LORAMbis
A bistatic VHF/UHF SAR experiment for FOPEN

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***Abstract*— LORAMbis is the experimental part of a joint research program between Sweden and France. The objective is to evaluate the performance of low frequency bistatic SAR for clutter suppression in various applications, e.g. under-foliage target detection or mapping of urban scenes. The airborne bistatic SAR data are acquired using the VHF/UHF component of the ONERA SAR system SETHI and the VHF/UHF LORA system operated by FOI. The first data collection campaign was conducted in December 2009. Focused bistatic SAR images have been formed and indicate that the implemented synchronization method is sufficient. It is based on a GPS disciplined 10 MHz reference signal that is generated in both systems.**

I. INTRODUCTION

Many studies on bistatic SAR modes have been made to analyze the benefits of such imaging geometry. One obvious advantage is that it allows the vulnerable transmitter to be moved away at safe distance whereas the passive receiver can stay close to a hostile area of interest. For low frequency sensors (< 1 GHz) another advantage is that an increase of the target-to-clutter ratio that can be achieved due to the dihedral-like scattering mechanism that dominates many of the strong clutter returns, e.g. in foliated or urban areas. This has been shown in simulations at VHF band for forests.

The LORAMbis experiments are defined to demonstrate the potential of this clutter reduction based on real VHF/UHF SAR data, with focus on the possibility to improve the foliage penetration (FOPEN) capability. The paper presents the two airborne SAR sensors, the implemented synchronization method and the first bistatic SAR images over foliated terrain.

II. AIRBORNE SAR SYSTEM DESCRIPTION

A. SETHI

SETHI is an airborne SAR system developed by ONERA, the French Aerospace Lab. It combines two pods under the wings which are able to carry different kinds of heavy and cumbersome payloads, ranging from VHF/UHF to Ku band and/or optical sensors, and allows a wide range of acquisition geometries [1]. The pod-based concept allows an easy integration and testing of new systems under the single certification of the pods issued by the authorities.

SETHI is integrated onboard a Falcon 20 (Fig. 1) designed by Dassault Aviation, and operated by AVDEF (a French company based at Nîmes airport).

Figure 1. Falcon 20 with pods after take off.

The SETHI cabin installation includes five bays and two operator seats (Fig. 2). Most of control and operation parts are automated and centralized.

Figure 2. Cabin installation viewed from operator seats.

There are two pods (Fig. 3) installed under the wings for antennas and cameras.

Figure 3. Pod under the right wing.

During the first LORAMbis campaign period three SAR sensors (VHF/UHF, L and X band) and an optical camera were integrated in the two pods (Fig. 4 and Fig. 5).

Figure 4. X band, L band and optical camera in the right pod.

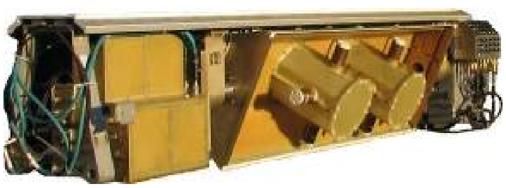


Figure 5. VHF/UHF band in the left pod.

Only the VHF/UHF component was, however, in use during the dedicated LORAMbis flight missions.

Table I summarizes the characteristics of the SETHI VHF/UHF band and Fig. 6 shows the layout of this part.

TABLE I. VHF/UHF BAND SETHI CHARACTERISTICS

Frequency band	222 – 460MHz
Polarization	Full polarization
Transmit peak power	500W
Antenna	2 full polarimetric dipoles
Elevation aperture	100°
Azimuth aperture	50°
Sampling channels	4
ADC sampling frequency	2GHz
ADC bandwidth	3GHz
ADC dynamic	10bits
Maximum data rate	360MB/s per channel
Record capacity	1.6TB

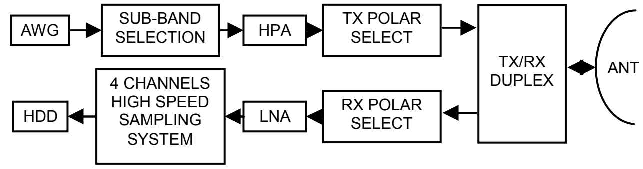


Figure 6. Synoptic view of SETHI VHF/UHF band.

On transmit, the 10bits and 10GS/s Arbitrary Waveform Generator (AWG) sequentially generates the stepped-frequency waveform composed by four transmitted pulses (one pulse per sub-band). The High Power Amplifier (HPA) raises these pulses up to 500W peak that are fed to the correct antenna element (ANT) through the Transmit Polarization Selector (TX POLAR SELECT) and the Transmit/Receive Duplexer (TX/RX DUPLEX) elements.

