseline due to resonances in the sample cell.

Figure 2: Photograph (Left) and schematic (Right) of the vector network analyzer's transmitter and receiver equipped with horn antennas in the transmission configuration.

The samples for the Fourier spectrometer measurements were placed in a polyethylene cell that provided 1mm path length through the soil, as shown in figure 3. The polyethylene flanges were wedged to inhibit etalon resonances.

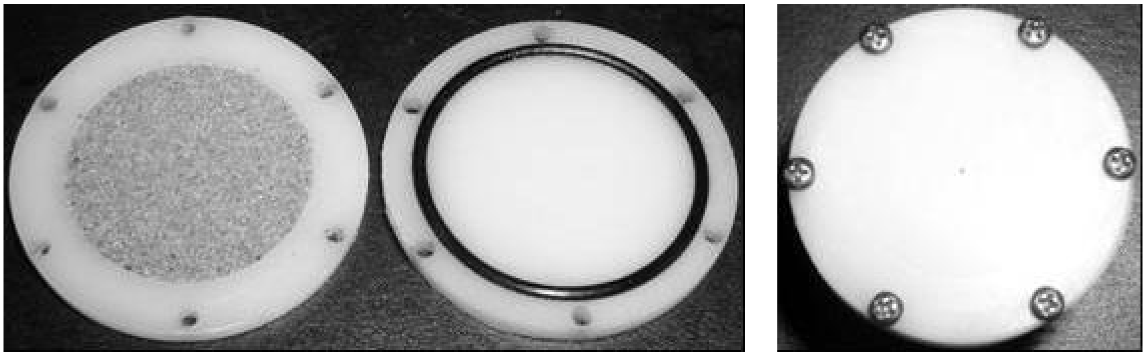

Figure 3: Polyethylene sample cell providing 1mm path length through soil. Inside view with FL sand (Left) and sealed top view (Right).

The sample cell for the vector network analyzer was made of polystyrene and provided 2.2 cm path length through the sample (Figure 4).

Figure 4: Polystyrene sample cell with 2.2 cm path length of Virginia Clay (Left), White Beach Sand (Middle), and Bank Run Gravel (Right).

Far-infrared transmission spectra were collected over the range 300-1500 GHz for 12 soil samples obtained from National Resource Conservation Service (NRCS). These samples were pulverized with a mortar and pestle and sieved for maximum particle size of 250 micron. Samples were maintained in a laboratory environment with ~40% relative humidity.

Geologists recognize 12 different soil orders.[5] The NRCS samples belong to six of these. The orders are differentiated by chemical and other characteristics of their horizons. Our “Surface” samples are A-horizon, where much of the original rock structure has been obliterated, where soluble minerals have been leached out, and where humified organic matter has been accumulated. Anti-personnel mines would exclusively be located within A-horizons. Our “Subsurface” samples correspond to upper B-horizon, which occurs below the A-horizon. Though, much of the original rock structure is also obliterated, the B-horizon is compositionally distinct from the A-horizon. Anti-tank mines could conceivably be buried in B-horizon soils. Some characteristics of the NRCS soils are collected in Table I.[6]

The “Sibley” samples are Mollisols, which usually have thick dark surface horizons.[5] They are not massive or very hard when dry. They are characteristic of steppes, are extensive in sub-humid to semi-arid regions, on plains of North America, Europe, Asia, South America, most extensively at mid-latitudes. They have enough available moisture to support perennial grasses. The fertile horizon is due to long term addition of organic matter from plant roots. Mollisols are found on ~6.9% of the ice free land on earth and ~21.5% in the U.S.

The “Minvale” samples are representative of the Ultisol order. These soils usually have clay coatings on the surface of granules or pores, or as bridges between sand grains.[5] Ultisols are most extensive in warm humid climates with seasonal precipitation deficit. Utisols are strongly leached, and are often acid forest soils in older stable landscapes. They often have a strong yellow or red color from Fe-oxides. Utisols are found on ~8.5% of the ice free land on earth and ~9.2% in the U.S., especially in the southeast region.

