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Influence of Soil Moisture on the Detection of Buried Objects Using an Airborne GPSAR

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***Abstract* — For the detection of buried objects in applications such as humanitarian demining, avalanche victims localization, or archaeology, airborne systems employing ground-penetrating synthetic aperture radars were proposed in recent years. Their results, however, depend significantly on environmental factors, such as soil type and moisture. This paper shows that soil moisture and the signal-to-background ratio of targets are strongly linked. It is concluded, that for a side-looking geometry, the intrinsic attenuation of the soil and the transmittance at the boundary layer between air and soil are both significant factors. Metal targets are best detected under dry conditions.**

***Keywords* — synthetic aperture radar, ground penetrating radar, multicopter, UAV, transmittance**

I. Introduction

An unmanned aerial vehicle (UAV) was proposed in [1], where a $1\,\mathrm{GHz} - 4\,\mathrm{GHz}$ frequency modulated continuous wave (FMCW) radar sensor was mounted on an industrial multicopter. With highly accurate localization it is possible to generate high-resolution ground penetrating synthetic aperture radar (GPSAR) images using backprojection. As shown in [2], the system is suitable for the detection of buried objects in sand, at least under dry enough conditions.

To allow a meaningful interpretation of the results for research and practical applications, the dependence of the performance on environmental factors such as soil type and moisture needs to be known. Therefore, the influence of soil moisture on the detection of objects is investigated in this paper using GPSAR measurements. The analysis in this paper is limited to metal targets in sand, but the main effects can be generalized to other soils as well.

II. Relevant Loss-Effects

The moisture content has great influence on the complex-valued relative dielectric constant ε_r as well as the conductivity of the sand. In the relevant frequency band, the real part $\varepsilon_\mathrm{r}' = \Re(\varepsilon_\mathrm{r})$ can be as low as approximately 2.5 for perfectly dry sand. The moisture contained in a low-loss medium like sand also influences the intrinsic attenuation $\alpha(\omega)$. At frequencies of $1\,\mathrm{GHz}$ and above, the attenuation increases significantly with the water content [3], [4].

For side-looking radar systems, refraction at the interface between air and sand must be considered during backprojection. With changing ε_r' the transmittance of the electromagnetic waves entering the soil changes as well.

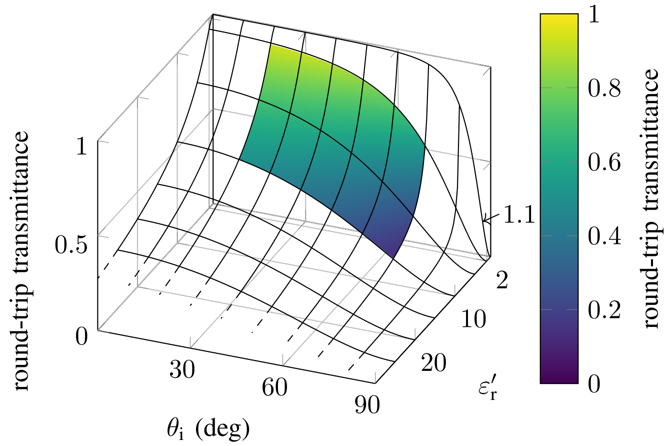


Fig. 1. Round-trip transmittance depending on angle of incidence θ_i and ε_r'.

Applying the Fresnel equations for refraction, Fig. 1 shows the round-trip transmittance

$$T_\mathrm{rt} = t_\mathrm{i} \cdot t_\mathrm{s},$$

where t_i is the transmittance of the incident wave at the boundary of air and soil and t_s is the transmittance of the wave scattered at the target returning to the radar sensor. Although less power can be expected to return from a target with rising ε_r', this effect is additionally increased at high incidence angles.

The back-scattered signal from non-metallic objects in soil depends on the difference between their dielectric properties and the moisture-dependent properties of the soil. To avoid this added dependency, this analysis is limited to metal targets only.

III. GPSAR Measurements

In multiple experiments, GPSAR measurements of a fixed setup of buried metal targets are conducted under varying weather conditions. The moisture content of the soil varies depending on these conditions.

A. Setup

The flight trajectory consists of six horizontally shifted circles with a diameter of $15\,\mathrm{m}$ at a constant height of $5\,\mathrm{m}$ above ground level (AGL). Two types of targets were buried at approximately $4\,\mathrm{cm}$ below the surface, metal can lids and aluminum cylinders, see Fig. 2. An overview over the

(a) Metal can lid, diameter 6 cm (CAN).

(b) Aluminum cylinder, diameter 8 cm, height 4 cm (CYL).

Fig. 2. Buried metal objects (pictures not taken in sand).