In reception mode, the Receive Polarization Selector block (RX POLAR SELECT) provides the chosen polarization of the received signal to the Low Noise Amplifier (LNA). After an initial manual real-time adjustment of the signal dynamic by the operator, the four sub-bands are simultaneously recorded by the four channels 10bits and 2GS/s sampling system and a 1.6TB storage capacity (HDD).

The design of this radar system has been realized in cooperation with the SAR team at FOI.

B. LORA

LORA is a VHF/UHF SAR/GMTI sensor developed by FOI (Swedish Defence Research Agency). The system is installed onboard a Sabreliner (Fig. 7). This business jet is equipped with an antenna array to also enable moving target detections and integrated in two forward push booms [2].

Figure 7. Sabreliner with the two push booms.

The electronic racks which control the radar and handle all data registrations are housed inside the cabin, including two operator seats (Fig. 8).

Figure 8. LORA in-cabin electronic racks.

Table II summarizes the characteristics of LORA, and Fig. 9 shows a schematic block diagram of the system.

TABLE II. VHF/UHF BAND LORA CHARACTERISTICS

Frequency band	200 – 800MHz
Polarization	H
Transmit peak power	500W
Antenna	5 wideband bi-cones per boom
Azimuth aperture	90°
Sampling channels	8
ADC sampling rate	25.6MHz
ADC bandwidth	10MHz
ADC dynamic	12bits
Maximum data rate	310 MB/s
Record capacity	1TB

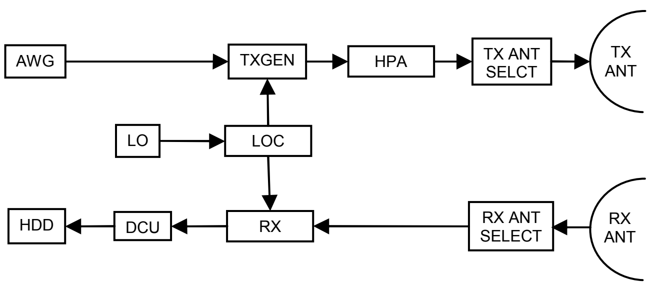


Figure 9. Synoptic view of LORA.

A more detailed description of the LORA design can be found in [3]. The main difference with the SETHI VHF/UHF mode is that LORA has eight 10MHz bandwidth receivers, i.e. a maximum instantaneous bandwidth of 80 MHz. This implies that LORA must receive sub-bands sequentially to cover the full bandwidth planned for the experiment whereas SETHI has a receiver capability that allows simultaneous registrations. The necessity to use a scheme of sub-bands has to be taken into account in the remote synchronization method.

III. REMOTE SYSTEM SYNCHRONIZATION

Coherence between transmitter and receiver systems is very important for the SAR image formation process. In bistatic SAR mode, the most difficult challenge is that the transmitter and the receiver are remote systems without any interconnection.

Three difficulties have to be overcome by the synchronization procedure:

- Stepped-frequency waveform: LORA has to configure its receiver to the same sub-band as SETHI transmits.
- Phase synchronization: the SETHI and LORA RF signals have to be in phase during all tracks to obtain a coherent system. This point is of high importance to be able to focus the bistatic SAR image.
- Timing synchronization: during an imaging track we have to avoid any drift between the trigger that positions the sampling window in the passive receiving system (for example SETHI) and the timing of the useful pulses transmitted by the other airborne radar (LORA in that case).

A. *Reference clock and trigger synchronization*

To obtain synchronization between the remote airborne radar systems, GPS receivers have been used as reference clock and trigger generator.

All GPS receivers produce a signal called 1-PPS[1] which is a pulse generated at each GPS time second change. The GPS time is an accessible common frame for any user, so the 1-PPS signal becomes a common trigger useful for our bistatic requirements. It resolves the timing synchronization difficulty.

Some GPS receivers offer a 10MHz reference clock synchronized to the 1-PPS signal. Such a type of GPS disciplined oscillator is used as our system reference clock and is the solution for the phase synchronization problem.

Hence, the 1-PPS signal in combination with the GPS disciplined 10MHz oscillator allow both airborne SAR systems to become coherent and synchronized.