The soil samples "Wakeland" are representative of the Entisol order, which is characterized by the absence of distinct subsurface diagnostic horizons within 1 m of the surface.[5] Such soils are found in steep rocky settings. This is the most extensive soil order containing ~16.2% of the ice free land area on earth and ~12.3% in the U.S.

The soil samples "Doakum" are representative of the Aridisol order, which is characteristic of arid climates with little or no leaching.[5] Soluble salts may accumulate in these soils. There is no plant available water for more than half the time that the temperature is above 5 ºC, when it is warm enough for growth. The soil never has water continuously available for as long as 90 consecutive days when the temperature is above 8 ºC. This soil also contains $CaCO_3$. Aridisols are found on ~12.0% of the ice free land on earth and ~8.3% in the U.S.

The "Montevello" samples are representative of the Inceptisol order. These soils have weakly developed subsurface horizons.[5] Inceptisols are found on fairly steep slopes. Inceptisols are found on ~9.8% of the ice free land on earth and ~9.7% in the U.S.

The samples "Angola" are representative of the Alfisol order. These soils are moderately leached with subsurface clay accumulation.[5] Alfisols are found in temperate, humid, and sub-humid regions. Alfisols are found on ~9.7% of the ice free land on earth and ~13.9% in the U.S.

The six remaining soil orders were not studied at this time due to their unusual locations or low abundance on earth. They are Gelisols, Histosols, Spodosols, Andisols, Oxisols, and Vertisols.[5] Gelisols are soils found in very cold climates and contain permafrost within 2 m of the surface. They are found on ~8.6% of the ice free land on earth and ~8.7% in the U.S. Histosols are soils composed of 30-40% organic materials and are only found on ~1.2% of the ice free land on earth and ~1.6% of the U.S. Spodosols are acid soils containing a subsurface accumulation of humus which is complexed with Al and Fe. They are found on ~2.6% of the ice free land on earth and ~3.5% in the U.S. Andisols are soils formed in volcanic ash and are found on ~0.7% of the ice free land on earth and ~1.7% in the U.S. Oxisols are very highly weathered soils found in intertropical regions. They are found on ~7.5% of the ice free land on earth and ~0.02% in the U.S. mainly in Hawaii. Vertisols are clay rich soils that shrink and swell with changes in moisture. They are found on ~2.4% of the ice free land on earth and ~2.0% in the U.S.

Table I: Soil Sample Taxonomy[6]

Order	Soil	Total Organic Carbon %	Total Inorganic Carbon %	Clay %	Silt %
Mollisol					
	Sibley A	1.06	0.49	23.5	69.7
	Sibley B	0.72	0.52	26.9	68.0
Ultisol					
	Minvale A	1.89	0.99	6.1	59.0
	Minvale B	0.10	0.07	23.6	44.2
Entisol					
	Wakeland A	0.92	0.00	23.8	64.7
	Wakeland B	0.56	0.25	21.1	66.4
Aridisol					
	Doakum A	0.28	0.08	10.8	24.8
	Doakum B	0.39	0.18	29.3	15.0
Inceptisol					
	Montevello A	3.55	0.62	6.0	69.0
	Montevello B	0.42	0.26	19.0	42.0
Alfisol					
	Angola A	3.72	0.96	32.1	56.1
	Angola B	----	----	----	----

Table I shows that all B-horizons except Doakum are lower than A-horizons in organic carbon. Also, all B-horizons except Wakeland are higher in clay.

Millimeter wave transmission spectra were collected (90-140 GHz) for 8 different soil samples (6 from Night Vision and Electronic Sensors Directorate Mine Lane Facility (NVESD) Fort Belvoir, VA[7] and 2 sourced locally at UCF) using a vector network analyzer. These samples contained a wide range of particle sizes, including rocks of up to cm dimensions. Data were collected for these samples in their original mixed state, after sieving for a maximum particle size of 0.5 mm, and for the coarse remainder of sieving.

