Water detection in thermal insulating materials by high resolution imaging with holographic radar

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ABSTRACT

The present research is aimed to the application of high resolution holographic images for the detection and characterization of low water content (0.2 - 1 gr) water patches in insulating materials. The images acquired with manual scanning with high frequency holographic radar (7GHz) with I/Q outputs are compared with a high speed electromechanical scanner with 4 GHz holographic radar. Small patches of the order of 22 mm x 22 mm buried at 18 mm into insulating materials with low dielectric constant, have been accurately reconstructed with the high frequency holographic radar but they can be also detected with the lower frequency holographic radar even at greater depth.

***Keywords**: holographic radar, water patches, thermal insulating material, robotic electromechanical scanner.*

1. INTRODUCTION

Thermal insulation materials are mainly built with dielectric foams and are widely used in building roofs, cryogenic systems but also in high technological engineering design like the protection of spacecraft propellant tanks. Some of these materials are typically characterized by a high porosity that results in a dielectric constant close to 1 and low attenuation in the microwave band. For the maintenance of thermally-insulated structures, it is important to detect the presence of water because when subjected to large thermal gradients, it can degrade the thermal protection of the structures. Because of the large difference between the dielectric constants of water and thermal insulating materials, the research group started a series of preliminary studies on different materials (compositions and thicknesses) using the high-resolution imaging offered by holographic radar [1][2][3]. This type of radar is extensively used for construction sounding using a scanning head (holographic antenna) that is manually moved over the surface of the investigated material. The operating frequency can be selected based on the material characteristics with, the aim to obtain the maximum spatial resolution at the maximum sounding depth and also detection of small quantities of water. Because of the large area of investigation an electromechanical scanner based on a moving platform has been developed with a scanning head at 4 GHz (RASCAN-4/4000) interfaced to the robotic scanner electronics [4]; this automatic scanner provides millimeter-accuracy spatial sampling over the whole scanned area. For comparison, a more recent design of the holographic radar operating at 7 GHz (RASCAN-5/7000), operated with manual scanning, has also been employed. Technology of holographic subsurface radar of RASCAN type was described in [5].

2. EXPERIMENT DESCRIPTION

Two thermal insulation panels of 18 mm thickness each have been used as the reference material. The electromagnetic characterization provide ε_r=1.1 and tanδ=0.0015 measured at 1.0 GHz with a laboratory instrument. The water patches are located in the middle of the two panels and the bottom panel was glued on a metal sheet acting as a reflector for the incident field.

The water patches (targets) were built with very thin cotton gauze wetted with a controlled amount of water. The following table summarizes the dimension of the 4 gauze patches and their water contents measured with an accuracy of 0.1 grams. All experiments were carried out at room temperature.

Table 1: water patches description

Target #	Dimension [mm]	Water content [grams]
0	95 x 45	0 (DRY)
1	95 x 45	1.2
2	45 x 45	0.4
3	22 x 22	0.2

Figure 1 shows the four water patches described in Table 1. One of the two largest targets (#0 and #1) was included in the experiment to verify that the thin cotton material is transparent to the incident field.

