Terahertz/millimeter wave characterizations of soils for mine detection: transmission and scattering

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ABSTRACT

Transmission spectra were measured over the range 90-4200 GHz for a locally sourced soil sample composed mostly of quartz sand with ~200 micron particle size. A vector network analyzer covered the spectral range 90-140 GHz. A Fourier spectrometer collected transmission spectra over the range 120 to 4200 GHz. Transmission drops to zero for wavelengths shorter than the characteristic particle size of the sample as a consequence of scattering. Transmission spectra were also measured for various liquids in the 90-140 GHz and 450-1650 GHz ranges in the interest of index matching. These liquids were mixed with the soil sample and were found to reduce scattering and increase transmission through the soil at higher frequencies. This work is relevant to mine detection using THz and millimeter wave (mmW) radiation.

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

1. INTRODUCTION

There are an estimated 100 million land mines placed throughout the world[1] as a byproduct of war. The threat to civilians persists and impedes economic and social recovery. 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 has 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. Soils with particle sizes larger than the wavelength have low transmittance due to scattering.[5] Reflections occur at the boundaries between the soil particles and air causing the light to scatter. The reflections at the soil particle/air boundaries can be reduced by replacing the air surrounding the soil with an index matching fluid. An index matching fluid with low absorption in the THz/mmW ranges will reduce scattering and increase transmission through the soil. This paper reports the transmittance of a locally sourced soil sample composed primarily of ~200 μm grains of quartz sand in the THz/mmW ranges. An increase in transmittance at higher frequencies when the soil is mixed with an index matching liquid is found.

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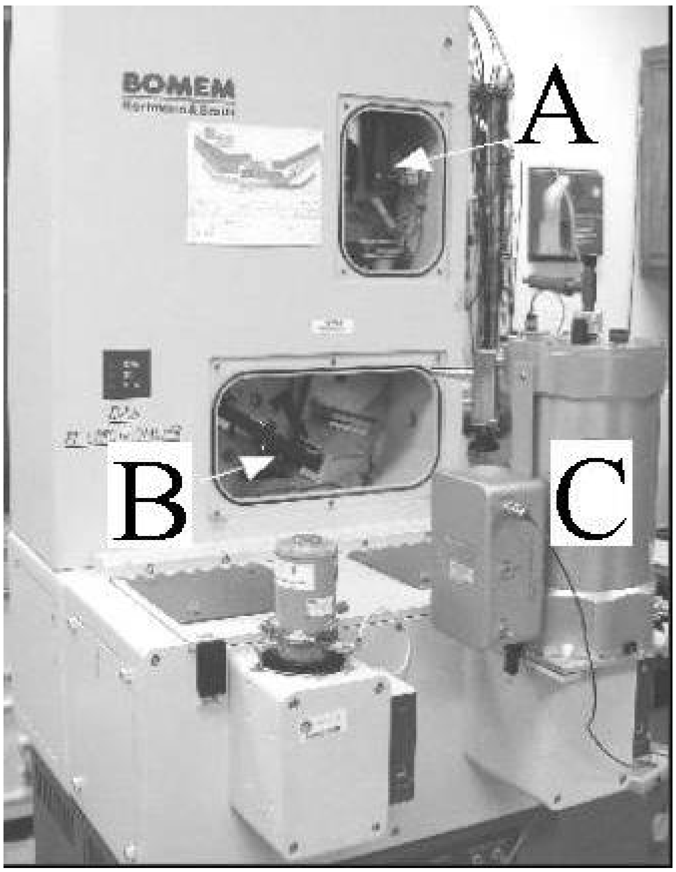
2. EXPERIMENTAL METHODS

Transmission spectra were measured for soil in the 90-4200 GHz range. A Bomem DA8 Fourier spectrometer equipped with Hg arc lamp, pellicle beamsplitter, and Infrared Labs Si bolometer (Figure 1) collected transmission spectra from 120 to 4200 GHz. Measurements were taken in the 120-450 GHz range using a 100 μm mylar beamsplitter at 60 GHz resolution with a 1.8 K Si bolometer. 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 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 soil samples studied. The 1 mm sample cell was placed in front of the off-axis ellipsoidal mirror, whereas the thicker 2.2 cm sample cell was placed after the mirror to reduce scattering loss.



