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INVITED REVIEW ARTICLE

# Invited Review Terahertz Transmission, Scattering, Reflection, and Absorption—the Interaction of THz Radiation with Soils

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**Abstract** Terahertz radiation has been proposed as a useful tool in the study of soils and related materials from such diverse perspectives as detection of non-metallic landmines to improving soil fertility by agricultural charcoals produced by pyrolysis of organic material. The main barrier to such applications is that soils are rather opaque at terahertz frequencies. In this article, the main findings to date on the interaction of terahertz radiation with soils are reviewed, organized around the four phenomena of terahertz: transmission, scattering, reflection, and absorption. Terahertz transmission through soils is generally low and decreases with frequency. Terahertz scattering is evident in many THz-soil interactions, as the wavelength of the radiation is of the order of the particle size. Terahertz reflection is important to communications as these develop from the GHz into the THz band. Terahertz absorption on diluted soil samples has been demonstrated to be effective in identifying soil constituents, such as aromatic compounds, and soil contaminants, such as pesticides.

**Keywords** Terahertz · THz · Soil · Sand · Biochar · Transmission · Scattering · Reflection · Absorption

## 1 Introduction

When terahertz radiation strikes soil, four things may happen (Fig. 1). The radiation may bounce back from the soil, or be reflected. The terahertz radiation may

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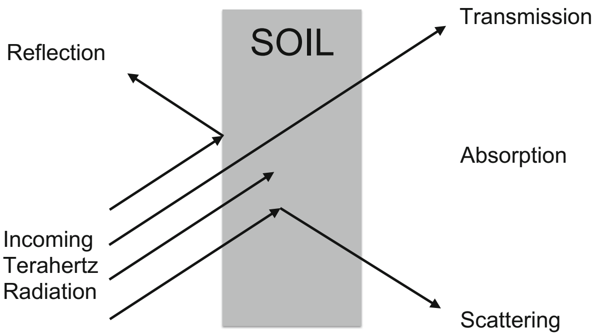


**Fig. 1** Incoming terahertz radiation may be reflected, transmitted, absorbed, or scattered when meeting soil

pass through the soil, or be transmitted. The radiation may be stopped in the soil, or absorbed. The radiation may go into the soil and emerge in a different direction, or be scattered. (While these are convenient classifications, it is recognized other terminology may be useful in some contexts. For example, specular and diffuse reflection may be distinguished, and forward and back scattering, and direct and diffuse transmission; reflection may be referred to as back scattering; a consequence of absorption is often emission; and so on.) These phenomena are general to electromagnetic radiation. According to the principle of the conservation of energy, all of the energy of the incoming radiation must end up somewhere and may be conveniently thought of as ending up in one or more of these four channels. In general, some of the incoming radiation may be transmitted, some reflected, some absorbed, and some scattered.

In terms of terahertz radiation acting with matter generally, sometimes, one or other of these four phenomena predominate [1]. For example, for metals, most incoming terahertz radiation is reflected; the reflectivity increases as the frequency decreases. To take another example, for water and other polar molecules, strong absorption occurs, particularly at specific frequencies. To give a third example, many plastics predominantly transmit terahertz radiation. When it comes to soil, little terahertz radiation is transmitted; much is scattered, the scattering depending on the size of the soil particles relative to the wavelength of the terahertz radiation; some is absorbed, in which case the characteristic frequencies of absorption may be used to identify the particular chemical species responsible; and some is reflected, which is a consideration in terahertz-frequency communications. Each of these four phenomena will now be evaluated in turn.

## 2 Transmission

Transmission of various soils at a variety of frequencies has been reported, often in connection with the proposed detection of landmines [2–9]. To sum up this work, terahertz radiation does not transmit very well through soils, typically penetrating a distance of only millimeters or centimeters.

A example of the results is given in Fig. 2. In dry sand, an attenuation of about 5 dB/cm is measured at 0.1 THz, increasing steadily to 22 dB/cm at 0.35 THz, and increasing further beyond that. Adding water to the sand further reduced the transmission; for example, the peak amplitude in the terahertz signal was reduced by an order of magnitude for a water weight of about 2%, the water absorption being estimated at 8 dB/cm. Another illustration is shown in Fig. 3. Here, the transmission of both surface and subsurface samples of six soil types are shown. The general behavior as the frequency increases is that the transmittance begins at about 0.5 at 0.1 THz, halves from that value by about 0.3 THz, and becomes negligible by 1 THz. The soil samples used in this work were 1 mm thick. A study of four soils in the frequency range 0.34–0.36 THz yielded attenuations of between 1 and 4 dB/mm [9]. No transmission of detectable intensity was found at either 1.627 or 2.523 THz.

