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Characterisation of Attenuation by Sand in Low-THz Band

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***Abstract*—Research to quantify the attenuation of 150 GHz and 300 GHz EM waves in sand has been conducted and the results are presented in this paper to investigate the performance of low-THz sensing for outdoor applications when a antenna radome might be contaminated by sand, which is one of the most common types of contaminant in outdoor environments. The signal power deviation has been studied as a function of sand thickness and granule size. Five kinds of granule-size-calibrated silica sands and natural sand were used in the experiment. While the results confirms expected greater attenuation at 300 GHz than that at 150 GHz, it has also been shown that sand composed of coarser particles provide greater attenuation than that of finer particles, which challenges some previously reported results.**

Keywords—Low-THz wave; transmissivity; sand; automotive

I. INTRODUCTION

The Low-TeraHertz (low-THz) band is in the frequency range between 0.1 THz to 1 THz and this band is currently attracting significant attention due to its potential to deliver high resolution imaging in security, medical, material characterization and automotive applications [1]-[5].

In order to estimate the performance of low-THz systems in outdoor environments, the attenuation of low-THz waves on a radome covered by various types of contaminants that may occur in uncontrolled outdoor environments needs to be studied thoroughly. Contaminants include water, sand (pure or as a part of soil), leaves, mud and etc. Signal reduction through a radome covered by uniform thickness of water has been reported in [6]. The presented paper also investigates the extent at which realistic radome contaminants affect low-THz signal propagation.

Sand is a common contaminant for outdoor application as is the main component of soil and it is also used in road construction/repair. Small particle sizes of sand are more likely to be airborne for a finite period of time before falling down to ground permanently or temporarily before becoming involved in “road spray” activity. This means sand has a high probability to become a radome contaminant and hence needs to be considered before low-THz devices can be considered for outdoor environments.

Many Research [7]-[9] has been conducted to investigate the attenuation of Electro-Magnetic (EM) waves in sand. In [7] and [8] a dielectric constant of sand with different particle sizes and different moisture levels was measured at 10.45 GHz and 11 GHz, respectively. The results of these works indicate that finer particles will lead to higher attenuation for both dry and moist conditions. In [9], it is shown that the attenuation is less than 4 dB within the frequency region 0.5 GHz to 12.6 GHz for dry sand. All reported research were conducted at relatively low frequencies meaning no results regarding sand attenuation at low-THz frequencies has been published.

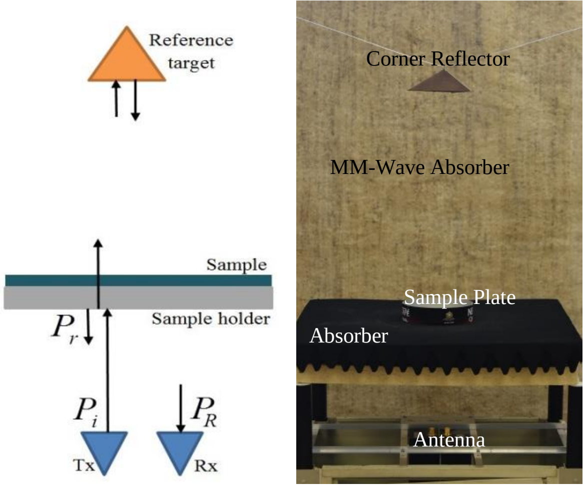
The reduction of signal power during propagation within a lossy medium is strongly dependent on the signal frequency and thickness of the medium. In this paper, a methodology is proposed to investigate the changes of transmissivity through sand when sand thickness is increasing at two frequencies: 150 GHz and 300 GHz. To get a further insight into the effects within a sand-filled medium, the dependence on granule size was studied by using five types of size-calibrated-sand. The results were compared with that of natural sand.

II. EXPERIMENTAL METHODOLOGY

In order to investigate the attenuation of low-THz waves with increasing sand layer thickness and with different granule size ranges within such medium, laboratory measurements of radar transmissivity through uniform layer of sand were conducted in the Microwave Integrated Systems Laboratory, University of Birmingham, UK.