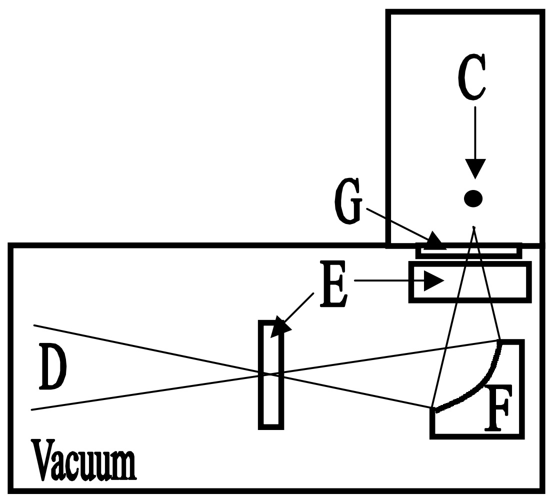


Figure 1: (left) A Fourier transform spectrometer equipped with Hg arc lamp (A), pellicle beamsplitter (B) and cryogenic Si bolometer (C) and (right) sample compartment with modulated beam (D), sample cell (1 mm or 2.2 cm) (E), off-axis ellipsoidal mirror (F), and Polyethylene window (G).

An Anritsu ME7808A vector network analyzer equipped with 16 degree horn 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.