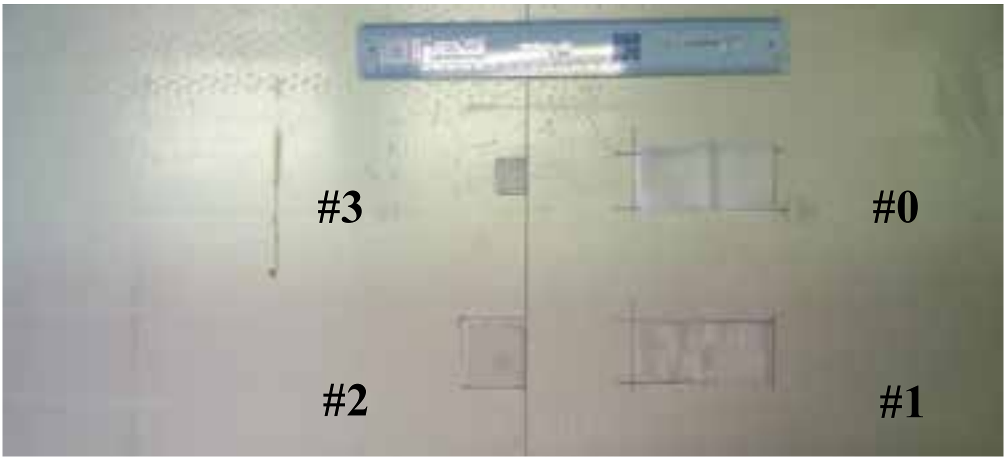

Fig. 1. *Layout of the four wet targets. The distance between the two large ones (on the right) and the two smaller (on the left) is 80 mm. The dry target #0 is on the top-right .Horizontal scan lines from left to right.*

Scans were made with the robotic scanner with a spatial sampling of 5 mm and a scan length of 350 mm with five discrete frequencies (3.6, 3.7, 3.8, 3.9, 4.0 GHz) as shown in Figure 2. The holographic radar equipment used in this case has two output channels with parallel and cross polarization: for the comparison with the 7 GHz holographic radar only the parallel polarization images were considered because is the only available in the high frequency version. The RASCAN-5/7000 was manually-scanned along a length of 400 mm and over a plastic mat with line grid separated of 10 mm. By the optical wheel, the In-phase and Quadrature components of the received field are sampled with a step of 5 mm. Using the software interface RASCAN-Q, the measuring head is calibrated over a homogeneous area of the two panels (overall thickness 36 mm) on top of the metal bottom reflector. The calibration adjusts the electronic chain power and gain levels to have a signal amplitude at half full scale of the ADC. The five discrete frequencies generated by the RASCAN-5/7000 are: 6.4, 6.5, 6.6, 6.7, 6.8 GHz.

Fig. 2. *Robotic scanner with a 4 GHz (RASCAN-4/4000) holographic radar during the thermal insulating panels inspection. It is possible to see on the bottom left corner the two panels of 18 mm thick one over the other with minimal air gap.*

3. IMAGE RECONSTRUCTION WITH IN-PHASE – QUADRATURE HOLOGRAPHIC DATA AT 7 GHZ

The image reconstruction with the focusing algorithm was performed with data acquired at the five available discrete frequencies. For each frequency and according to the estimated relative dielectric constant of the thermal insulating material ($\varepsilon_r = 1.1$), the focusing algorithm [6] generates the holographic image reconstruction at different depths. A series of images corresponding to the nominal targets at depth equaled to 18 mm are shown in Figure 3. The effective target depth is different from the nominal one because the Teflon protective cap of the antenna is few mm thick and this distance must be added up to the target depth and this causes a slight defocusing. In practice the phase delay introduced by this additional layer changes the wavelength at which the four targets can be focused. Thanks to the possibility of the set of five I/Q images, it is possible to obtain best reconstruction at 6.7 GHz (wavelength 4.2 cm) at which corresponds a high contrast ratio respect to the background.

The benefit of the focusing is the estimation of the targets dimension avoiding the fringing effects along the edges typical of the holographic images. This estimation can be performed by the cross sections of the reconstructed image at 6.7 GHz for the targets #0, #1, #2, #3 as shown in Figure 4. The cross sections have been selected as the middle horizontal scan line for each pair of targets and evaluated at -6dB respect to the maximum response for each target.

Table 2: Estimation of target largest dimension

Target #	Largest Dimension [mm]	Estimated Dimension (-6dB) [mm]	Water content [grams]
0	95	Not detected	0 (dry)
1	95	64	1.2
2	45	32	0.4
3	22	20	0.2

The results reported in Table 2 are interesting because the demonstrate the good agreement between effective dimension and estimates done by high resolution holographic image reconstruction. Even in the case of very small target (#3) the dimensions remain accurate. It is interesting to observe in Figure 4 that the dry target (#0) is not detected; moreover the high peak response on the left shows the reference line of the scan marked by a thin (0.2 mm diameter) copper wire buried between the two panels at depth 18 mm. This target is visible in all the focused images in Figure 3 and it is useful to check that the focusing algorithm is working properly.