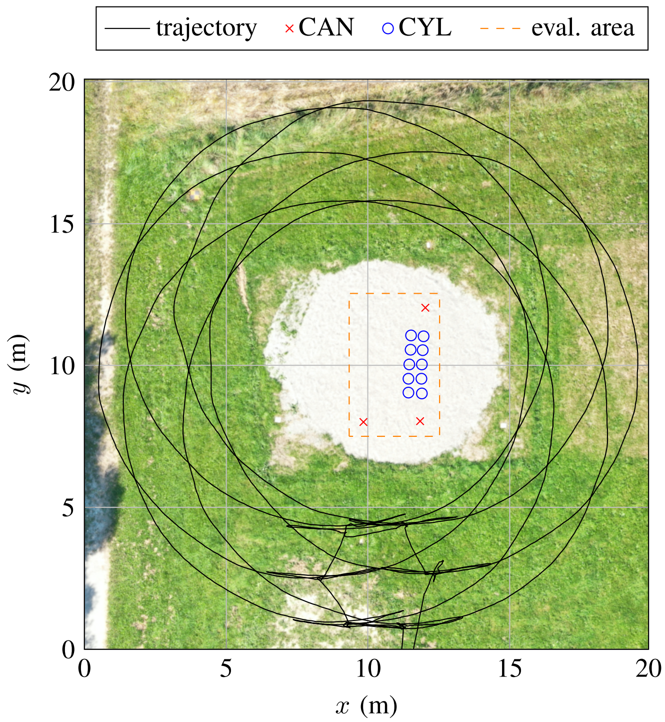


Fig. 3. Orthomosaic map of measurement setup with flight trajectory, buried objects, and evaluation area.

measurement area, flight trajectory, and the buried targets is given in Fig. 3 using an orthomosaic map.

Fig. 4 shows the precipitation at the closest weather monitoring station during the time period of measurements. The dashed vertical lines represent the dates, where the six measurements $M1$ to $M6$ were conducted. The bar plot shows that the weather improved continuously from frequent heavy rain in July to more dry and sunny days at the beginning of September. There was again precipitation just before $M6$ though.

In between $M1$ and $M3$, the sand test field was additionally covered with a tarp to protect it from direct precipitation. This does however not prevent the top sand layer from being wet after rain. Condensation of soil moisture on the inside of the tarp is likely one of the main reasons. Therefore,

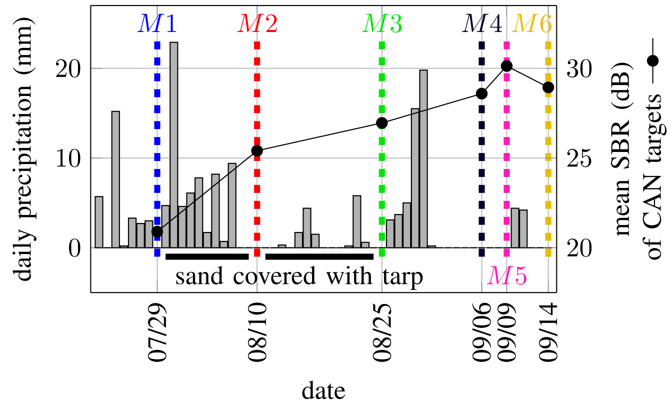
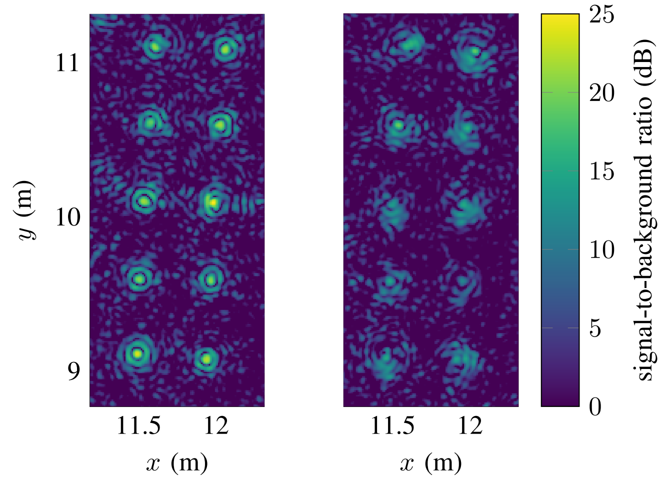


Fig. 4. Daily precipitation at the closest weather monitoring station in 2021 (data basis: Deutscher Wetterdienst). During the horizontally marked time, the sand area was covered with a tarp. For every measurement $M1$ to $M6$, —●— shows the mean signal-to-background ratio (SBR) for the CAN targets.



(a) Measurement $M5$.

(b) Measurement $M1$.

Fig. 5. GPSAR images of the CYL targets at a focusing depth of -4 cm.

with drier weather conditions, the tarp was removed to allow the top layer of the sand to dry.

B. Results

For each measurement, GPSAR images are focused for each circular aperture and for focusing depths from -8 cm to 0 cm in 1 cm steps. The images from the six apertures are then coherently combined to form one image per focusing depth. Here, focusing depth refers to the offset in the z-direction between the ground surface and the focusing plane, where the image is calculated. Example images for two measurements are displayed in Fig. 5.

