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***Abstract* — Airborne radar platforms are useful to get image data bases of targeted areas selected for their interest regarding research topics. Airborne platform and embedded sensors are more flexible than space ones, and have bigger coverage than ground ones. It can be used as prototype of future airborne or space radars, and as algorithm and performance validation test bench. The ONERA SETHI platform has been used for several experiments that require soil penetration capabilities.**

This paper presents results of experiments during which buried objects were detected for different ground types and humidity conditions. First experiment has been realized over the Sahara desert, second one over Greenland Ice Sheet and last one in France over dry sand.

***Keywords* — Airborne SAR, multi frequencies, ground penetrating radar.**

I. Introduction

Whether in the civilian or military domains, Earth observation from airborne radar systems has been of great interest for research laboratories, as it allows for short time wide coverage and imagery configurations similar to future satellite (or operational airborne) surveillance systems. These observations also make it possible to provide calibrated and informed databases to scientists in order to better understand the wave/material interaction phenomena.

Among the wide range of research topics using these data, one particular topic presents increasingly interesting results due to advanced sensors with higher performances: Ground Penetrating Capabilities for above-ground target detection.

This paper presents ground penetration results obtained by ONERA and more specifically by the airborne remote sensing platform SETHI [1] over different ground and buried target types.

II. Experimentations and Detection Results

A. Pipeline under Sahara desert (Tunisia)

In 2010 the platform flew over desert areas in southern Tunisia in order to study the signature of arid zones to P-band wavelengths (as part of the ESA Biomass space program) and to find ancient river beds feeding an oasis for geological work (University of Bordeaux) [2].

During this experiment the VHF-UHF band SETHI sensor [1] (covering P Band) has been used with configuration presented Table 1.

Table 1. SETHI VHF-UHF sensor parameters for 2010 South Sahara campaign

Geometry				
Altitude	18500 ft		**Incidence**	45°
VHF-UHF Band				
Tx Power	500 Wc 5 Wavg		**Antenna aperture**	90° El 45° Az
Central Freq.	420 MHz		**Polar**	Full linear (H/V)
BW	40 MHz		**Resolution**	4 m

Fig. 1 presents a comparison between the optical (Google Earth ®) and SETHI SAR images of desert area.

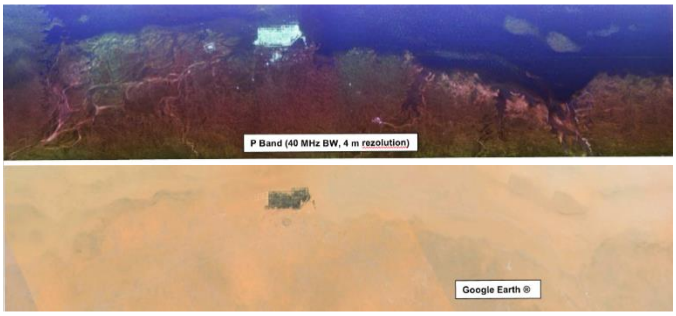

Fig. 1. Full polarized VHF/UHF (up) and optical (down) images of Saharan subsoil and Ksar Guilane oasis (Tunisia)

We can clearly see on this image that some geological structures (rocks, river beds …) are detected under the Sahara dry sand.

By observing a zoom on the Ksar Guilane oasis VHF-UHF radar image (Fig. 2) a buried structure that could be a pipeline (probably for water) is clearly visible between an oasis well and a small fenced construction (construction surrounded by wire mesh). This result was an opportunity structure detection, but political and social events in this area prevented us for going back to this interesting site to explore the sub-surface geological structures and investigate the observed pipeline (depth, size, material).

This first result motivated ONERA to continue the work to demonstrate the P-band ground-penetration capacity and quantify it. However, some years later and in a completely different environment, this capacity was used operationally.

Fig. 2. Zoom of full polarized VHF-UHF Band (right) and optical (left) images on pipeline detection, and photo of corresponding ground (down)

B. Titanium airplane engine component under ice sheet (Greenland)

In April 2018, Airbus and BEA (French authority responsible for safety investigations for aircraft accidents and serious incidents) missioned the SETHI team to search and locate A380 lost engine pieces buried under snow/ice of Greenland ice cap [3] [4].

During this experiment the VHF-UHF, L and X band SETHI sensors [1] have been used with configurations presented Table 2.