The six soil samples were obtained from the NVESD were Magnetite (Lane 1), Loam (Lane 2), Crusher Run Gravel (Lane 3), Bank Run Gravel (Lane 4), Virginia Clay (Lane 5), and White Beach Sand (Lane 6). Magnetite is a poorly graded gray sand containing no sizable rocks. It contains 74% Quartz, 20% Magnetite, 4.1% Ilmentite, 1.1% Plagioclase, and 1% total Phyllosilicates.[7] Magnetite has a higher amount of Fe_2O_3 than the other soils. Loam is a low-plasticity brown clay containing some rocks a few mm wide. It contains 89% Quartz, 6.1% total Phyllosilicates, 2.6% K-Feldspar, and 1.2% Plagioclase.[7] Crusher Run Gravel is a browngravelly silty sand containing many rocks from 0.5 to 4 cm wide. It contains 46% Plagioclase, 22% quartz, 18% total Phyllosilicates, 9.2% K-Feldspar, 2.8% Dolomite, and 1.1% Calcite.[7] Bank Run Gravel is a gravelly low -plasticity reddish brown clay containing many rocks 0.1 to 5 cm wide. It contains 73% Quartz, 16% total Phyllosilicates, 7.2% Goethite, 2.7% K-Feldspar, and 1.5% Plagioclase.[7] Virginia Clay is a reddish brown gravelly silty sand containing many rocks 0.1 to 2.5 cm wide. It contains 89% Quartz, 8.4% total Phyllosilicates, 1.9% K-Feldspar, and 0.5% Plagioclase.[7] White Beach Sand is a light gray poorly graded sand containing traces of rocks a few mm wide. It contains 98% Quartz and 1.8% total Phyllosilicates.[7] Two samples were sourced locally from Orlando, FL. They were FL Sand and Brick Sand. Both samples are free from rocks or debris and have uniform particle sizes of ~200 μm.

Transmission spectra were collected for some organic materials, shown in figure 5, using the vector network analyzer in the range 90-140 GHz (Figure 8). Materials studied include wet and dry sod, organic debris (leaves, roots, sticks, etc) and water.

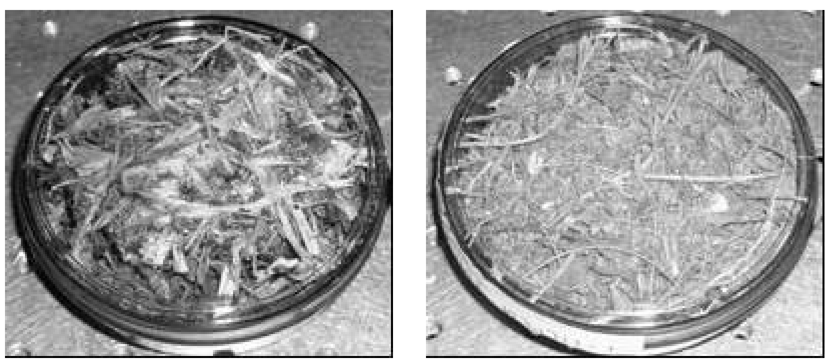

Figure 5: Polystyrene sample cell with 2.2 cm path length of Dry Sod (Left) and Organic Debris (Right).

3. RESULTS

Transmittance spectra of the 12 NRCS soil samples for the range 300-1500 GHz are shown in Figures 6 & 7. The high frequency range is dominated by a roll-off due to scattering. The characteristic cutoff wavelength is similar to the characteristic particle size, as determined using an optical microscope. For instance, the surface samples of Figure 6 tend to zero transmittance for frequencies in the range 900-1200 GHz, which corresponds to wavelengths in the range 333-250 μm. This correlates well with the 250 μm maximum particle size obtained by sieving. Soil transmittance is seen to increase at lower frequencies because decreased scattering allows more signal to be collected by the bolometer (Figure 1). This occurs when the wavelength is longer than the particle size. At the low frequency end of the measured band (300 GHz), the transmittance ranges from 0.2 to 0.75 for 1 mm sample path length.

The subsurface specimens of Minvale, Wakeland, Doakum, and Montevallo have a lower cutoff frequency and smaller transmittance than the corresponding surface samples. The Sibley and Angola spectra tend very slightly in the opposite direction. This may be due to small differences in the particle size distribution but it may also be due to the difference in chemical composition. We note that[8] near surface soils tend to be leached of soluble or quickly altered minerals.

