An Evanescent Channel Microwave Waveguide Sensor for Metal Detection through Variable Sand Depth

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ABSTRACT

Based on previous studies we were able to design and demonstrate an evanescent channel microwave dielectric waveguide sensor capable of detecting metal through sand without direct contact with the metal object, or direct radiation into the external environment. The waveguide sensor exhibits sensitivity to changes in the external environment for several potential metal/dielectric applications. We present microwave waveguide transmission results for two metal targets, one having dimensions much larger than, and the other smaller than the wavelength, detected through a layer of sand.

KEYWORDS: *Evanescent microwave sensor, metal/dielectric applications.*

I. INTRODUCTION

We discuss fabrication and testing of a microwave evanescent waveguide sensor based on a preliminary technology demonstrator (2015), for a wide range of potential sensing applications. Further microwave-based evanescent sensors not covered in this paper are discussed in a recent Plymouth University Research and Innovation Report demonstrated for various applications including: refractive index, corrosion, and temperature sensing [1]. Such evanescent microwave sensors can probe the near surface region across the millimetric to metric scales, without direct radiation into the external environment, with potential for detection of various dielectric or metal target materials. These evanescent sensing microwave-based devices follow similar integrated optics channel sensor device designs already proven by the author and his co-workers [2]. This paper will look at use of an evanescent microwave sensor for metal through sand detection, based upon a device currently under patent application [3-4]. This paper will first discuss the theoretical background of integrated waveguide sensors before looking at the experimental methodology used. Results and a discussion of results are then presented, followed by some ideas for future work and the conclusions.

II. THEORETICAL BACKGROUND

a. Integrated Channel Microwave Wave Guide Sensor Devices

Traditional methods of sensing using microwaves mostly concern direct outward emitted radiation of microwaves from a transmitter into the external environment, relying on microwave reflection or back-scatter from a point, surface, or volume source. Current microwave sensing methods such as radar will radiate energy in a dispersive geometric manner with cumulative addition losses from absorption and scattering, resulting in high experimental loss and enhanced likely detection of transmitting action which may be undesirable for certain activities, e.g. military radar operations. However, Attenuated Total Reflection (ATR) has been used for several decades to couple optical radiation into waveguide modes of thin films for evanescent sensing with prisms [5-7] and most recently in planar waveguide or channel waveguide geometries [3,8] but optically have strong limitations on environmental applications as they only sense the near surface region to typically tens of wavelengths. However, the geometries of planar and channel waveguides offers high sensitivity for *in-situ* probing of attached surface layer properties because of their extended surface path length and flatness.

An increased interaction length and extremely strong confinement of electromagnetic fields within similar Microwave Wave Guide Sensors (MWGS) (typically 1 cm to 10 cm in wavelength) provides an alternative probe to the more common radiative methods, i.e. those based on radar pulse delay ranging or the use of the Doppler effect. Evanescent fields bring reduced detection probability, and *may* prove important in near-field sensing. Due to high losses in water most electromagnetic waves do not achieve useful range with the exception of high power Light Detection And Ranging systems. Such evanescent waveguide sensors offer an alternative potential route for near-field sensing of terrestrial and aquatic near sub-surface objects. Microwave waveguide mode theory has been considered elsewhere [9]. Here we demonstrate the potential of this prototype device for through sand detection based on the first literature demonstration of this class of device [4]. An initial patent application for this work is now registered [3]. No other workers have so far explored this general area of applied research, as supported in a recent extensive patent application search. One previous microwave patent [10] was composed of an open resonator proposed for measuring the dielectric constant of materials and contained two reflectors, elements for input and output microwave signals and a circular waveguide. In their case the waveguide length had to be a multiple of the radiation wavelength, with the material sample under test arranged along the waveguide axis. In our case there is no requirement for the waveguide to be a precise multiple of the radiation wavelength, nor for it to be circular, nor for specific placement of the sample material. A different patent looked at the possible application of microwave moisture sensing conducted via a waveguide with a regular spaced slotted array [11]. This patent related to a proposed apparatus and method for sensing the permittivity of a material, and focused on moisture sensing of timber using microwave technologies, which could potentially be applied in other applications but did not look at loss measurements directly. Neither device has been demonstrated as a working prototype.