During the preparation phase of the first campaign we thoroughly investigated and measured the 1-PPS and 10MHz deviations between two GPS receivers. The results for the former showed that two independent GPS systems have, after about a 5 minutes warm up period, a maximum drift of 150ns between the 1-PPS signals during 3 hours of measurements (Fig. 10).

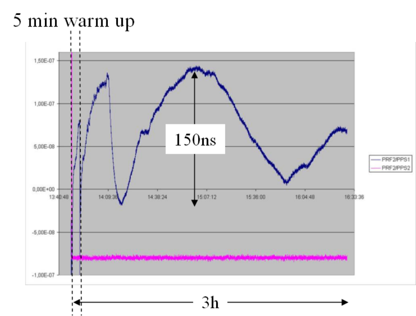


Figure 10. 1-PPS deviation between two GPS receivers.

Considering the transmit duration (5µs) and the size of the sampling window (35µs) defined for the campaign, this 150ns deviation is acceptable for our application. In addition, the deviation illustrated in Fig. 10 corresponds to a flight of 3 hours. The duration of a typical imaging pass is in the order of 2 minutes where the temporal drift will only be a few nanoseconds according to the generally smooth deviation characteristics. Based on these laboratory results we decided to synchronize our two systems through this common trigger.

The 10MHz reference clock has to have a pure frequency spectrum with short term stability and low phase noise. The Epsilon EBO3 board chosen for our experiment (already tested with LORA at VHF band [4]) delivers a pure GPS disciplined 10MHz sine wave thanks to a high quality OCXO[2] oscillator (Fig. 11). The ovenized control increases the frequency stability of the integrated quartz oscillator.

Figure 11. EBO3 board. It contains a GPS receiver and an oscillator.

[1] **P**ulse **P**er **S**econd
[2] **O**ven **C**ontrolled **X**-tal(Crystal) **O**scillator

With this hardware one can expect a warming up time of around 25 minutes (quartz temperature and frequency stability regulation on the board) and this dovetails fairly well with the preparation time needed before first airborne registration (time for take off, transit to the test site and system initialization).

B. *Common waveform*

The LORA SAR system works with a stepped-frequency waveform technique [3]. It sequentially transmits and receives a burst of sub-band pulses with different centre frequencies. The full bandwidth is reconstructed in the signal processing. The signal bandwidth used in the campaign (222-460 MHz) requires four sub-bands with some overlap (Fig. 12).

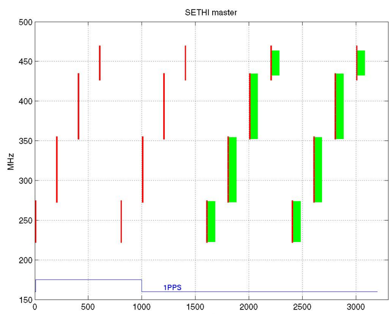


Figure 12. LORA stepped-frequency waveform.

In Fig. 12 red lines represent the SETHI transmitted pulses and the green parts the LORA received sub-bands. At the beginning of the imaging pass launched by the 1-PPS signal, LORA is in an initialization mode, i.e. it doesn't receive the SETHI pulses (no green areas). Then after two full transmission sequences the bistatic receiving mode starts. The four sub-bands selected to cover the full bandwidth are:

- First pulse bandwidth: 222-305MHz
- Second pulse bandwidth: 272-355MHz
- Third pulse bandwidth: 352-436MHz
- Fourth pulse bandwidth: 400-460MHz

Using a stepped-frequency waveform for the bistatic measurements means that the SETHI transmitter system and the LORA receiver system have to shift to the same sub-band at the same radar recurrence.

For the opposite configuration (LORA transmitting and SETHI receiving) we don't have this problem. The SETHI VHF/UHF component has four simultaneous sub-band receivers and four sampling channels (Fig. 6). Hence, it can simultaneously record any part of the bandwidth at each recurrence.

To make sure that the two systems are working at the same sub-band in the most critical configuration mode, i.e. SETHI transmitting and LORA receiving, it was decided that during the first radar recurrence after the 1-PPS trigger signal the first narrow-band pulse (222-305MHz) should be used. The next should be the second, followed by the third and fourth ones and then repeated periodically according to this pattern.

To take this constraint into account ONERA developed an electronic board with microcontroller and CPLD[3] components (Fig. 13). This device configures all the SETHI switches depending on the radar recurrence number versus the 1-PPS signal.