For below-ground focusing it is always assumed that $\varepsilon_r' = 8$. Due to the small burial depth of the objects, this value has only a minor influence on the focusing quality of targets. Choosing an erroneous value will lead to a small z-shift of the target signatures. This is the main reason for the selected range of focusing depths.

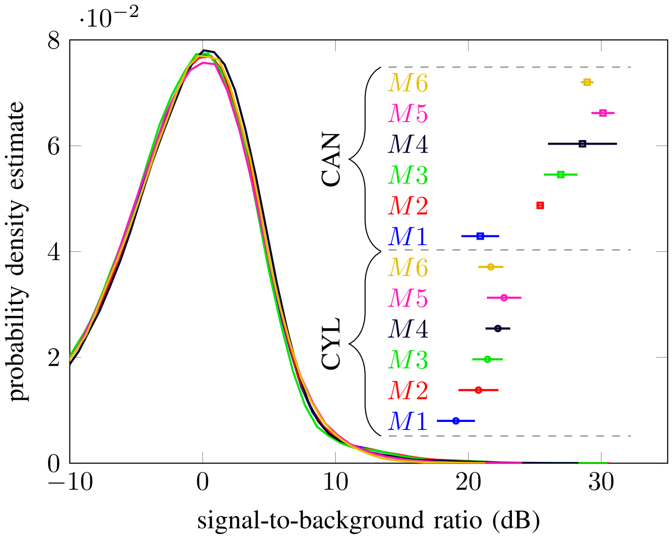


Fig. 6. Background level and mean target peak level with standard deviation.

Targets are evaluated based on their signal-to-background ratio (SBR), which is the ratio between the maximum target pixel value and the background level. The background level is defined as the maximum of the probability density estimate (PDE) over all pixel values in the evaluation area and is calculated using a normal kernel smoothing function. The evaluation area is displayed in Figure 3 (dashed orange line).

To enable a graphical comparison, the PDE of all measurements is displayed in Fig. 6. Additionally, the mean value of the target SBR of each target type per measurement and their standard deviation are shown.

As expected, the values from the CAN targets are more unstable because of the smaller number of objects. The CAN targets represent stronger targets in comparison to the CYL targets because of the inside corner with a 90° angle.

For both types of objects, the SBR increases from $M1$ to $M5$, then decreases for $M6$. This is because of changing moisture content due to the weather when comparing the time periods before each measurement in Fig. 4.

Due to rain on the days before $M1$, the moisture content was at its highest level. There was more precipitation between $M1$ and $M2$. But there are now two days without rain right before the measurement, which reduced the moisture content in the sand even though it was covered on these days. In the time period before $M3$, there was significantly less rain. Although the sand was covered again, the moisture content was likely reduced again by the time of $M3$. In contrast, there were multiple sunny and dry days before $M4$ and even more before $M5$, which would explain another reduction in moisture, especially because the sand was not covered and exposed to wind and sun at that time. Afterwards, the weather worsened, and there was again some precipitation before the last measurement $M6$.

In agricultural sciences, the field capacity describes the amount of water a type of soil can hold after a precipitation or irrigation event. Here it is used as a rough estimate of the maximum moisture to be expected in the test area. For sand, a field capacity of $\theta_{\mathrm{FC}} \leq 0.15\,\mathrm{g/cm^3}$ is assumed here [5]. According to [6], this results in an upper limit of $\varepsilon_{\mathrm{r}}' \leq 10$.

For this situation and geometry, the corresponding part with

$$2 \leq \varepsilon_{\mathrm{r}}' \leq 10 \text{ and}$$
$$20^\circ \leq \theta_{\mathrm{i}} \leq 70^\circ$$

is highlighted in Fig. 1. The limits for θ_{i} are determined from the position of the targets and UAV over the selected flight path. In a worst-case scenario, a maximum loss of

$$L_{\mathrm{T,max}} = \max_{\theta_{\mathrm{i}}} \left(\frac{T_{\mathrm{rt}}\left(\theta_{\mathrm{i}}, \varepsilon_{\mathrm{r,min}}'\right)}{T_{\mathrm{rt}}\left(\theta_{\mathrm{i}}, \varepsilon_{\mathrm{r,max}}'\right)} \right) \approx 6\,\mathrm{dB} \qquad (1)$$

can be expected.

In practice, additional losses are caused by the intrinsic attenuation of the sand, which increases significantly with higher moisture content. In this measurement, this leads to a change in mean SBR for the CAN targets of approximately 9 dB from the best to the worst results. The change for the CYL targets was approximately 4 dB. For small metal objects, this reduction in SBR can prevent detections in moist soil.

When generalizing this to other soils, it has to be considered that higher parts of loam and clay are involved, which raises θ_{FC}. Therefore, more moisture is retained in the soil, which decreases the SBR.

IV. Conclusion

In this publication, it was shown that the residual moisture content in sand has a strong influence on the amplitude and the SBR of metal targets. To achieve the highest possible SBR, the soil must be as dry as possible. When dependent on the weather, this requires a longer dry period before measurements are conducted. For soils with higher field capacity, this period is significantly longer.

Acknowledgment

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