4. COMPARISON OF 4 GHZ AND 7 GHZ HOLOGRAPHIC IMAGES

Figure 5 shows the images obtained with the holographic radar at two frequencies: 3.9 GHz (λ_1=7.1 cm) with automatic scanner on the left and focused image at 18 mm with In-phase and Quadrature components at 6.7 GHz (λ_2=4.2 cm) on the right. In both cases the detection of the minimum water content (0.2 grams) has been verified, demonstrating the high sensitivity of the holographic radar imaging method. Regarding the spatial resolution (estimated to be a quarter of a wavelength) the best size estimation of the patches is for the higher frequency. The focusing does not account for the thickness of the Teflon adapter in front of the antenna that means a more accurate estimation can be done. The automatic scanner can detect quickly the water patches with almost zero set up time and real time imaging. In the future, a RASCAN-5/7000 head will be mounted on the robotic device. In Figure 5 we also observe that the thin copper wire is almost missed by the 3.9 GHz acquisition.

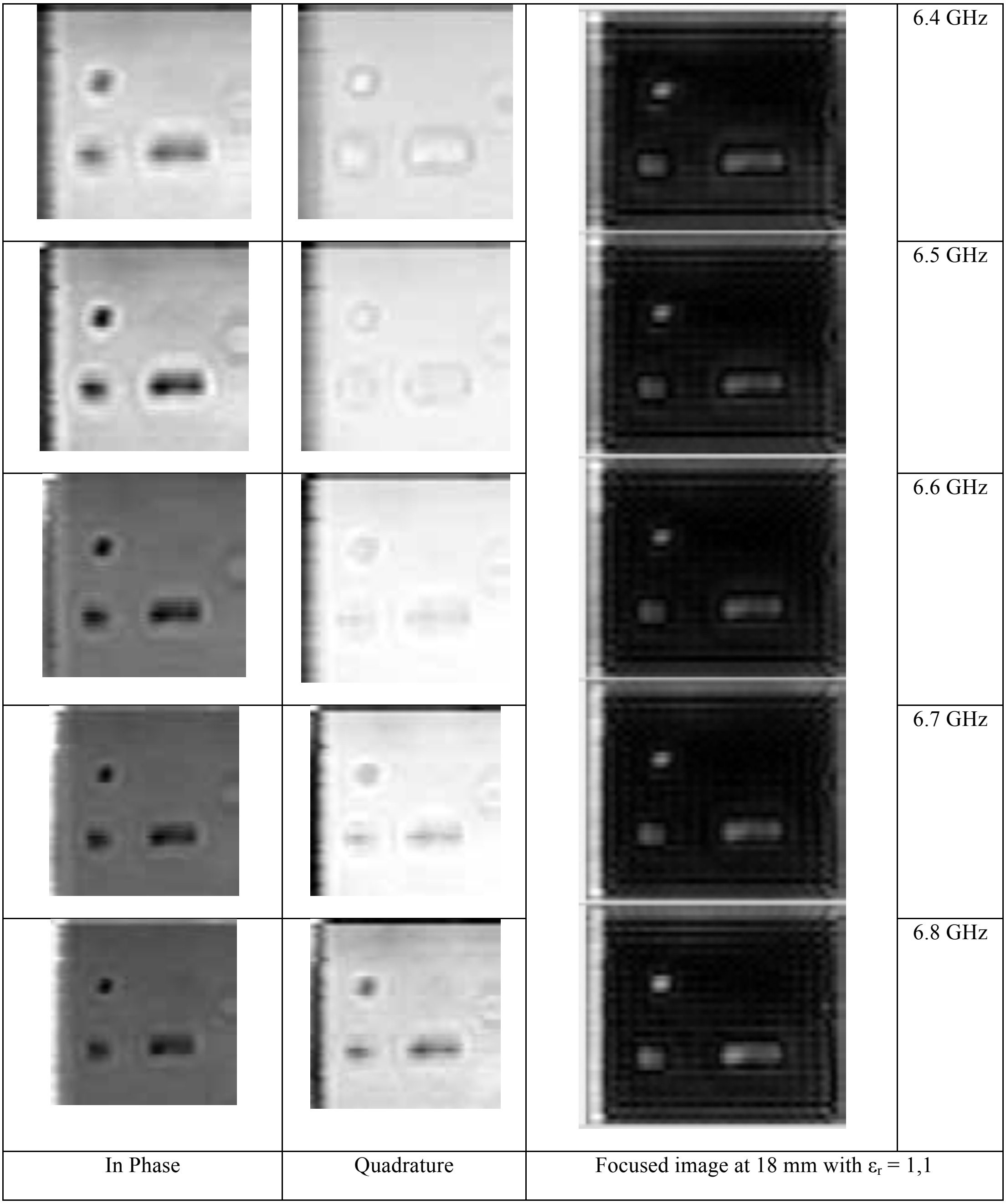

Fig. 3. *Holographic images after focusing at five frequencies (at the nominal depth of 18 mm).*