Table 2. SETHI VHF-UHF, X and L sensor parameters for 2018 Greenland campaign

Geometry				
Altitude	12000 ft 18000 ft		**Incidence**	30° 40° 50°
VHF-UHF Band				
Tx Power	500 Wc 100 Wavg		**Antenna aperture**	100° El 50° Az
Central Freq.	340 MHz		**Polar**	Full linear (H/V)
BW	240 MHz		**Resolution**	60 cm
L Band				
Tx Power	300 Wc 60 Wavg		**Antenna aperture**	30° El 10° Az
Central Freq.	1325 MHz		**Polar**	Full linear (H/V)
BW	150 MHz		**Resolution**	75 cm
X Band				
Tx Power	200 Wc 30 Wavg		**Antenna aperture**	16° El 16° Az
Central Freq.	9675 MHz		**Polar**	Full linear (H/V)
BW	720 MHz		**Resolution**	20 cm

Fig. 3 presents a comparison between the optical (photo from SETHI window) and VHF-UHF, L and X band SETHI SAR images of ice sheet.

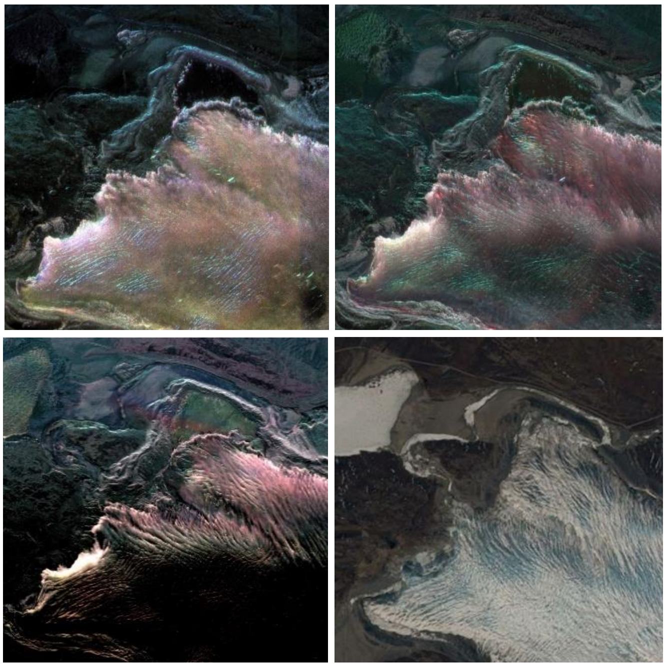

Fig. 3. Full polarized VHF/UHF (up-left), L (up-right), X (down-left) and optical (down-right) image zooms of Russel Glaciers (Greenland)

Many wavelengths and geometries have been tested over the 100 km² search zone. Longest wavelength (VHF-UHF band sensor) demonstrated significant capacities of penetration. Fig. 4 is the search zone VHF-UHF image, on which we can clearly see under-ice crevasses. We estimate their depth varying from 30 to 45 meters under ice sheet surface. On this image we can also detect lakes under the ice cap surface. This very complex and non-uniform ice sheet structure has compromised the use of this long wave-length images to automatically detect a small piece (~ 60 cm) in such a big area and with an even larger explored volume area.

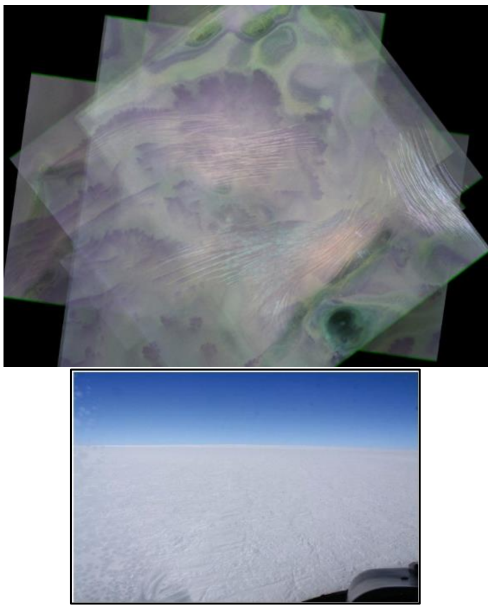

Fig. 4. Mosaic of full polarized VHF/UHF (up) 10 x 10 km² images and photo from helicopter (down) of search area over the Ice Sheet (Greenland).