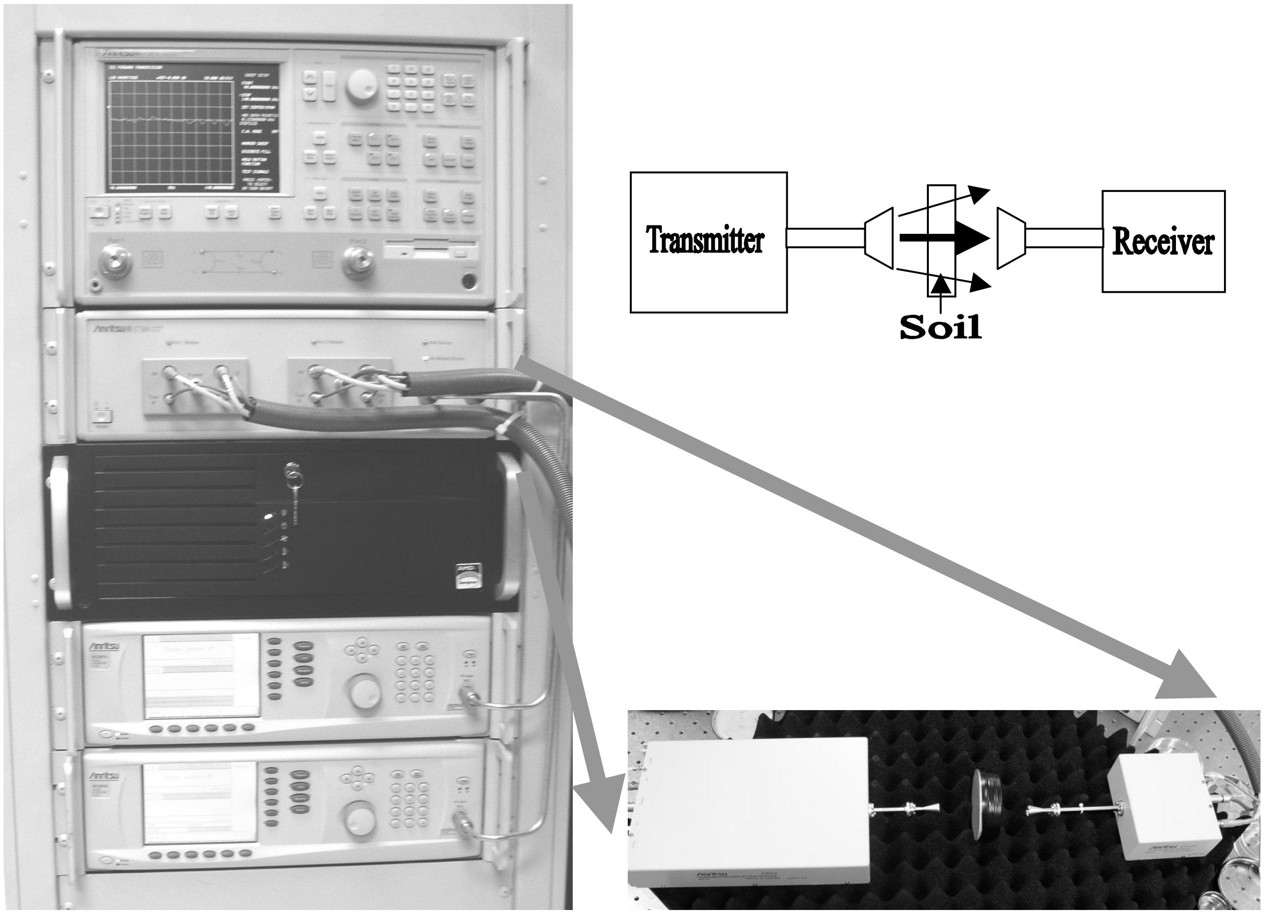


Figure 2: Photograph of the vector network analyzer (Left) and schematic (Top Right) and photograph (Bottom Right) of the vector network analyzer's transmitter and receiver equipped with horn antennas in the transmission configuration.

The samples for the Fourier spectrometer measurements from 350 to 4200 GHz 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.

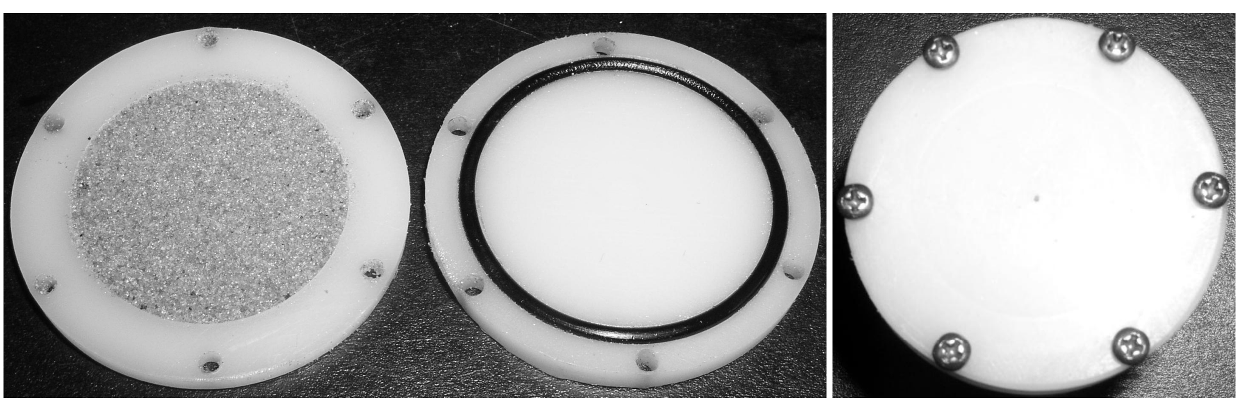


Figure 3: Polyethylene sample cell providing 1mm path length through soil. Inside view with FL sand (Left) and sealed top view (Right).

A polystyrene sample cell with 2.2 cm path length through the soil was used for the measurements taken with the vector network analyzer and the Fourier spectrometer form 120-450 GHz using the 1.8 K Si bolometer (Figure 4).

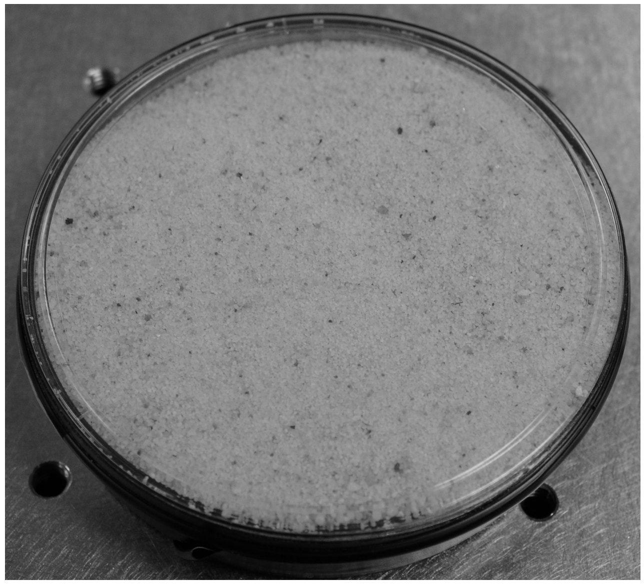


Figure 4: Polystyrene sample cell with 2.2 cm path length of the soil sample.