A. System Setup

The system setup is shown in Fig.1. A monostatic radar system is deployed in this setup and placed below the sample holder. The sample holder used in the experiment is foam made of closed cell polyurethane [10] which demonstrated less than 2 dB attenuation at Low-THz frequencies in the experiments. The sample holder thickness is chosen to be 5 cm, which equals to an integer multiple of half wavelength corresponding to 150 GHz (2 mm) and 300 GHz (1 mm). A sample plate made from thin paper with a radius of 7.5 cm is used here to constrain the sample within the illuminated area. The bottom of the plate is wider than the illuminated area to allow the signal transmitting entirely through the sand. Extra layer of absorber material is put around the sample plate to reduce the multi-path effect. A Trihedral Corner Reflector (TCR) with a known RCS is suspended above the sample holder as a calibrated target. The distance between the antenna and sample holder is 0.2 m, and the distance between antenna and target is 2.2 m.



(a) (b)

Fig. 1 Experimental system:(a) general view (b) actual system setup

Signal attenuation through uniform layer of sand have been measured with two radar systems with the operating frequency of 150 GHz and 300 GHz. Frequency Modulated Continues Wave radar (FMCWR) which is sweeping from 145 GHz to 151 GHz developed from ELVA-1, mm-wave division in collaboration with the University of Birmingham [11]. The measurement instrument at 300 GHz is a Stepped Frequency radar (SFR) driven by an Agilent FieldFox portable Vector Network Analyser (VNA) whilst being connected to frequency up- and down- converters from VivaTech [12] with a 16 GHz sweeping bandwidth. Both azimuth and elevation antenna beamwidths for both frequencies are 10°. The output power of 150 GHz and 300 GHz systems are 11 dBm and -17 dBm, respectively. The parameters of two radar systems are shown in Table I.

TABLE I. PARAMETERS FOR TWO RADAR SYSTEMS

Working Frequency	150GHz	300GHz
Frequency Bandwidth	145 GHz-151GHz	282 GHz-298 GHz
Sweeping Bandwidth	6 GHz	16 GHz
Antenna Beamwidth Azimuth	10°(-3 dB)	10°(-3 dB)
Antenna Beamwidth Elevation	10°(-3 dB)	10°(-3 dB)
Output Power	11 dBm	-17 dBm

B. *Description of Samples*

Five kinds of particle-size-calibrated sand were tested and the results are presented in this paper. The uncrushed silica sand from the Lower Greensand (Leighton Buzzard, UK) [13] are named fraction A-E, the granule sizes span from 2.36 mm-90 um. The equivalent sample thickness is calculated from the function with respect to sand volume and the area of the sample plate with equation (1).

$$Thickness = \frac{V_S}{A_t} = \frac{V_S}{\pi \times r_t^2} \tag{1}$$

where V_S is the volume of the sand in the sample plate in cm^3 and r_t is the radius of the sample plate in cm. In order to increase the sample thickness with a sufficient order of accuracy, the densities of five fractions are measured before the experiment. As it mentioned earlier, this paper concentrated on the signal reduction through uniform layer of sand, a known volume of sand is added each time to increase the thickness to provide a uniform distribution of sand.

The six samples under test are shown in Fig. 2.

Fig.2 Six samples adopted in the experiment

All the details of five types of calibrated sand are described in Table II

TABLE II. DESCRIPTIONS OF FIVE SAND SAMPLES

Elements	Fraction A	Fraction B	Fraction C	Fraction D	Fraction E
Colour	Brown	Light Brown	Light Brown	White	Light Cream
Particle Size(mm)	2.36 - 1.18	1.18 - 0.6	0.6 - 0.3	0.3 - 0.15	0.15 - 0.09
Density(g/cm^3)	2.74	2.71	2.66	2.56	2.58
SiO_2	94.61%	99.39%	99.72%	99.80%	97.13%
Fe_2O_3	4.01%	0.10%	0.048%	0.009%	0.45%
Al_2Oo_3	0.36%	0.19%	0.07%	0.04%	0.67%
Others	1.02%	0.32%	0.162%	0.151%	1.75%

Table 2 shows that the main chemical components of the five fractions measured in the experiment and each sand type is almost entirely made from Silica (>94%). For comparison, natural sand from Aegean Sea is also measured in this paper. The natural sand sample is sieved with different aperture size meshes to separate and measure the proportions of various size particles in the sample. According to the measurements, the particle size of natural sand mainly locates between 1.5 mm and 0.05 mm. On this point, natural sand can be assumed to be the mixture of different sample fractions.