Surface soils are rich in insoluable quartz, clay minerals, and iron oxide alteration products, but they are poor in calcium carbonate.

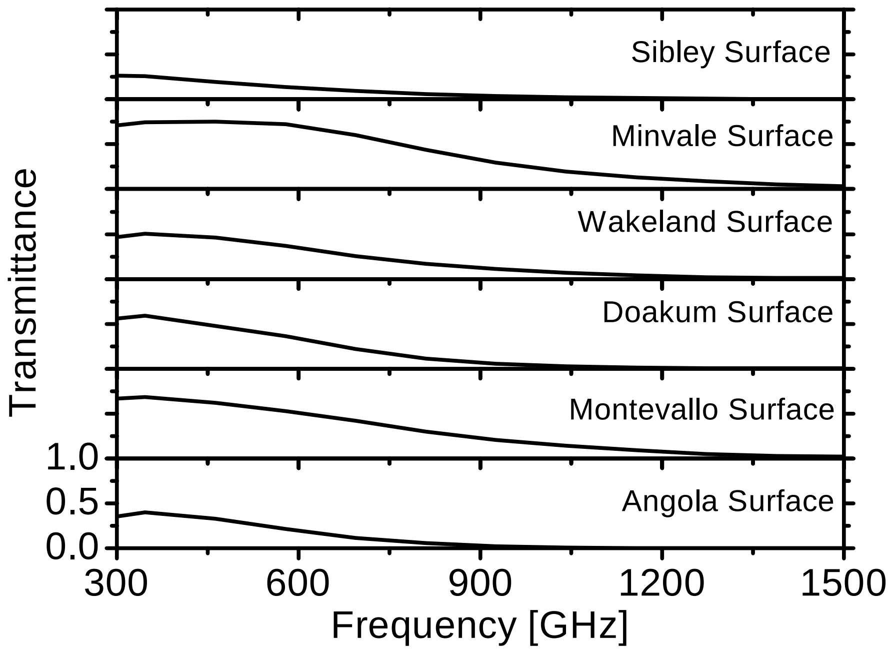

Figure 6: Transmittance spectra for 1 mm thick surface soil samples.

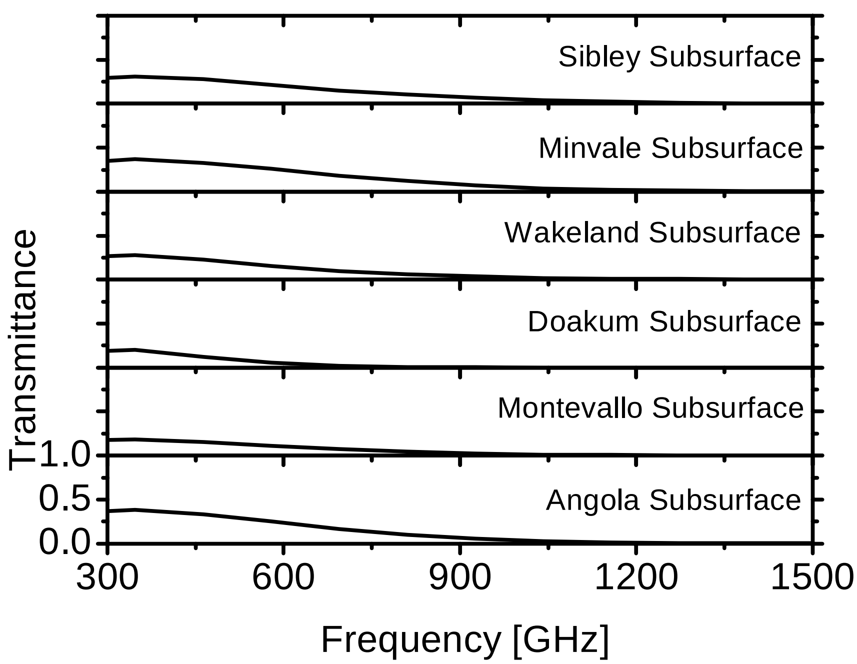

Figure 7: Transmittance spectra for 1 mm thick subsurface soil samples.