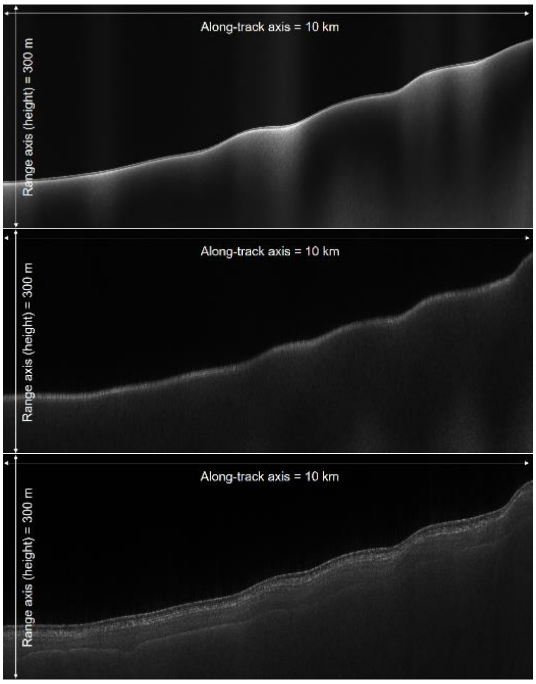

Fig. 5. Height profile in sounding mode (0° incidence angle) in X (up), L (middle) and VHF-UHF (down) bands.

Fig. 5 presents penetration capacity comparison of VHF-UHF, L and X Band SETHI Sensors in sounding mode (nadir looking) over the ice sheet (seasonal horizons are clearly visible in lower frequencies). We estimate on these data X, L and VHF-UHF band penetration around respectively 3, 11 and 40 meters.

Thus L Band also demonstrated penetration capacities but because of its limited performances (resolution of the order of the object) and deep penetration capacity which generates a background too complex and bright compared to the desired target (low contrast) the SETHI team directed its efforts on X Band use. This choice has been validated by depth estimation (few meters) of the engine piece by ballistic calculation experts.

High frequencies like the X Band have less penetration capabilities (Fig. 5) but offer the advantage of higher resolution (20cm). A specific process cumulating around 430 independent SAR images acquired over two weeks in different polarisations, geometries and azimuth angle (all re-localized by estimating the daily displacement of the ice cap), the SETHI team has delivered the GPS coordinates (with 3 meters depth estimation) of a bright point with a high level of confidence. This result has allowed a glaciologist Danish team (GEUS) to excavate the piece which was under 3.5 meters under the ice cap surface, and the BEA and Airbus investigations to understand the incident.

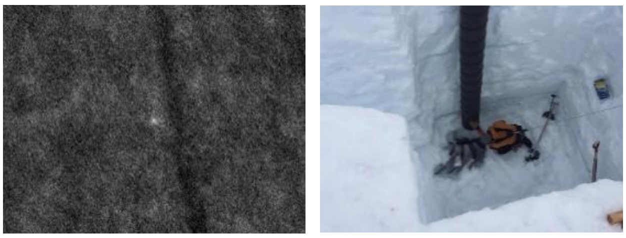

Fig. 6. X band engine piece detection near a crevasse (left) and excavation photo (right).

This new experiment confirms the airborne radar ground penetration capacities and SETHI team skills in this field. This success motivated an experiment for the benefit of the French Ministry of Defence in South of France to detect objects and structures under sand (typical of Sahelian soils), with objective of penetration and buried object detection capacity quantification.

C. Cables under dry sand (France)

The selected test site of this last experiment is a military restricted area located in South-West of France, having sand soil and dunes relatively similar to those in the Sahel, and used, among others, for the test of new sensors before operational use.

Objects representative of operational targets have been buried in precise locations and depths, to be imaged by the VHF-UHF and X Band SETHI sensors in order to verify its detection capabilities.

The objective was also to quantify its penetration performances using precise field measurement parameters (humidity versus depth, dielectric constant versus depth ...).

Radar and geometric configurations are presented Table 3.

Airborne measurements have been conducted at different seasons and temperature/humidity conditions.

The confidentiality level of the data does not allow their presentation in this paper but we focus on opportunity detections observed on the processed images: old buried cables detected on VHF-UHF images presented Fig. 7 (compared to optical image).

This result confirms low-frequency advantages for buried objects detection. We can also observe that buried cable detection is possible under forest coverage (Fig. 7 zoom).

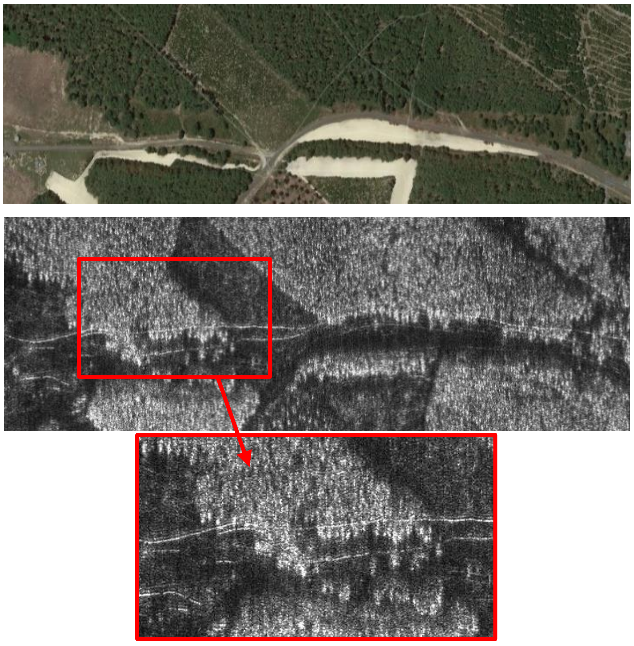

Fig. 7. VHF-UHF image of buried cables (middle) and zoom on forest area (down), compared to optical GoogleEarth ® view (up).