Several other examples may be cited to illustrate further the (lack of) penetration depth. For example, 1, 3, or 6 mm of sand shows negligible transmission at 1 THz, while for 3 or 6 mm of dried soil, the transmission is already negligible at 0.3 THz [4]. Thus, the useful depth of penetration has been estimated at 6 cm for 1% water weight [2]. Buried objects have been detected under ∼2 mm of sand [4]. Measurements through 2.8 cm of either wet or dry soil showed no transmission above 0.1 THz (although some transmission at sub-terahertz frequencies, around 0.04 THz, was observed) [8].

To overcome these limitations, one needs to go beyond the terahertz frequency range. So, for example, in a study of transmission through oil-water-soil media characteristic of an underground soil reservoir over the range 0.1–120.0 THz, it was concluded the optimum frequency window for transmission was 70–85 THz, well above the region normally considered to be embraced by “terahertz” [10]. In the opposite frequency direction, by using sub-terahertz frequencies, 0.020–0.060 THz, surrogate landmines could be detected at 3–5 cm below the surface [11].

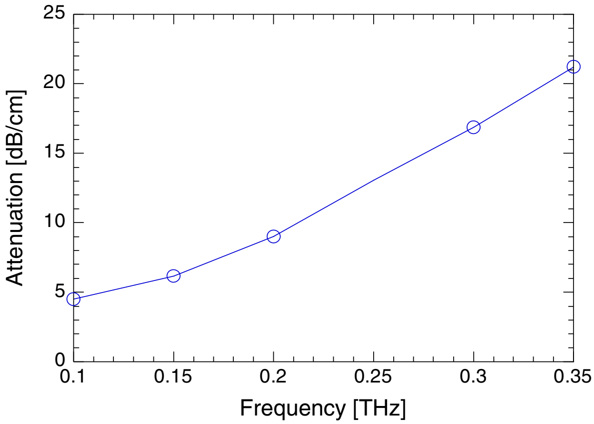


**Fig. 2** Attenuation of terahertz radiation by dry sand [2]

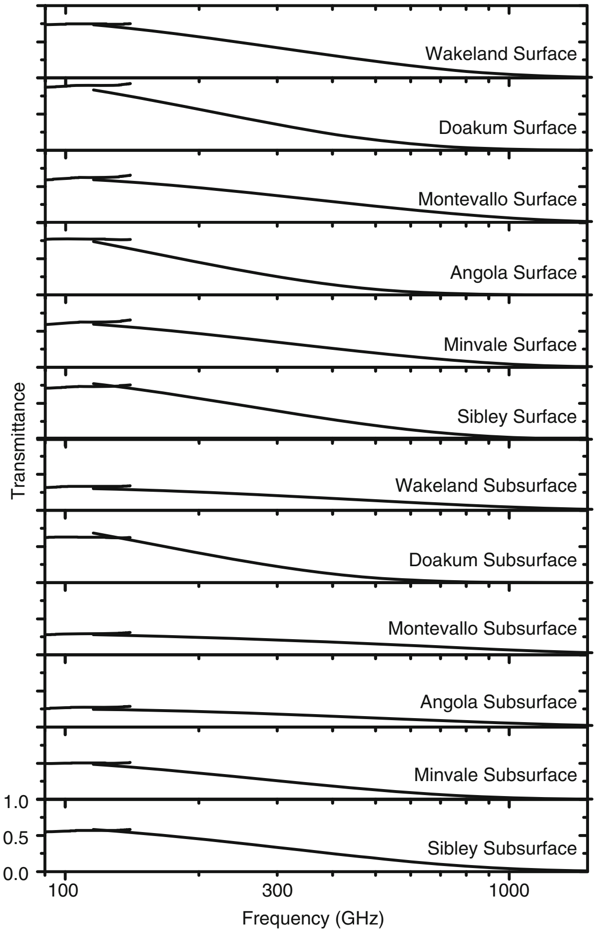


**Fig. 3** Transmission of terahertz radiation through six surface/subsurface soils [7]

The fundamental physical trade-off here is that lower frequencies (microwaves) are needed to penetrate soil to depths beyond a centimeter or so, but these longer wavelengths do not have the spatial resolution to detect small objects such as anti-personnel landmines. The problem should not be seen as insurmountable, but further research is required to solve it.

## 3 Scattering

If not much of the terahertz radiation that impinges on soil is transmitted through the soil, where does it go? A lot of it is scattered. This is the robust conclusion of a series of investigations into the matter [4–8].