Transmittance spectra in the 90-140 GHz range for NVESD samples Loam, Virginia Clay, Bank Run Gravel, Crusher Run Gravel, are presented in figures 8, 9,10, and 11 respectively. The sieved samples all have transmittance in the range 2% to 30%, which is higher than the non-sieved samples by ~2-3 orders of magnitude. The coarse remainder has transmittance even lower, by a fractor of up to 1000. These results show that large particle sizes in the range 0.5 mm to ~cm cause strong scattering of millimeter waves (2-3 mm wavelength). This observation is in agreement with that already made for the NRCS samples, namely that transmittance is high when the wavelength exceeds the soil particle size.

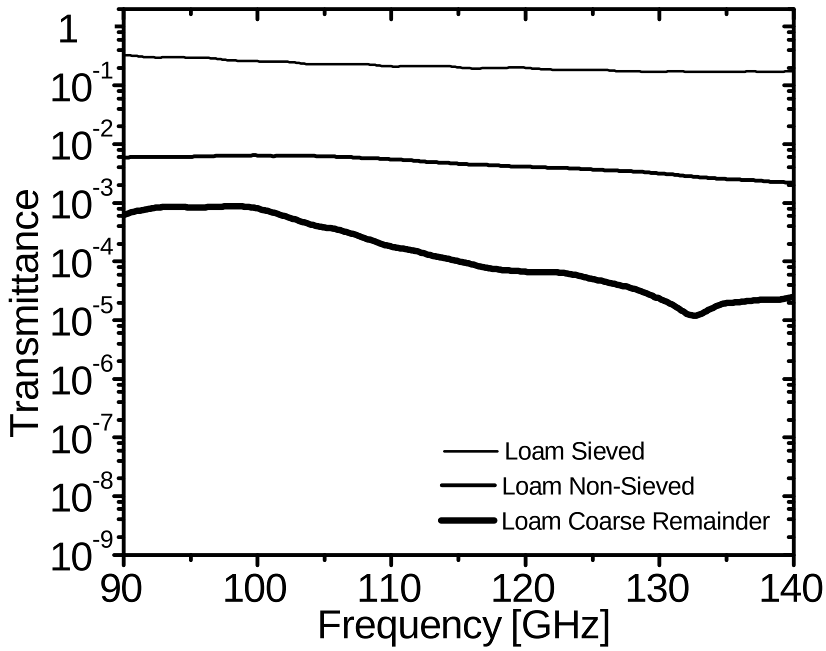

Figure 8: Transmittance spectra for 2.2 cm thick Loam soil samples.

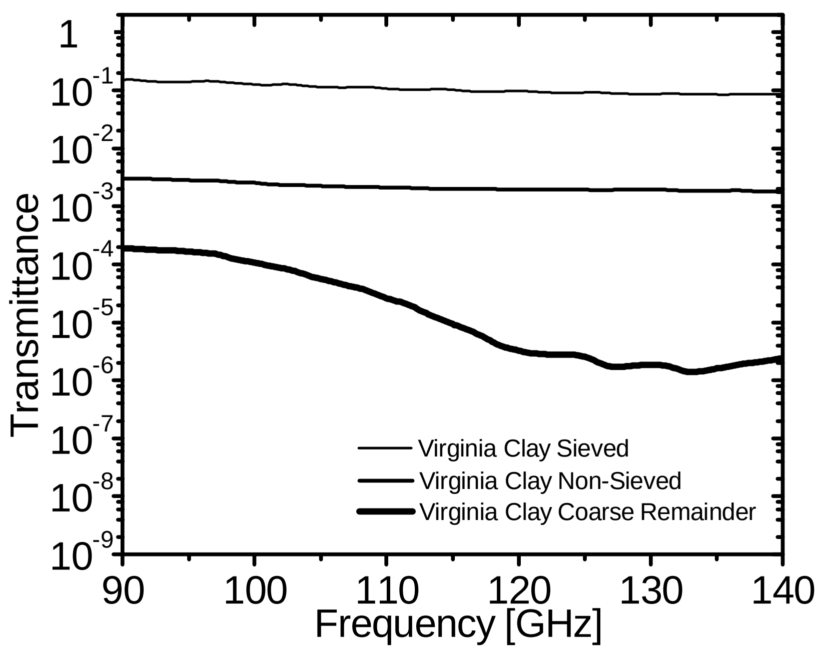

Figure 9: Transmittance spectra for 2.2 cm thick Virginia Clay soil samples.