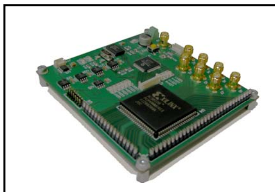


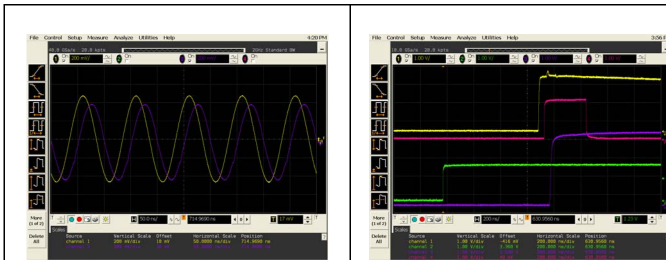
Figure 13. SETHI CPLD board.

Thanks to this board the configuration system is GPS disciplined, and knows at each recurrence which sub-band it has to transmit and receive.

IV. Synchronization Ground Tests

A first common synchronization test took place in the ONERA Salon de Provence laboratory in southern France in the end of the year 2008. The objective was to show that the proposed synchronization methodology is working. The LORA SAR system was installed and transported in a van and placed close to the SETHI hardware at the ONERA location.

Time synchronization with the independent 1-PPS signals was checked as well as the phase synchronization based on the GPS disciplined 10MHz reference clocks (Fig. 14).



SETHI and LORA 10MHz references | SETHI and LORA 1-PPS and triggers

Figure 14. SETHI and LORA synchronization tests.

During these measurements clocks and triggers were well synchronized with very little drift. To investigate the drift performance LORA collected four minutes of the transmitted SETHI signal. Fig. 15 presents the result obtained after pulse compression (extract for memo [5]). The range error evolution to the right in Fig. 15 shows that the observed drift in range is well below 100 ns during 4 minutes.

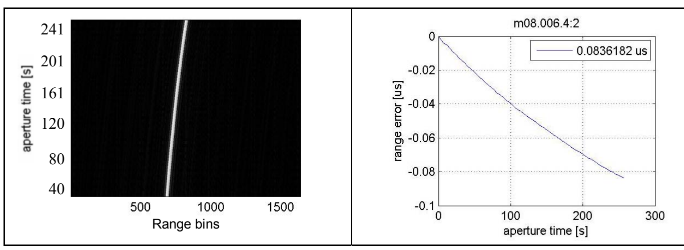


Figure 15. 4 minutes long LORA registration of SETHI transmitted signal.

The laboratory tests validated the synchronization solution as a feasible implementation and confirmed that the common stepped-frequency waveform could be handled with SETHI as transmitter and LORA acting receiver or vice versa.

[3] **C**omplex **P**rogrammable **L**ogic **D**evice

V. PRELIMINARY BISTATIC FLIGHT TEST

In the bilateral research program three experiments are defined. The first one is the laboratory synchronization test presented in the previous section. The second is the airborne verification tests of the concept, briefly described in the following. The final campaign is application oriented and will take place in Sweden in 2010. Different targets will be deployed to investigate the clutter suppression performance to improve under-foliage target detection or urban surveillance.

The airborne verification tests were undertaken during one week in December 2009. The flights were planned to evaluate the applied synchronization principle and the quality of the acquired VHF/UHF bistatic SAR data.

A. *Test area and flight geometry*

1) *Test area*

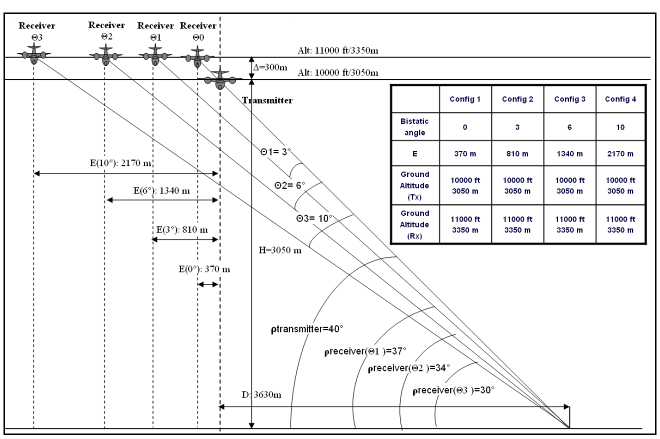
A test site close to Mende in southern France was selected. This is a fairly rural region and therefore well suited to reduce the impact on the radar systems from strong external transmitting sources. The radio frequency interference (RFI) environment can thus be expected to be fairly low.

The test site is located about 1000m above sea level and there is a considerable topographic relief in some parts. For a large fraction of the forest-covered areas a very good ground truth of the different stands are available.