C. *Measurement Methodology*

As shown in Fig.1, P_i, P_r and P_R represent the power of incident signal to the sample from transmitter, reflected signal from the bottom of sample (given the attenuation of sample holder is very small) and received signal at the receiver respectively. When the signal comes from the transmitter and reaches the bottom of sample, part of the incident power (P_i) reflects back to the antenna (P_r). The rest of the signal transmits through the sample holder as well as the sample, reach the target and finally back to the receiver (P_R).

In this paper, the reduction of signal due to presence of the sample is defined as the combinational effect of reflection, refraction, absorption and scattering. All of these are referred as 'Transmissivity' and can be computed with the following equation [6]:

$$T(dB) = 10\log\left(\frac{P_t(t)}{P_t(t_0)}\right) - 10\log\left(\frac{P_R(t)}{P_R(t_0)}\right) \qquad (2)$$

where $P_t = P_i - P_r$ represents the power of the signal transmits through the sample. $P_t(t_0)$ and $P_t(t)$ are the power of the transmitted signal propagating through the sample plate without any sample and with the sample, respectively . $P_R(t_0)$ is the power of the received signal with empty sample plate while $P_R(t)$ is the power of the received signal transmit through the sample.

III. EXPERIMENT RESULTS AND DISCUSSION

The sand thickness in the experiment increases from 0mm to 45 mm stepped by 3 mm, for both 150 GHz and 300 GHz. To reduce the experimental error during the measurements, each individual thickness is measured 3 separated times for both frequencies, and 5 sample measurements are collected every time. All the results shown in this section is the average over total 15 samples. Before the measurement, all the samples are heated to 120°C in oven for 20 minutes to provide dry sand for the measurement.

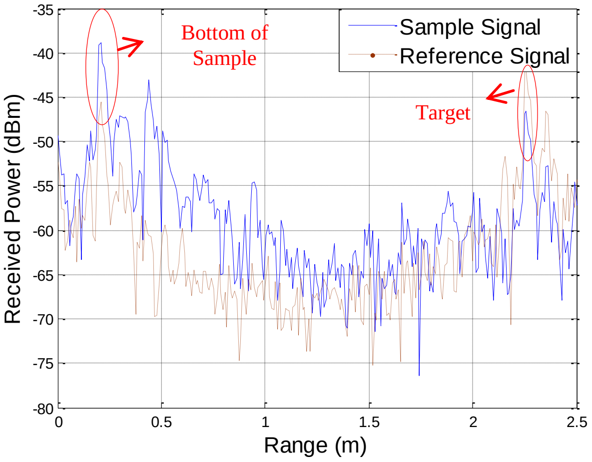


Fig.3 Reference signal and sample signal when sample plate is filled with sand sample at 300GHz

When the sample thickness increasing on the sample holder, the power of reflected signal from sample holder increases while the power of received signal from the target decreases. The reference signal is collected when there is no sample on the sample holder. One reference signal and one sample signal are shown in range-power domain in Fig. 3 as an example to show the increase of reflected signal from the sample and decrease of received signal from the target during the measurement.

During the experiment, the power of the reflected signal and received signal are measured until no obvious peak can be found at the target position or the sand thickness reaches the pre-set maximum value (45 mm). The maximum attenuation can be measured in the experiment is about 25 dB at 150 GHz and 20 dB at 300 GHz, which are decided by noise level.

Fig. 4 shows how the transmissivity changes for the six measured samples as a function of sand thickness at 150GHz.

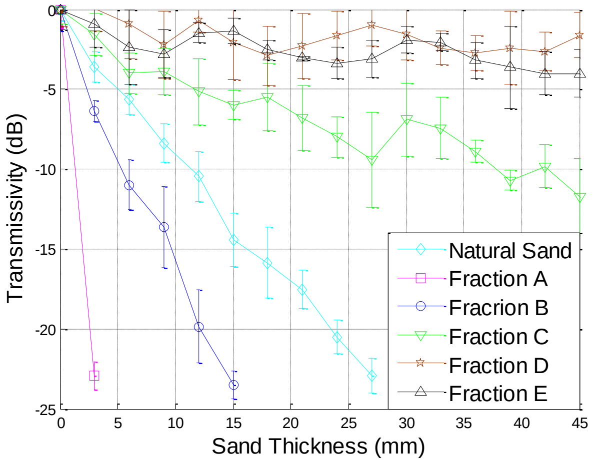


Fig.4 Transmissivity through 6 sand samples at 150GHz

As shown in Fig.4, transmissivity decreases with an increased in sand thickness for all the samples. Fraction A provides the greatest attenuation by which the transmissivity decreases more than 23 dB with only a 3 mm thickness of the sample medium. But for fraction B and natural sand, the thicknesses to produce equivalent attenuation are 15 mm and 27 mm respectively. The decrease produced by finer particles (fraction C) is less than 13 dB with 45 mm sample thickness. For even finer samples (fraction D and E), the degradation of signal is smaller than 5 dB with 45 mm thickness, and the result of fraction D and E overlaps.