Same area has been imaged by SETHI at different seasons, days and humidity conditions. Fig. 8 presents multi-temporal colour composition of same area with [R,G,B] = [autumn season, summer and low humidity, summer and dry soil].

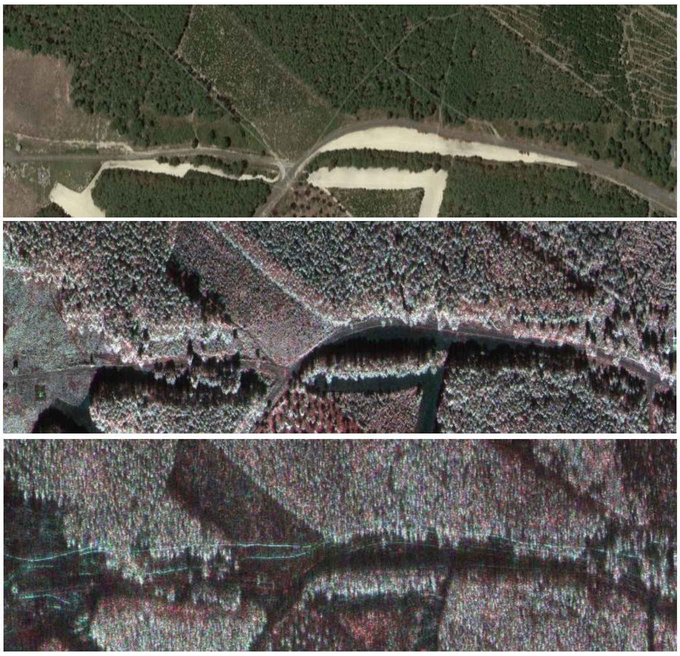

Fig. 8. Optical (up), multi-temporal X (middle) and VHF-UHF (down) band images of buried cables.

No matter how wet the soil is, no cables are detected on X band images (Fig. 8), while they are on VHF-UHF band ones, particularly under dry conditions.

Detected cables have been identified and ground truth has been collected. Cables have 125 mm external diameter with metallic shielding, and a depth varying between 50 and 80 cm.

Table 3. SETHI VHF-UHF and X sensor parameters for 2020 French Dry Sand campaign

Geometry			
Altitude	5000 ft	**Incidence**	65° 45°
VHF-UHF Band			
Tx Power	500 Wc 50 Wavg	**Antenna aperture**	100° El 50° Az
Central Freq.	302 MHz	**Polar**	Full linear (H/V)
X Band			
Tx Power	200 Wc 20 Wavg	**Antenna aperture**	16° El 16° Az
Central Freq.	9675 MHz	**Polar**	Full linear (H/V)

III. Conclusion and Outlooks

Presented results on airborne buried object detection experiments have given encouraging and promising results about Radar and SAR interest for that topic. We have seen that depending of the size and shape of the buried object, the optimum frequency can be a lower frequency as in the Landes experiment, or a higher frequency as demonstrated in the Greenland campaign. We have to remember that in order to detect, the contrast between the background and the target has to be maximised.

$$RCS_{measured} = RCS_{background} + Attenuation_{Ground} * RCS_{target}$$

Low frequency means larger background volume (higher penetration), smaller attenuation trough the medium but lower radar cross section while higher frequencies decrease the background volume (less penetration), increase the attenuation and usually increase the object radar cross-section. Detection capabilities and performances depends on sensors characteristics (wavelength, resolution, sensitivity), ground type and humidity, and contrast between target RCS and clutter (ground and above ground contributions) in given geometry and wavelength.

Signal and image processing will be pursued to improve image quality and detection. Radar signatures from different humidity conditions and season, will then be compared to ground measurement (humidity, permittivity, conductivity) obtained on site and in laboratory on soil samples. Finally, observed scene (clutter and target) will be modelled and compared to real data to be able to refine models and then apply it to other ground, targets and sensors. Other experiments with the SETHI platform over different grounds and targets are planned in 2021 to enrich these databases and improve the models to better understand and control the physical behaviours and wave/target/ground interactions.

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