The general expression for the scattering of electromagnetic radiation from spherical particles has been derived by Mie and the approximation in the case when the wavelength of the radiation is much greater than the particle size has been given by Rayleigh. As well as scattering from a single particle, in an assembly of particles, which is the case for soil, multiple scattering may occur.

Immediate evidence that scattering plays an important role in the interaction of terahertz radiation with soils is given by experiments in which different sized soil particles were separated by sieving. For loam, Virginia clay, and bank run gravel, a 0.25 mm sieved sample (smaller particles) shows a greater transmission than an unsieved sample and that, in turn, displays a greater transmission than the coarse remainder (larger particles). These measurements were made at around 0.1 THz, corresponding to wavelength of about 3 mm [5, 7]. This analysis is confirmed by adding index-matching liquids, such as extra virgin olive oil, silicone oil, nujol mineral oil, or WD-40 to soil samples, resulting in an improved transmission across the spectral range 0.5–1.5 THz [6, 7].

The analysis of scattering has been put on a quantitative footing. For example, the model of Rayleigh scattering accounts well for the roll-off with frequency observed for the transmittance of dry sand (Fig. 4).

Similar modeling gives good agreement with the experimental transmittance of sand mixed with olive oil as a function of frequency, as well as predicts the improved transmittance at higher frequencies for sand mixed with liquids of index 1.4, 1.6, 1.8, 2.0, and 2.2 [7]. In related work in the sub-terahertz range, 0.001–0.1 THz, Mie scattering was found to account well for the transmission of dry soil and Mie scattering (and Rayleigh scattering) to account well for the transmission of wet soil [8].

Likewise at lower frequencies, corresponding to longer wavelengths, in the range of 1 cm to 1 m, the scattering of ground penetrating radar (GPR) from soils has been investigated. It is found that the scattered microwaves exhibit a fractal dimension [12–14]. Such studies have not yet been extended to the terahertz frequencies.

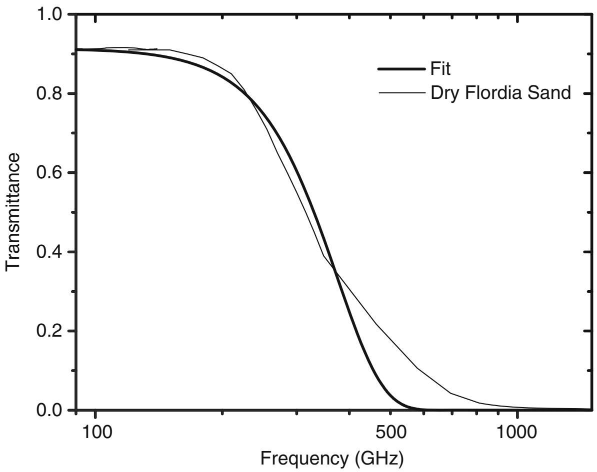


**Fig. 4** Transmittance of terahertz radiation in dry sand as a function of frequency and a theoretical model based on Rayleigh scattering [7]

To conclude, for many typical soils, particle sizes are comparable to the 0.03–3-mm (vacuum) wavelength characteristic of 10–0.1 THz photons. Thus, scattering is often important in soils. It is modeled well either by Rayleigh scattering, in the approximation of the wavelength being large compared to the particles, or, more generally, by Mie theory. Indeed, terahertz scattering is a useful probe of soil particle size.

## 4 Reflection

Reflection of terahertz-frequency radiation from soils has been reported in the contexts of imaging [15] and telecommunications [16]. A representative set of data is given in Fig. 5. Similar data has been reported for sand and for gravel (as well as for brushed and unbrushed concrete and asphalt shingles) [16]. It may be observed that the backscattering coefficient increases with elevation angle and is slightly polarization-dependent [16]. (Similar work has been reported for metals and dielectrics [17, 18].) Early work demonstrated that reflectivity of soil is below 0.05 for low moisture content, but increases to around 0.2 for water contents around 40%, that is, near the saturation value of the soil [15].

## 5 Absorption

Absorption at terahertz frequencies is usually associated with the excitation of particular vibrational modes in a material and so may be used to identify the material by means of a characteristic “signature” or “fingerprint.” In this way, soils have been investigated to determine their composition [19–27]. Typically, a small amount of soil is analyzed, often diluted in a terahertz-transparent medium. Detection of metal