Microwave waveguides have until now been considered largely from a simplistic viewpoint that they are only a passive means of transferring high levels of microwave radiation along sealed metal waveguides, delivering radiation from source to antenna, without considering that waveguides *may* act as sensors in specific sites in the microwave propagation path with low level microwave signals. Planar optical slab waveguides and channel optical waveguides have been used extensively as research probes utilising the interaction of evanescent fields, notably with the detection of refractive index changes in the superstrate media adjacent to the waveguide surface [8, 12]. Similarly designed and fabricated robust dielectric microwave waveguides which include lateral constraint or *channels*, can probe changes in microwave absorption spectrum of adjacent '*optically*' thick surface layers, and changes in the local environment's microwave complex refractive index properties (n + ik) due to the presence of different metal and dielectric materials, and varied material thickness.

III. METHODOLOGY

a. Experimental Arrangement

The experimental equipment used in our experimental arrangement to set up the microwave cavity consisted of a 2.8 cm (10.7 GHz) microwave transmitter and receiver units with tapering guide horns (Philip Harris). These were securely mounted on an optical bench with 500 mm rails and mounting stages allowing various degrees of freedom and movement (Eliot). The optical rails allowed accurate alignment of the microwave units and permitted cavity variation, and thus waveguide length. A typical arrangement is shown (fig. 1) with a moulded wax waveguide, but can include a variety of waveguide materials such as Polytetrafluoroethylene (PTFE) used in this reported work with the PTFE dielectric waveguide encased within a metal 'cladding' layer of aluminium foil (fig. 2).

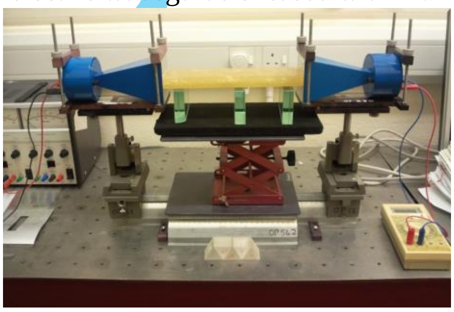
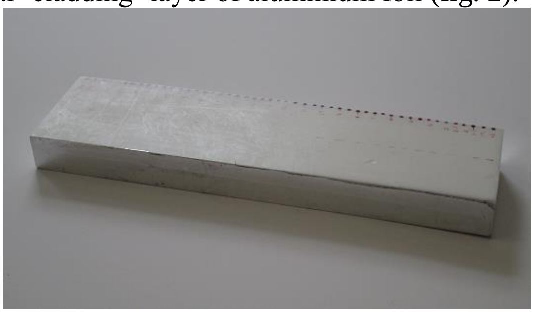

Fig. 1 (left): Typical microwave cavity arrangement with transmitter (blue) to the left, and receiver (blue) to the right (shown with waveguide installed) and operated in Transverse Magnetic (TM) mode. Fig. 2 (right): PTFE aluminium clad channel waveguide.

Transmitter and receiver were mounted on tiltable stages firmly clamped and centralised with the cylindrical part of the respective transmitter and receiver unit's housing at the rear. Horns were centralised on the stages at the front face. Longitudinal centrelines were drawn on the microwave units and the clamps to allow horizontal alignment of all the components of the cavity using the horizontal millimetric adjustment screws on the rail mounts. Both stages were aligned vertically by firstly ensuring each was horizontal using a spirit level on the stage base. Then both units were brought face to face and adjustment of the vertical millimetric screws on each rail mount carried out until alignment was achieved. Once aligned stages could be slid apart on the rails. Laminated aluminium foil masks could be added to the front of the microwave horns. Masks used measured 82 mm × 82 mm externally (the dimensions of the perimeter of the horn face) with a centralised aperture 36 mm wide × 17 mm depth cut out. The mask aperture was ½ the actual internal horn width aperture of 74 mm and greater than ½ λ (> 14 mm) depth.

Orthogonal centrelines were added to each mask to allow accurate alignment with the horns and stage clamps. These centrelines were subsequently used to align the waveguide once installed on the waveguide supports. Masks could be removed from the horns, rotated through 90° and re-attached when the cavity polarisation was changed from the initial Transverse Magnetic Mode, or TM mode characterisation, to Transverse Electric, the respective TE mode. The cavity microwave source itself was powered by a Farnell LT30-2 dual power supply with output set to 10 V (nominal). Output was checked with a Farnell DM141 multi-meter to monitor stability. A microwave receiver output voltage, recorded in mV, was monitored with 2 digital multi-meters – an RS T100B and a Fluke 89 IV for data logging purposes.