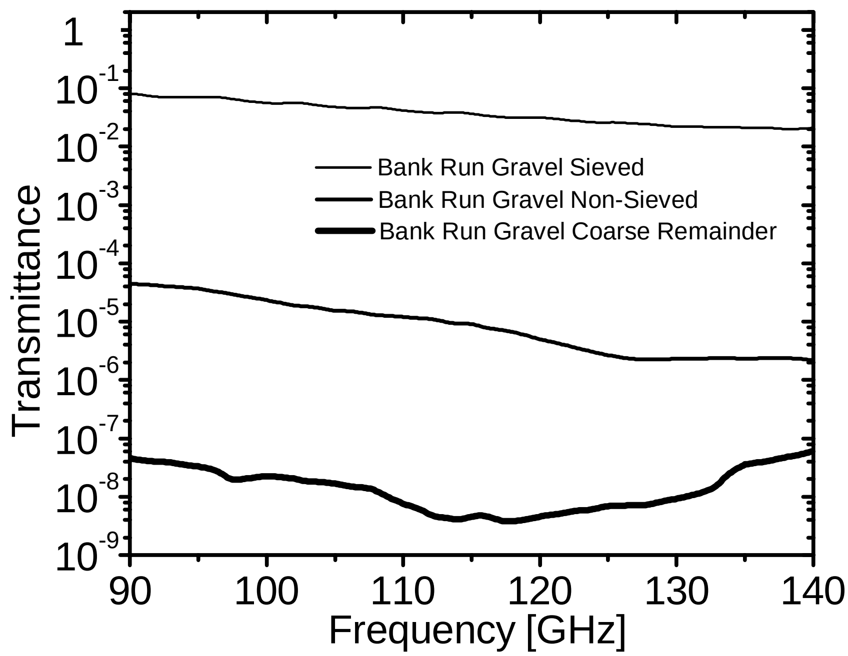

Figure 10: Transmittance spectra for 2.2 cm thick Bank Run Gravel soil samples.

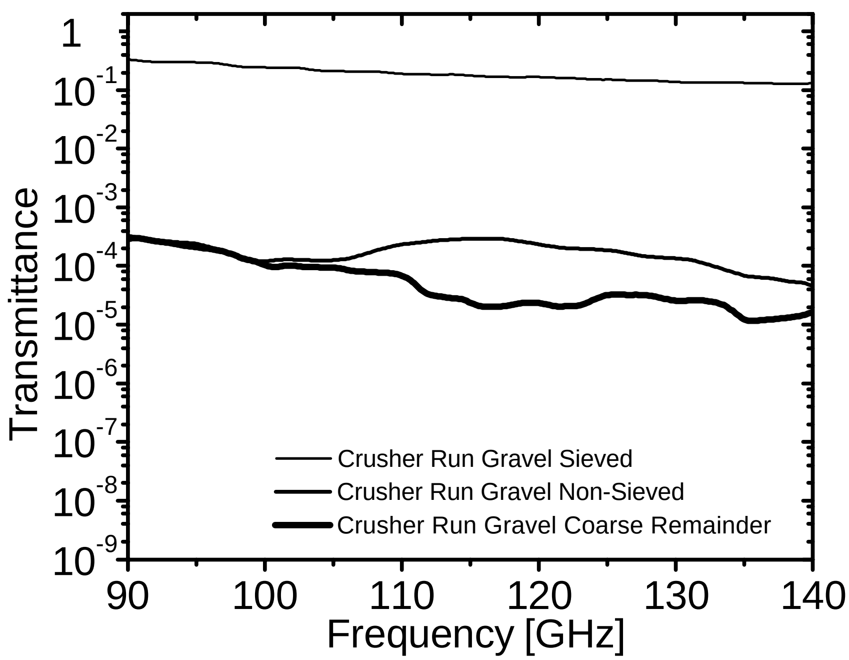

Figure 11: Transmittance spectra for 2.2 cm thick Crusher Run Gravel soil samples.