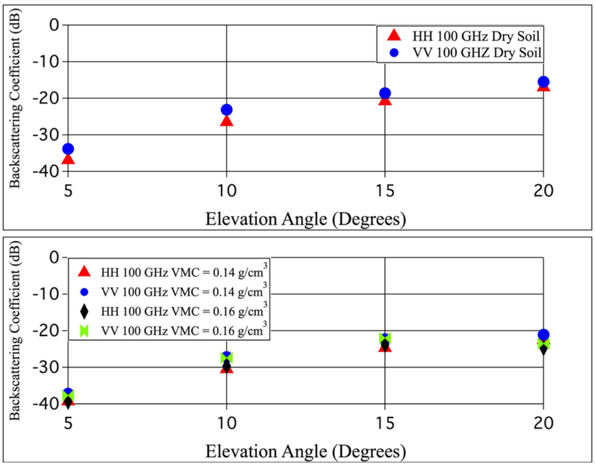


**Fig. 5** Back scattering from dry (*top*) and moist (*bottom*) soil at 0.1 THz as a function of elevation angle for two polarizations [16]

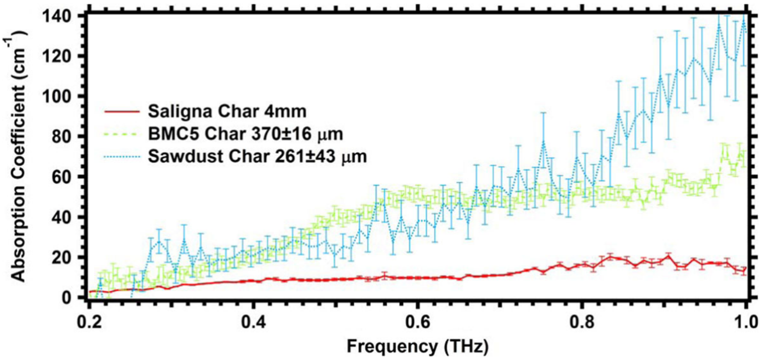


**Fig. 6** Spectroscopy of biochar in the low-terahertz range [24]

ion concentrations as low as 50 ppm have been reported [20]. Special holders have been designed to assist in this effort [21].

Examples of this application of terahertz spectroscopy to soils include the detection of metallic ions, such as copper sulfate or zinc sulfate [19]. Three characteristic absorptions were observed for both the copper and zinc compounds in soil. Another study has investigated these and the heavy metal ions $Pb^{2+}$ and $Cr^{3+}$ as well [20]. The focus of other studies has been the persistent organic pollutants aldrin, dieldrin, and endrin [22] and the pesticide difenoconazole [23].

Now, we turn from pollutants to components that improve soils. In particular, biochars, formed by the pyrolysis of organic materials, are known to improve soil health, but analytical methods for identifying biochar components have been lacking. In the low-frequency terahertz range, three different biochars have been distinguished on the basis of their broad absorption features, but specific vibrational bands have not been observed, Fig. 6. On the other hand, in the high-frequency terahertz range, distinct modes have been both observed and assigned (Fig. 7). The similarity between

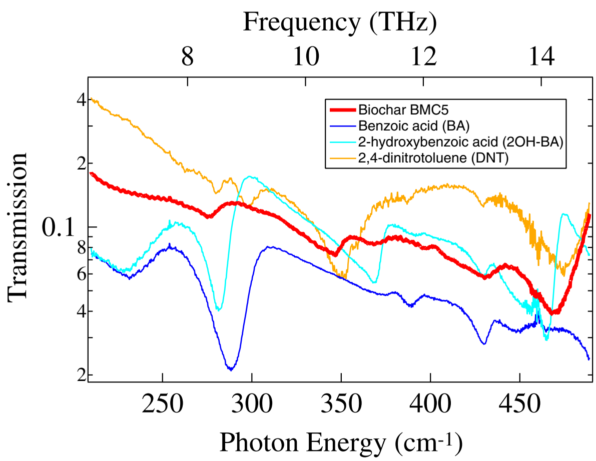


**Fig. 7** Spectroscopy of biochar in the high-terahertz range [27]

the biochar spectra and the spectra of aromatic compounds has led to a study of the latter as a step to a full physical understanding of the biochar spectra [25–27].

As mentioned in the Introduction, absorption may be followed by emission. Indeed, at any non-zero temperature, in general, a blackbody will radiate at all frequencies. Emission at microwave frequencies has been used to monitor soil water content [28], but thermal emission of terahertz radiation from soil does not seem to have been reported.

## 6 Conclusion

Terahertz methods show limitations but promise when applied to soils. Transmission is low, so detection of objects more than a few centimeters below the soil surface is challenging. Scattering is significant, since the terahertz radiation wavelength is typically of the order of the size of the soil particles, but offers diagnostic applications. Reflection is limited, but means that terahertz identification of other objects on the surface of soil is feasible. Absorption of characteristic modes of both harmful (pollutants) and helpful (fertilizers) soil additives has provided good preliminary information and may well open up new areas of research and application.

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