Temperature measurements were made using 3 instruments. Firstly, ambient laboratory temperature at the optical bench surface was monitored using a dual readout digital thermometer (RS 427-461). The unit also had a remote wired sensor which could be positioned for local temperature measurement. A thermocouple unit (RS 610-067) was also available for temperature measurement of samples, surfaces and the waveguides themselves. A cavity shield (300 mm × 150 mm × 150 mm) was constructed and clad with aluminium foil tape to cover the working section of the cavity, and prevent propagation of stray microwave radiation into the laboratory (fig. 3).

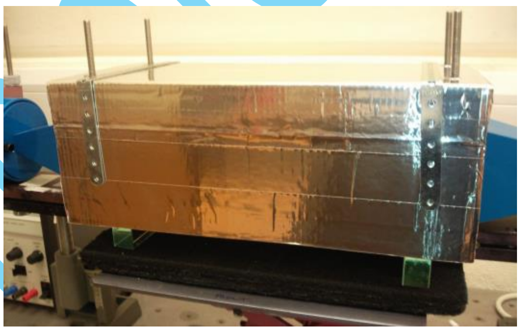

Fig. 3: Microwave cavity shield surrounding the channel waveguide.

IV. RESULTS AND DISCUSSION

a. Copper plate results

This section focuses on a careful examination of any observed dependence between microwave waveguide output signal level with changing depth of a copper plate of standardised dimensions covering the full width of the PTFE fabricated waveguide (fig. 2) through a monotonically increased layer of sand. The first copper target chosen was a copper plate having length and width greater than the microwave wavelength used, of dimensions: length 82.9 mm, width 61.9 mm, and depth 3.7 mm (fig. 4a).


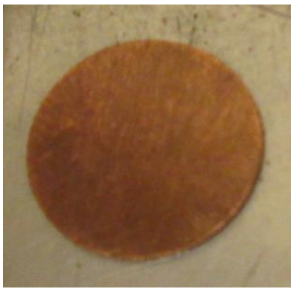

Fig. 4a left: 'large' copper Plate, Fig. 4b right: 'small' copper disc.

The experiment necessitated fabrication of a small sand tank constructed entirely out of Polymethyl methacrylate (PMMA or Perspex^{TM}). The tank had external dimensions: 102.3 mm length with respect to the waveguide propagation long axis between transmitter and receiver, 210 mm (width), and 106 mm (depth). The tank contains different sand thicknesses above the waveguide used to simulate depth *below* a prototype working device. The tank was orientated so the tank's length was placed across the actual waveguide in the width direction (fig. 5).

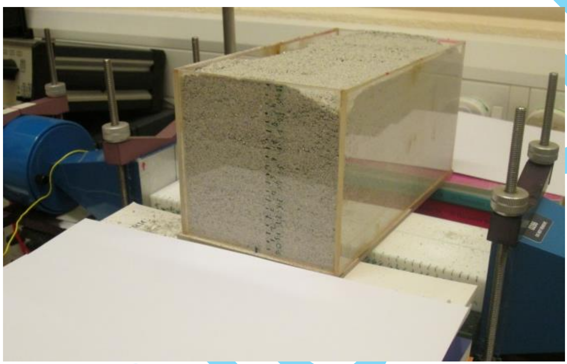

Fig. 5: PMMA tank filled with sand situated directly above, but not in contact with, the PTFE waveguide.

The PMMA tank was positioned so the waveguide would be close to, but not in direct contact with the waveguide itself. The tank was supported either side of the waveguide so no direct loading of the waveguide would occur, thereby avoiding output waveguide signal changes due to distortions of the waveguide under load conditions. The average tank height above the waveguide was 3 mm above the near side edge seen in fig. 5, and 5 mm from the far side edge, average 4mm overall.
A light grey fine sand was purchased from a local builders' merchant and used throughout the experiment. The sand was left to dry on a shallow tray in the laboratory for one week to remove any excess moisture, as this moisture will absorb microwave energy, given the well-known but complex behaviour of the real part of dielectric constant of water at 10 GHz and other frequencies as a function of temperature [13]. The methodology undertaken in this experiment recorded waveguide output as a function of time for different sand thicknesses with and without the copper plate placed in an identical position with respect to the PMMA tank. The PMMA tank was mounted 85 mm from the front of the microwave waveguide (centred on the waveguide's centre-line). The copper plate, having the same width as the waveguide, was positioned so it fully covered the central PTFE waveguide region directly below.
Microwave output voltage data was obtained from the receiver horn as a function of increasing sand depth in 1 cm sand increments are shown (fig. 6*)* as a function of time with both copper plate, and no copper plate present sequentially.