Figure 12 presents spectra of the three sand samples. These tend naturally to have a uniform particle size distribution. Only the NVESD White Beach Sand contained enough coarse particles to make sieving worthwhile. When isolated, the coarse remainder from the sample has transmittance of 20-45%, however the abundance of coarse material in the non-sieved sample is insufficient to lower that samples transmittance much below 90%. The sieved fraction and the other samples all have near 90% transmittance. We note that the 2-3 mm wavelengths are significantly greater than the particle size in this case, in agreement with our previous observations.

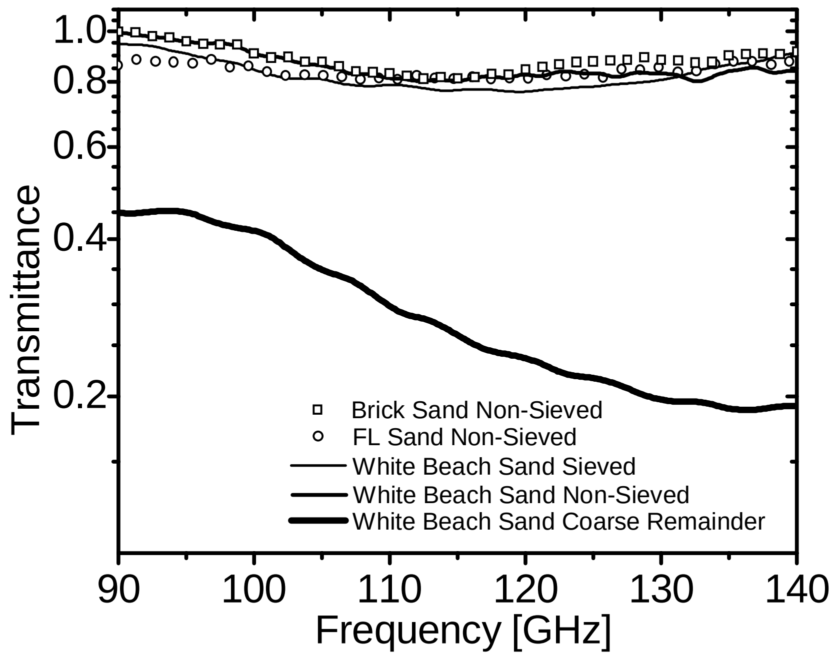

Figure 12: Transmittance spectra for 2.2 cm thick Brick Sand, FL Sand, and White Beach Sand soil samples.

Figure 13 presents mmW spectra for the magnetite sample. The results here do not follow the trend of transmittance vs. particle size noted earlier. Non-sieved, sieved, and coarse remainder all have transmittance below 0.01%. The latter two segregated samples both have higher transmittance than the non-sieved sample. The magnetite sample morphology was very different from that of the other NVESD samples. It contained a light colored sandy component of uniform sub-mm size distribution and a dark magnetic component that tended to stick together in clumps. The non-sieved sample contained few large particles; the fraction that passed through the mesh openings during sieving contained both the light and dark components. This unusual sample should not be considered typical of soils likely to be encountered in the field.