The soil sample studied was sourced locally on the campus of UCF in Orlando, FL. The soil is free from rocks or debris and has uniform particle sizes of ~200 μm determined using an optical microscope. “Dry” samples were maintained in a laboratory environment with ~40% relative humidity.

The liquids measured were WD-40, Nujol mineral oil, vegetable oil, extra virgin olive oil, canola oil, Florolube, heptane, and silicone oil for index matching experiments. The soil samples were fully saturated with the index matching liquids and placed into the sample cells.

3. RESULTS

Transmittance spectra of the soil sample for the range 90-1500 GHz using the vector network analyzer and Fourier spectrometer are shown in Figure 5. 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 micros cope. For instance, the soil sample tends to zero transmittance for frequencies in the range 1000-1500 GHz, which corresponds to wavelengths in the range 300-200 μm. This correlates well with the 200 μm particle size measured using an optical microscope. Soil transmittance is seen to increase at lower frequencies because decreased scattering allows more signal to be collected by the detector. This occurs when the wavelength is longer than the particle size.

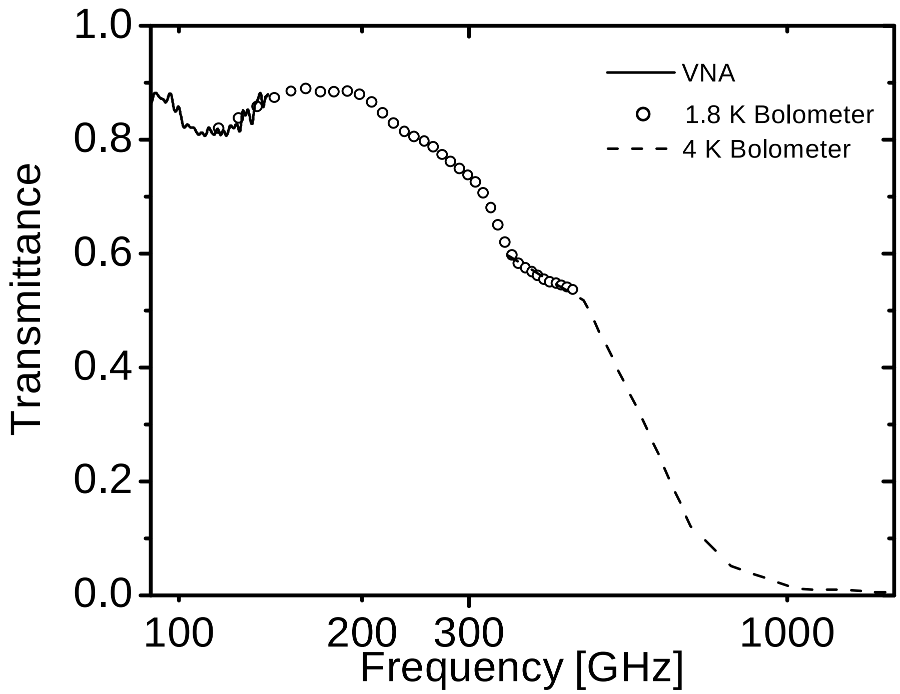


Figure 5: Transmittance spectrum of soil.

Transmittance spectra of some liquid samples over the range 90-140 GHz is shown in figure 6. Maximum transmittance ranges from 0.25 to 0.05. The path length of the mm-wave beam through the sample is 2.2 cm.