Mende is quite close to Nîmes-Garons airport where the LORA and SETHI aircraft were based.

2) *Flight geometry*

Validate of the synchronization between the two systems was the main objective of this campaign. Therefore it was decided to only have quite simple mutually parallel flight lines. Simulations of the effect of bistatic angle on target-to-clutter ratio allowed us to plan four flight configurations from 0° to 10° bistatic angle in elevation (Fig. 16). Each bistatic angle was realized with LORA as the transmitter then receiver, and SETHI as the receiver then transmitter.



	Config 1	Config 2	Config 3	Config 4
Bistatic angle	0	3	6	10
E	370 m	810 m	1340 m	2170 m
Ground Altitude (Tx)	10000 ft 3050 m	10000 ft 3050 m	10000 ft 3050 m	10000 ft 3050 m
Ground Altitude (Rx)	11000 ft 3350 m	11000 ft 3350 m	11000 ft 3350 m	11000 ft 3350 m

Figure 16. Bistatic flight geometries used in the first airborne campaign.

For the flight configurations in Fig. 16, the transmitter is always between the receiver and the point of interest, to avoid a saturation of the receiver channels by the direct path. The flight altitude is 10000ft for the transmitter and 11000ft for the receiver. The monostatic incidence angle is 50° and the bistatic angles are 0° (nearly monostatic), 3°, 6° and 10°.

Fig. 17 shows the trajectories for the four bistatic angles compared with the point of interest centered on the town of Mende. The red rectangle represents the area that will be imaged by the bistatic SAR geometry.

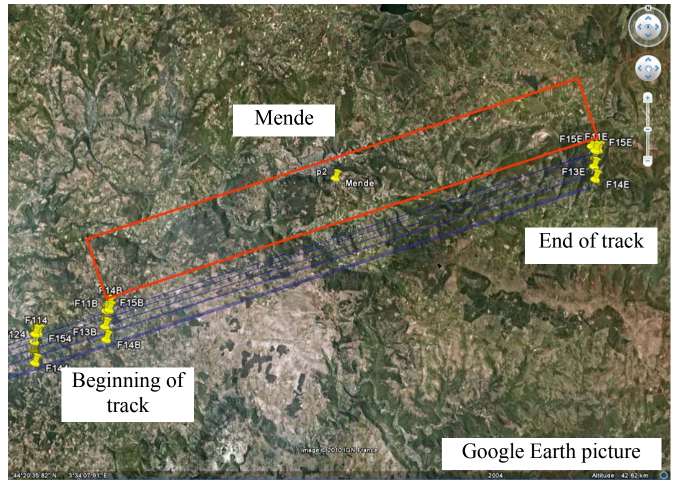
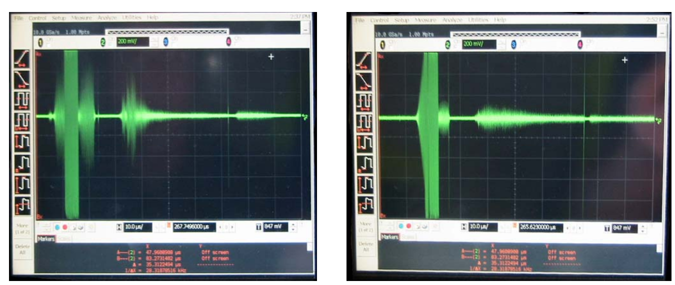


Figure 17. Pre-defined bistatic flight trajectories.

B. *Preliminary results*

1) *In-Flight real time signal control*

The SETHI system has a capability of real-time control of the received signals with additional laboratory equipments installed onboard. The registrations presented in Fig. 18 have been obtained with a 2GHz digital oscilloscope. Fig. 18a is the time signal of the second sub-band received in a monostatic mode (SETHI transmits and receives) and Fig. 18b is the time signal of the same sub-band received in a 3° bistatic angle (LORA transmits and SETHI receives).



(a) (b)

Figure 18. Signal received by SETHI in (a) monostatic and (b) 3° bistatic mode.

In both received signals the first very high level pulse is the direct transmitted signal, i.e. from LORA (Fig. 18b) and internal SETHI leakage (Fig. 18a), respectively. Next to this is the received and useful signal from the ground. What is important to note from the pictures in Fig. 18 is that SETHI can observe the LORA transmit signal without any drift. This confirms the very good GPS-based synchronization method. Hence, one can be rather confident that a good quality can be achieved in the generation of bistatic SAR images.