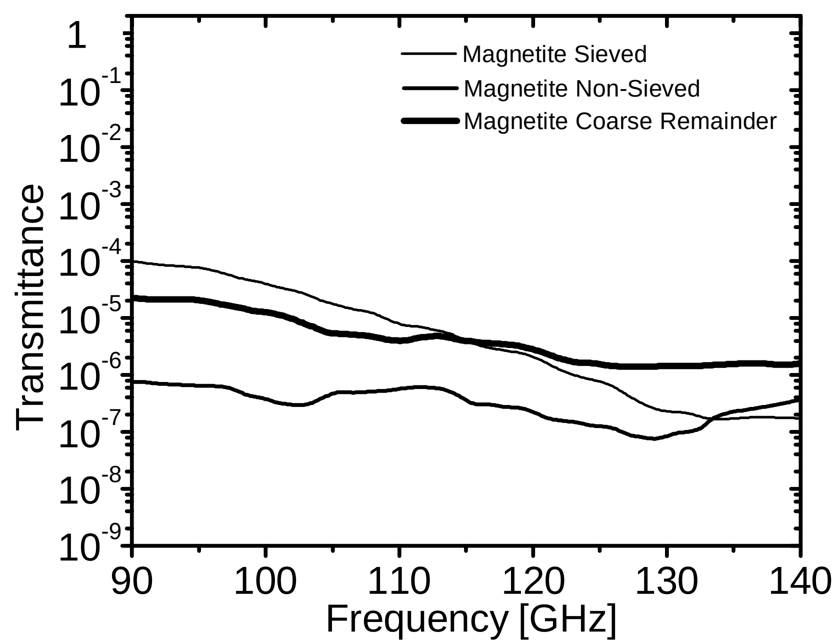

Figure 13: Transmittance spectra for 2.2 cm thick Magnetite soil samples.

The transmittance of some organic materials in the 90-140 GHz frequency range is presented in figure 14. Organic matter is a strong source of attenuation possibly because of efficient scattering of its relatively large particle sizes. A spectrum of water is also presented in Figure 14, and water is found to be a strong attenuator, which explains the relative transmittance of dry and wet sod samples. The dry sod has a slightly higher transmittance than the wet sod. Note that both wet and dry sod samples have lower transmittance than plain water, so that scattering by inhomogenities in the organic samples is apparently more important than absorption by moisture.

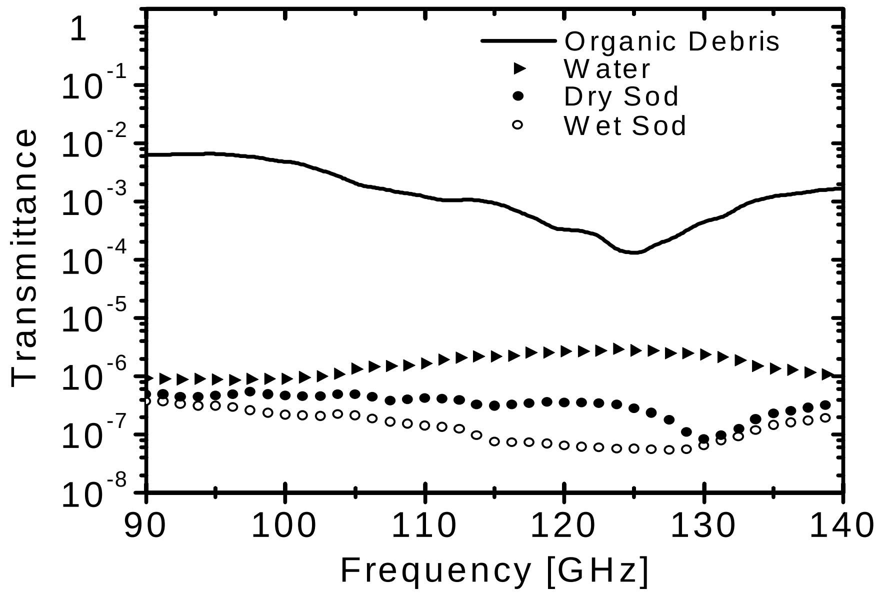

Figure 14: Transmittance spectra for 2.2 cm thick organic samples.

4. SUMMARY

Transmission of soils was measured in the 90-140 GHz and 300-4200 GHz range. The high frequency range is dominated by a roll-off due to scattering, which correlates with particle size. Samples with particles larger than the wavelength have low transmittance. Organic materials and water are a strong source of attenuation. High transmission was noted through some soils types when the particles are sufficiently fine. This shows promise for mmW/THz landmine detection in regions of the world where such soils are found.

ACKNOWLEDGEMENTS

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