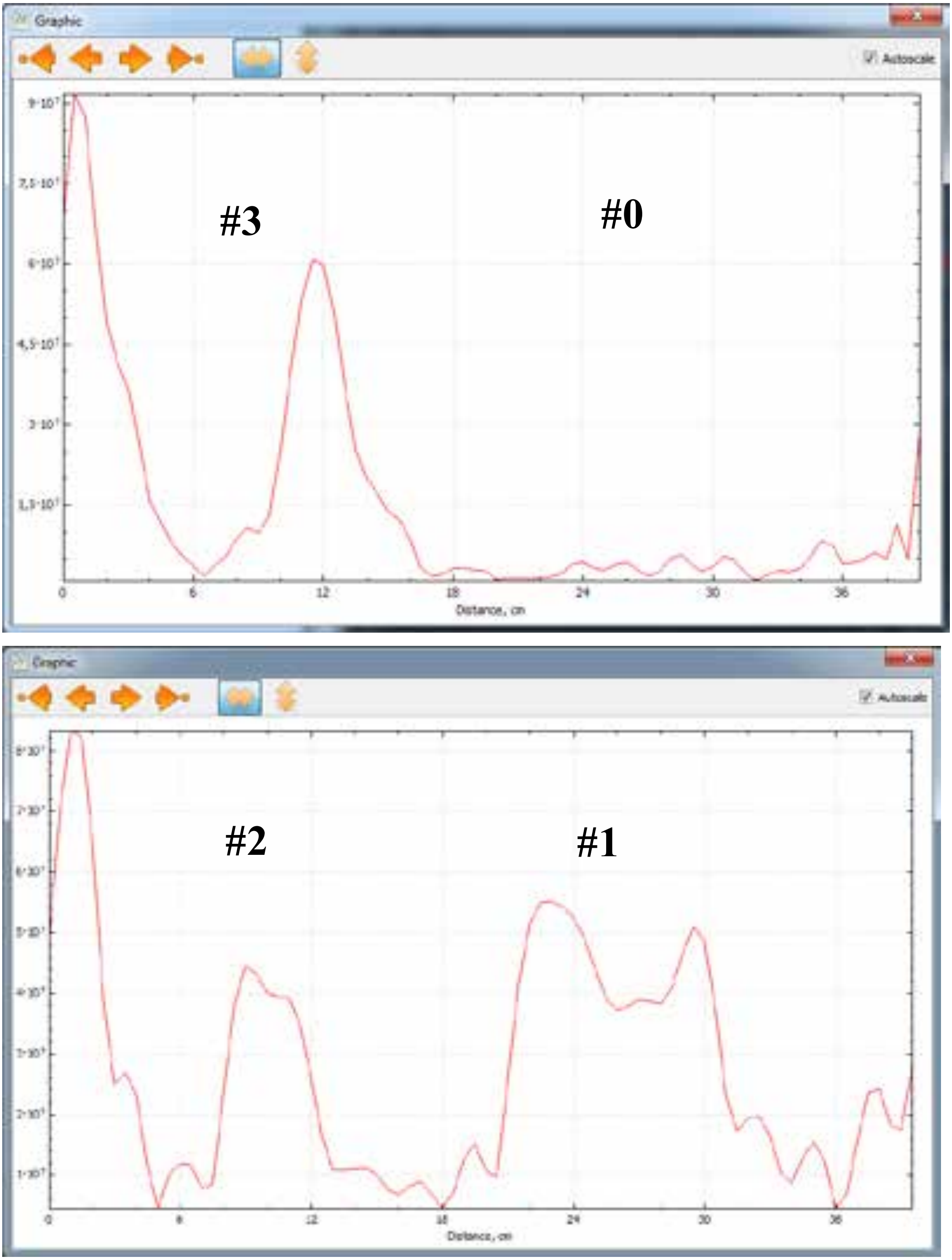

Fig. 4. *Images cross sections of target pairs: top target #3 and #0, bottom targets #2 and #1.*

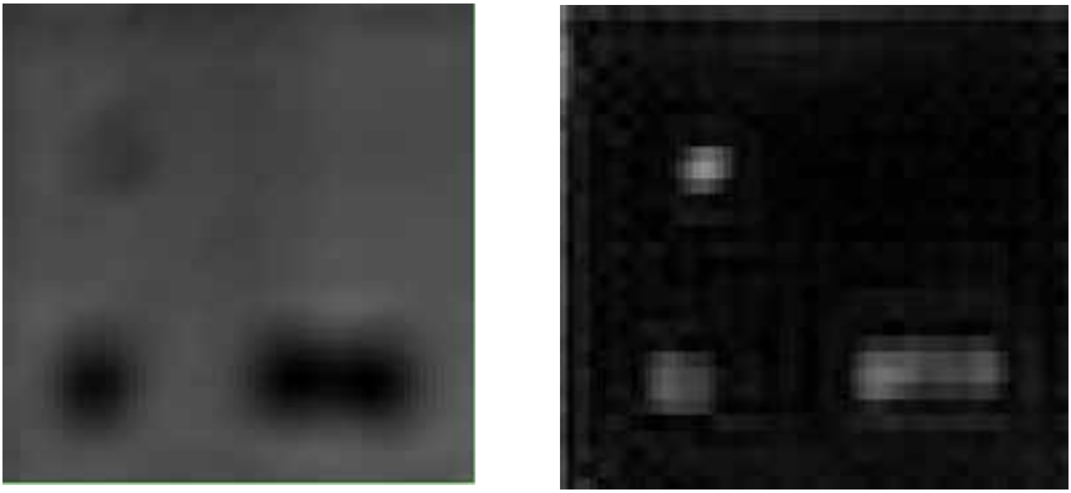

Fig. 5. *Comparison of holographic radar imaging in parallel polarization of the four targets shown in Fig. 1: 3.9 GHz (left), 6.7 GHz (right).*

5. CONCLUSIVE REMARKS

In this work we have investigated the capabilities of high resolution holographic radar for the detection, positioning and sizing of water patches into dielectric materials like thermal insulating panels. For the thickness up to 36 mm the use of high frequency (7 GHz) is convenient to have accurate sizing and positioning of the water patches with the best performances obtained with a 22 mm x 22 mm target with weight water content as low as 0.2 grams. For deeper targets or higher attenuating materials lower frequency radar can detect and locate the wet target as well but with a lower spatial resolution and imaging contrast.

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