The attenuation trend produced by natural sand is located between fraction B and fraction C. As we mentioned, the size analysis shows that the natural sand can be regarded as the mixture of different granule size fractions. The attenuation produced by natural sand can be considered as the combination effects by different granule size particles in the mixture.

All the trends in Fig. 4 indicate that the coarser particles produce greater attenuation than finer particles. The chemical analysis of five samples indicates that this is not due to the proportion of silica in the samples, because fraction E produces similar attenuation with fraction D, but its silica continent proportion is lower than fraction B and C.

This result challenges the point from [7] and [8], which stated that finer particles provide higher attenuation. The difference between research in this paper and in [7] and [8] is the test frequency. All the results and conclusion from [7] and [8] were conducted at X-bands or lower (0.5-12.6 GHz) and the corresponding wavelength is much larger than the sample particles. However, in the experiments in this paper, the wavelength is 2 mm at 150 GHz which is equivalent to the size of some large granule size samples, like fraction A, B, C and some of natural sand. This difference in parameters will cause different scattering mechanisms to be presents.

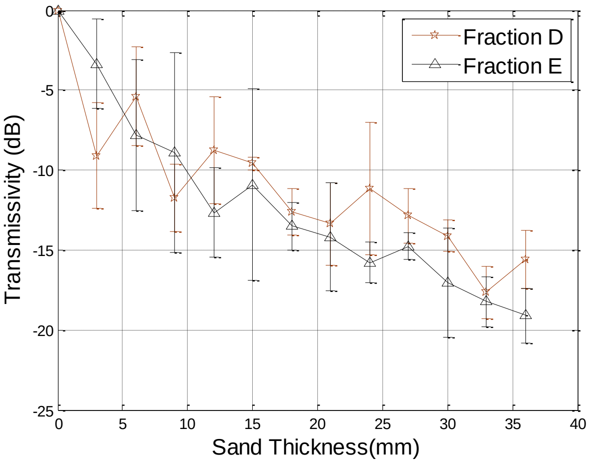


Fig.5 Transmissivity through fraction D and E at 300GHz

For the measurement at 300 GHz, no obvious peak at target position can be observed with fraction A, B, C and natural sand even with just a sample thickness of 3mm, because the received signal from the target is below the background level. Therefore, only the results from measuring fraction D and E are shown in Fig. 5. Similar with the results at 150 GHz, transmissivity is decreasing when the sample thickness increases. The attenuation reaches about 18 dB with 36 mm sample thickness for fraction E and 33 mm sample thickness for fraction D respectively and the results overlap.

The measurements collected from fractions D and E at 300 GHz had the same behaviour as the 150 GHz measurements, as a higher attenuation was present the higher the particle sizes with in the sand. The wavelength to particle size ratio was even smaller for these measurements compared to the 150 GHz scenario.

Comparison between the results at both frequencies show that the attenuation of EM waves by sand at 300 GHz is greater than that at 150 GHz. Moreover, for the low-THz frequency region with realistic particle sizes, the coarser particles produce higher attenuation than finer ones.

IV. CONCLUSION

The methodology and experimental results of signal attenuation through different thicknesses of uniform dry sand at two low-THz frequencies (150 GHz and 300 GHz) are presented in this paper. Five granule-size-calibrated-samples as well as natural sand are tested in this paper to investigate the effects on attenuation by particle size.

Results show a strong relation between the attenuation and sample thickness, particle size and frequency. The coarser particles produce higher attenuation than finer particles at both frequencies, which differs from the observations made in other research which used devices in relatively low frequencies with similar particle sizes.

Results from this paper can be used to analyse the performance of low-THz sensors in the presence of sand. Together with our previous paper about low-THz wave attenuated by water [6], all of these results can aid in a practicality test of Low-THz systems for realistic uncontrolled outdoor environments.

V. ACKNOWLEDGEMENT

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