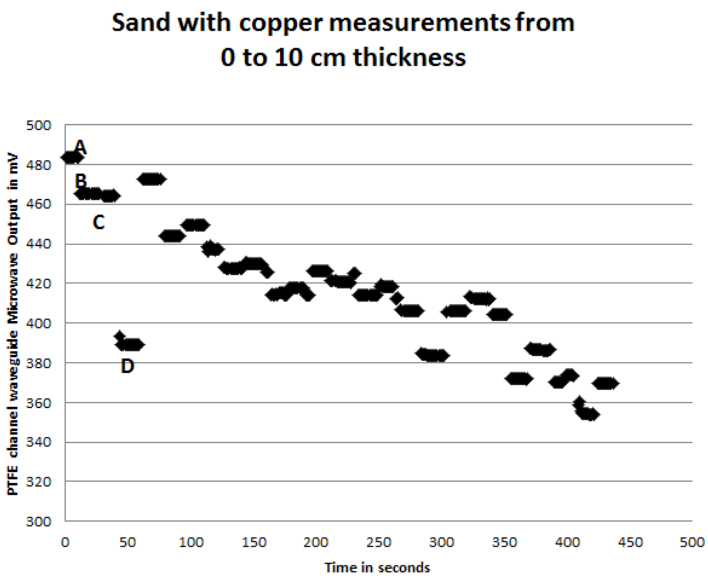

Fig. 6: Typical microwave output sand with copper plate measurements with varying sand depth.

The measurements recorded from the addition of the large copper plate to the tank for varying the sand thickness have some key points marked on the figure: Point A Bare PTFE waveguide output, point B (PTFE waveguide with empty PMMA tank attached), point C (subsequent sequence of measurements starting from unfilled tank C), and point D copper plate placed within the empty tank. The data logger was set to provide an averaged signal every 2 seconds.
To show clearly what is happening the preceding data from fig. 6 was divided into two separate output graphs. The first graph, (fig. 7) is for measurements taken for increased sand thickness over time. The second graph, (fig. 8) shows measurements taken only with the copper plate placed on top of different thicknesses of sand.
As can be seen from inspection of fig. 7 there is a clear and consistent linear monotonically decreasing value of the PTFE waveguide microwave output recorded in mV with increasing thickness of sand and a corresponding linear correlation between the waveguide microwave output signal over time and the specific sand thickness recorded in the PMMA tank placed just above the waveguide surface. The data points recorded for each thickness are averaged to produce the value shown at each thickness measured.

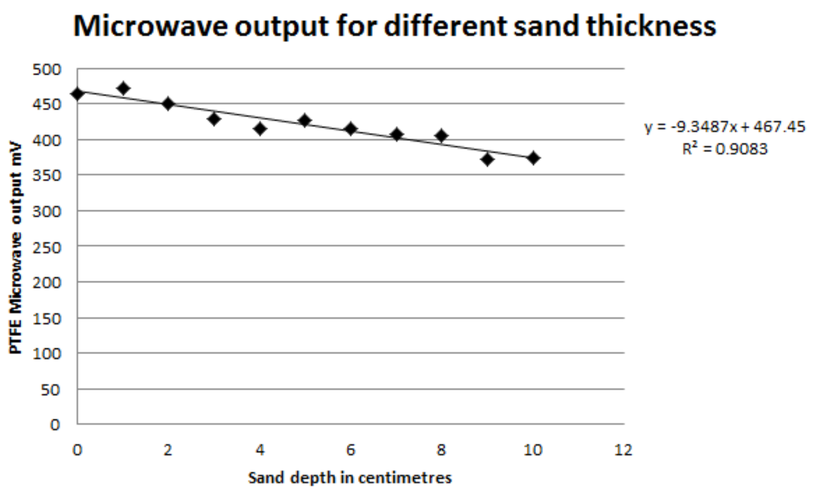

Fig. 7: Microwave output for copper plate on different depths of sand.