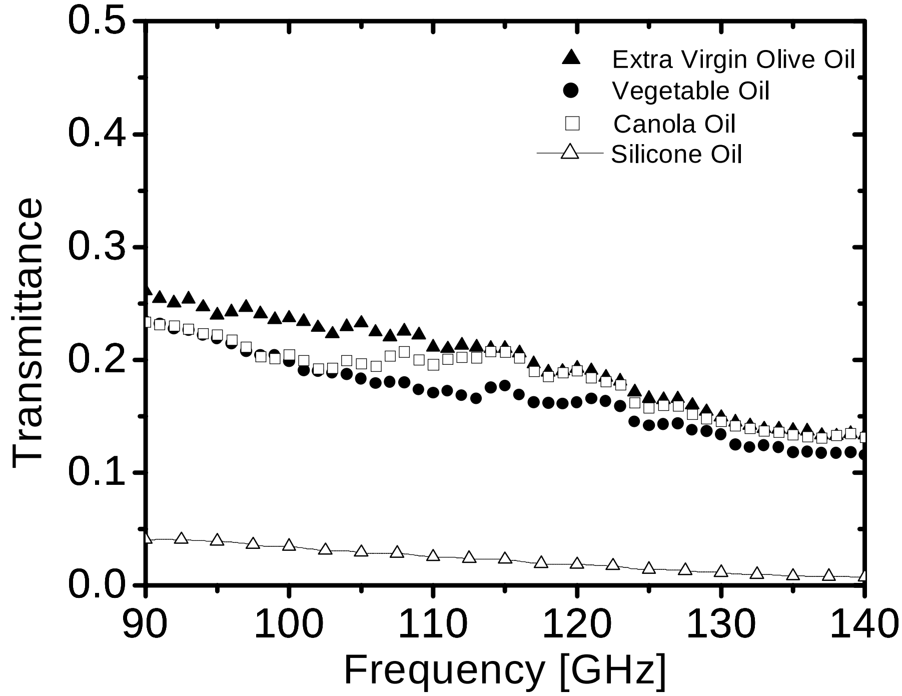


Figure 6: Transmittance spectra of 2.2 cm path length of potential index matching liquids in the 90-140 GHz range using a vector network analyzer.

Figure 7 shows the transmittance of some liquids over the range 450-1650 GHz. The transmittance of the index matching liquids ranges from 0.2 to almost 1. The path length through the sample is 1 mm. Some of the liquids have good transmittance and hence are potential candidates for index matching.

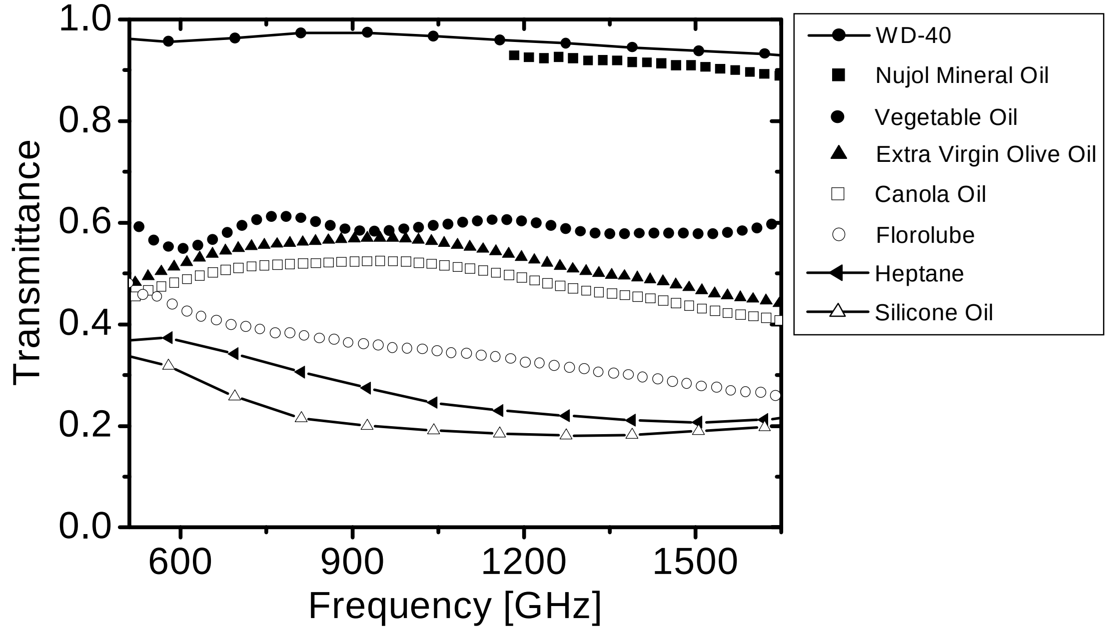


Figure 7: Transmittance for 1 mm path length of some liquids.

Several of the liquids were used to saturate soil samples for the purpose on index matching. Figure 8 shows the transmittance spectra. The transmission of the dry sample is high in this range because the wavelength is larger than the particle size. The fluids decrease the soil transmittance in this range due to their absorption.