Both LORA and SETHI registered the backscattered signal when transmitting to also enable monostatic SAR formation for comparison with the bistatic data simultaneously acquired in the passive airborne radar sensor.

2) Latest monostatic and bistatic SAR images

The complete monostatic and bistatic SAR data set are currently processed. When available the image quality will be evaluated in terms of various parameters like resolution. The FOPEN capability will also be investigated in more detail by ONERA and FOI. A first monostatic and bistatic SAR image example can, however, be presented in this paper.

Fig. 21 shows SAR images processed from data acquired by the SETHI system with one of the four sub-bands (i.e. not the full resolution) over the Mende area, also shown in an aerial photo (Fig. 21d). Fig. 21a is the monostatic SAR image. Fig. 21b and Fig. 21c are the corresponding bistatic SAR images (LORA transmitting and SETHI receiving) with 0° and 10° of bistatic angle, respectively. The SAR scenes are 35km long in azimuth and 4.5km wide in slant range.

Fig. 19 presents a coloured composition of the SAR images found in Fig. 21: Red is monostatic, Blue is 0° bistatic and Green is 10° bistatic. We have now to analyze these data to validate the interest of VHF/UHF bistatic system and select the best bistatic angle for the future campaign.

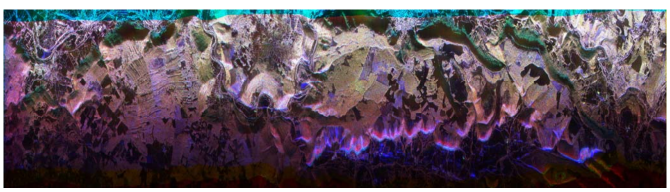
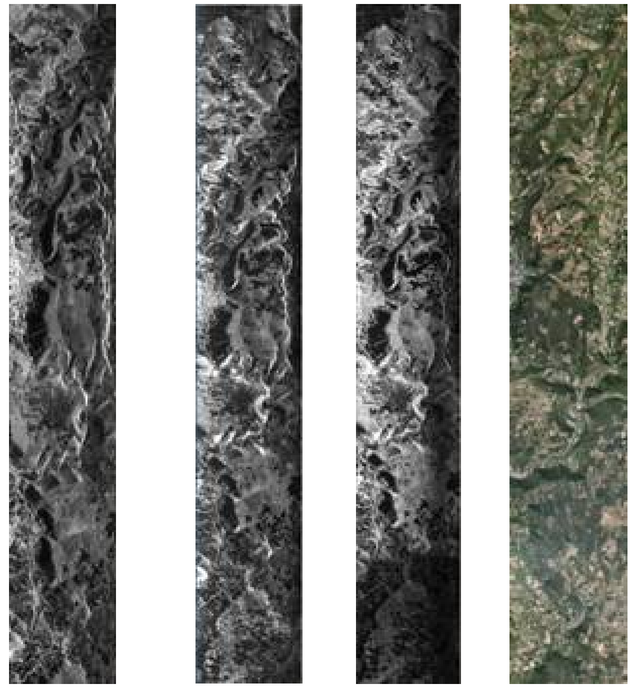


Figure 19. Monostatic and bistatic coloured composition of VHF/UHF SETHI SAR images.

Fig. 20 is a coloured composition of the SAR images obtained with 0° bistatic angle: Red is the first sub-band contribution (222-305MHz), Green is the second one (272-355MHz) and Blue is the fourth one (400-460MHz). Analysis of these data may demonstrate any differences of under-foliage penetration and concealed targets detection between the sub-bands used.

Figure 20. Coloured composition of the 0° bistatic SAR image sub-bands.



(a) (b) (c) (d)

Figure 21. SETHI (a) monostatic, (b) 0° bistatic and (c) 10° bistatic SAR images over the Mende area, with an aerial photo in (d).

VI. CONCLUSION

Ground tests and validation flights have been performed using two airborne VHF/UHF SAR systems. The obtained results show that the GPS-based synchronization works well and bistatic SAR images have been produced with a very good quality, although the complete data set have not yet been processed yet. The possibility to get an improved FOPEN capability with this imaging geometry will be investigated by comparisons with monostatic images. A more extensive campaign of under-foliage target detection will take place in Sweden in 2010.

VII. ACKNOWLEDGMENT

The authors wish to acknowledge the ONERA and FOI SAR teams involved in the design and operation of the systems. The Swedish Armed Forces and DGA are thanked for their support to this work, as well as FMV T&E and AVDEF for providing the airborne platform resources.

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