Using a simple regression analysis the PTFE microwave output y in mV is given by:

$y = -9.3487x + 467.45$ where x is the depth of sand in cm with a R^2 value of $R^2 = 0.9083$ showing very good correlation between microwave output power level and the thickness of sand introduced into the PMMA tank.

In a similarly manner the microwave output for a waveguide with a copper plate added was examined, as observed in fig. 8.

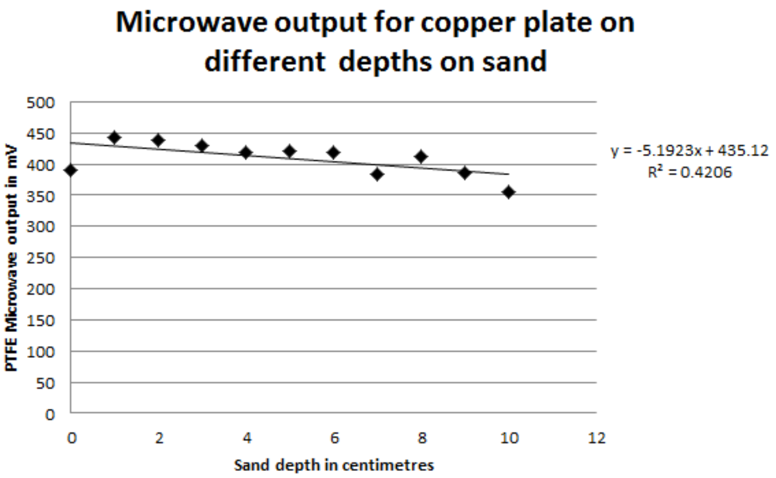

Fig. 8: Microwave output for different depths of sand.

As seen by examining fig. 8 in the same way as in fig. 7 there is also a linear relationship between PTFE microwave waveguide output in mV and the copper plate placed on varying depth of the sand within the PMMA tank above the waveguide surface. Using a simple regression analysis the PTFE microwave output y is given by:

$y = -5.1923x + 435.12$ where x is the depth of sand in cm with a R^2 value of $R^2 = 0.4206$ showing a good correlation between microwave output power level and the thickness of sand introduced into the PMMA tank, but not as good as with pure sand only.

However, it is reasonable to argue that the rationale for detecting copper using this method is for when you *cannot* see the copper or metal target because it is below the sandy surface. As such it is more appropriate to consider an R^2 value which ignores the copper plate returns at a sand depth of 0 cm (i.e. at the surface), as this significantly affects the consequent R^2 value. If this consideration is taken into account we can calculate a revised R^2 value for "hidden" targets with $R^2 = 0.8096$ where a linear relationship between microwave output y is given by: $y = -8.1097x + 455.54$ and where x is the depth of sand in cm.

b. Metal Through Sand Sensitivity with Small Copper Target

The second experiment involved testing device sensitivity against a much smaller copper target having radial dimension less than the evanescent probing microwave wavelength. Our previous experimental work suggested it could be possible to detect small metal objects through a thin layer of dielectric such as sand using the same PTFE waveguide.

Initially waveguide microwave output was recorded, to provide a baseline measurement for subsequent experimental data comparisons. A small rectangular plastic square box that fitted onto the waveguide was placed directly onto the waveguide having unfilled dimensions: 115 mm long, 20 mm deep, and 25 mm wide. The rectangular plastic box was filled with sand up to the required sequential depths, and a small flat copper disk filed and polished flat. The small copper disk had approximate thickness 1.3 mm, and a diameter of 20.3 mm, and is shown (fig. 4b) placed on the sand in the same position each time on the centre line.

The series sequence (1, 2, 3, 4) shown in fig. 10 corresponds to sand layers of: 5, 10, 15 and 20 mm thickness respectively, for a sequence observed from left to right: (i) bare waveguide, (ii) waveguide with empty pot on top, (iii) a pot filled with sand only, and (iv) a pot with sand and the copper disk added on top. Data is shown as output microwave signal (ii) to (iv), compared against the bare waveguide signal (i).