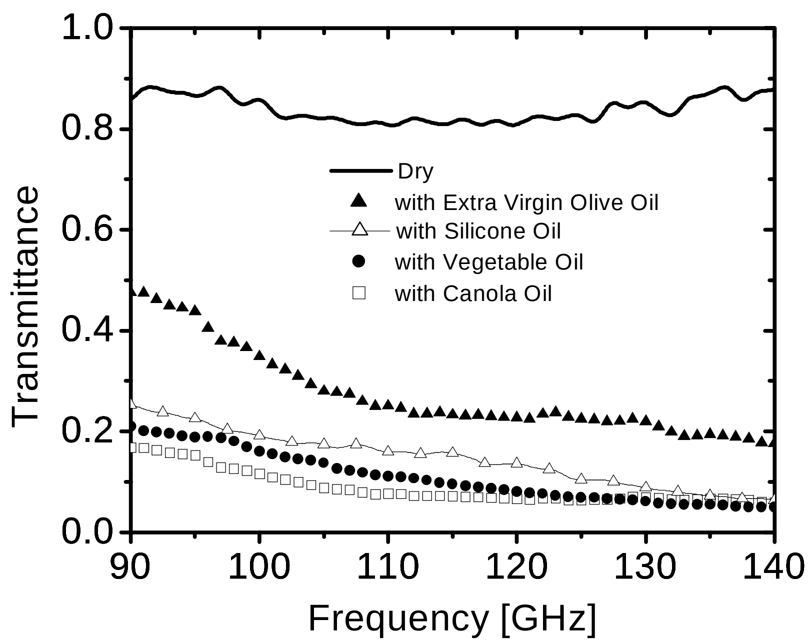


Figure 8: Transmittance spectra of 2.2 cm path length of several index matching liquids mixed with the soil sample.

At high frequencies, the addition of index matching fluid reduces scattering and increases transmission. Even though index matching has increased transmission, there is still a roll-off at high frequency. This is because the liquids studied are actually poor matches to the index of the particles (n_{quartz} ~ 2.1 and n_{oil} ~ 1.5 at 1 THz). Proper index matching can potentially push the roll-off frequency higher, extending the useful range further into THz.

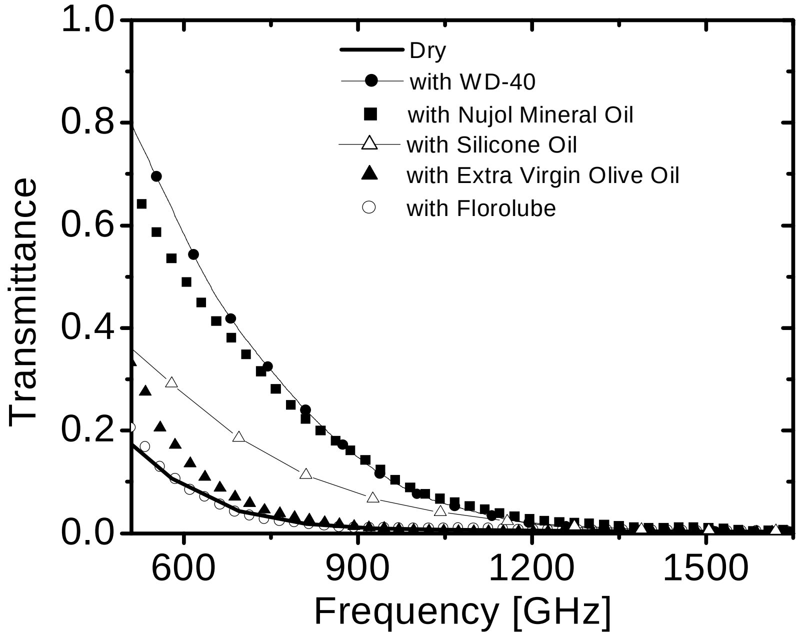


Figure 9: Transmittance spectra of 1 mm path length of the soil sample saturated with several index matching liquids.

4. SUMMARY

Transmission of soil was measured in the 90-4200 GHz range. The high frequency range is dominated by a roll-off due to scattering, which correlates with particle size. Saturation with index matching liquids reduces scattering and increases transmission at higher frequencies. A transparent low toxicity fluid with index of refraction closer to 2 would have great promise for use with terahertz imaging for mine detection.

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