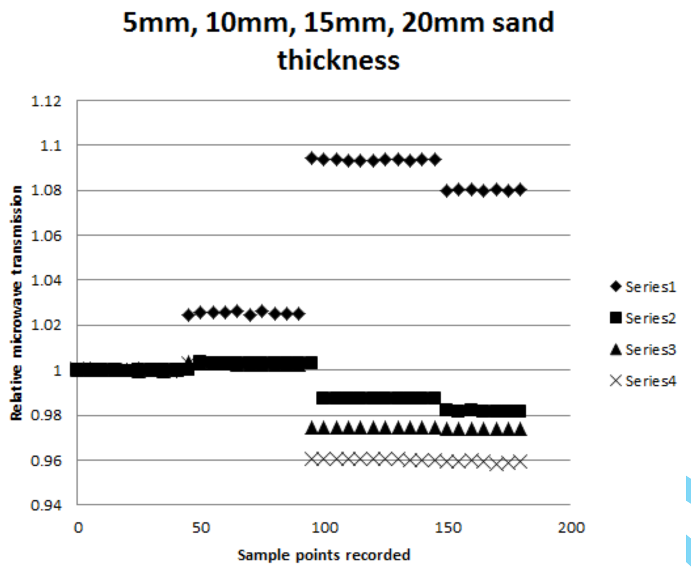

Fig. 10: Sequence of varying microwave outputs for different thickness of sand.

By observing fig. 10 the respective relative outputs of the various series for the channel waveguide are seen to be decreasingly sensitive to the copper disk as sand thickness is increased. We observe decreasing lower relative level of change, with the exception of the 5mm sand layer between the waveguide pot, with and without sand added. This was likely close to constructive interference conditions and sensitivity to the precise height and in-plane positioning of the small copper disk.
Detection of a prototype device of dimensions 20.3 mm diameter is seen to be possible up to a depth of 1 cm but little more than this. Detection could be tested for different sized copper disks and different metals/dielectrics composites of increasing size but targets of real interest are usually much larger.

V. FUTURE WORK

The experimental arrangement presented in this paper will be used shortly to characterise further sand, water, and mixed soil combinations (such as sandy loam or peat). A range of different sized and shaped metal targets will also be studied over a range of sand/peat depths. Channel waveguides will be fabricated from a wide range of materials in order to optimise waveguide transmission, and to minimise attenuation losses. Limitations on the sand thickness were imposed by the tank size constructed (maximum depth = 10 cm), and hence a larger and deeper tank would permit further device characterisation, and investigation of sensitivity at increased depth. More extensive measurement of the output microwave signal based on the size and shapes of the copper targets for both fixed depth and variable sand depths would then be possible.

VI. CONCLUSION

A PTFE channel waveguide allowed the dependence of microwave output voltage as a function of sand depth for a copper metal plate target placed on the sand to be investigated up to a depth of 10 cm. A very good linear dependency of relative microwave transmission output for pure sand was obtained: $y = -9.3487x + 467.45$ where x is the depth of sand in cm and y the output microwave signal in mV, having a R^2 value of $R^2 = 0.9083$. Repeating these measurements for the metal plate placed on sand, using a simple regression analysis, the PTFE microwave output y is given by: $y = -5.1923x + 435.12$ where x is the depth of sand in cm having $R^2 = 0.4206$ showing a good correlation between microwave output power level and the thickness of sand introduced into the PMMA tank. The correlation was not as good as with pure sand only, but this is to be expected with the addition of a strongly reflective metal layer which can generate partially constructive or destructive interference reflections which are highly dependent upon depth. Ignoring the copper plate returns for a sand depth of 0 cm at the surface we can calculate a revised R^2 value for "hidden" targets with $R^2 = 0.8096$ where again a linear relationship between microwave output y is given by: $y = - 8.1097 x + 455.54$ and where x is the depth of sand in cm can be found. Different materials significantly affect the observed transmission output [14]. Further materials were also characterised with the PTFE waveguide in this way [1].

We demonstrated evanescent channel waveguide microwave sensing can detect an extremely small and thin metal object through shallow sand using a straight waveguide up to 10 mm thickness of sand. Further optimisation would likely provide a small sensitivity increase for small metal target reflected microwave signal levels but is unlikely to improve significantly for such small target sizes. At greater than 2 cm depth it is not a worthwhile effort to focus on improving sensitivity as real world targets of significance are actually much larger, e.g. land mines typically having dimensions of 60 - 140 mm in diameter. Further evanescent microwave metal sensing measurement characterisation will include different sand types, and sand/soil/moisture combinations e.g. sandy loam vs peat, different 'buried' target objects, different metal/dielectric composite combinations and layer depth variation above and below the test materials.

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