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jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2011, VOL. 57, NO. 1, PP. 29–35
Manuscript received January 19, 2011; revised February 2011. DOI: 10.2478/v10177-011-0004-0

SETHI: The Flying Lab

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***Abstract*—This paper presents the new-generation test bench SETHI, developed by ONERA, the French Aerospace Lab. SETHI is a medium range platform dedicated to environmental, scientific and security applications. The first part of this paper describes the system architecture, the development state and the future capabilities. A set of recent significant results are presented: these results cover various applications, such as high spatial resolution imaging, change detection between two acquisitions, biomass measurement in the rain forest, bistatic imaging and innovative measurements, such as air-to-air imaging or circular imaging.**

***Keywords*—SETHI, flying lab, SAR, very high resolution, PolInSAR, bistatic images, radar-optronics complementarity, change detection, biomass, climate change, environment, security applications.**

I. Motivation

ONERA has a long history in airborne remote sensing acquisition systems for the French Air Force. In the 90's, Onera developed the RAMSES (SAR imaging) [1] and Timbre-Poste (infrared imaging) airborne test benches in order to provide entry data to define operational sensors. Thanks to this fruitful experience, Onera decided in 2004 to develop a medium range platform dedicated to research and science applications, with internal funding.

The key objective of the project is to propose a cost effective system offering the best performances. To achieve this aim, the general system architecture fulfills the following criteria:

- To use a non-dedicated carrier (rent-on-demand), able to operate worldwide,
- To choose a pod-based concept, allowing easy integration and new sensor testing,
- To implement an open and plug & play system design, offering configurations suited to the user's requirements,
- To choose a high modularity approach, enabling a large upgrade potential,
- To use a data exploitation process based on the existing in-house processing toolboxes and the Onera's experienced team.

II. SETHI System Concept

A. General Architecture

To provide cost-effective performances, SETHI was designed as an open system based on two pods carrying different payloads (SAR and E/O sensors) and an acquisition & control sub-system located in the cabin and operated by two persons [2]–[4].

Fig. 1. SETHI general view.

The carrier is a Falcon 20 (Fig. 1), a business jet designed by Dassault Aviation. This aircraft, based at the Nimes-Garons airport (Southeast of France), is operated by AVdef, a French private company. It offers $2\frac{1}{2}$ hours of autonomy and flies at a speed range between 160kt and 300kt, up to flight level 300. To support the SETHI system, the aircraft was equipped with specific wiring in the wings and a more powerful electrical generator.

In order to be able to operate worldwide, the SETHI system was designed in compliance with the European Aviation Safety Agency (EASA) standards.

The entire SETHI project was managed by Onera, from the preliminary definition phase up to the development, certification and operation phases. SETHI was developed and implemented with strong support from small and medium-size companies.

Today, SETHI supports four radar sensors and two optronics sensors, as well as offering an enormous potential of multispectral and hybrid radar/optronics imaging. It is a tool for complex remote sensing studies, such as climatology, agronomy, forestry, geology, etc.

B. Cabin Installation

The cabin sub-system is designed to command the payloads and control their states, to pilot data acquisition and storage, to verify the acquisition quality in near real-time and to ensure communication with the crew to achieve the scientific flight plan.

The cabin installation is designed to be operated by two persons. It is composed of five standard racks offering a 110U total capacity (See Fig. 2).

The system is equipped with an IMU[1] coupled with a real-time differential GPS receiver, which deliver high-accuracy

[1]IMU: Inertial Motion Unit

Physics and Astronomy Classification Scheme: 93-85.

SETHI development was funded with Onera investments. The measurement campaigns and image processing were sponsored by the DGA (French MoD) and the French (CNES) and European (ESA) space agencies.

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Fig. 2. Cabin installation.

localization information (around 20 cm). The latter is presented on a remote screen available in the pilot cabin. This is a key feature, especially for PolINSAR[2] and tomography applications, which require pilots to fly the same flight-line repeatedly with a high accuracy.

The hardware architecture is based on open standards.

All the equipment communicates through an internal CAN bus (See Fig. 3). Communication between the operators and the pods is provided by two hardened computers in standard PC/104.

Many monitoring functions are automated and displayed in real time on the payload operator screen, such as, for example, payload power supplies and environmental parameters (temperatures, humidity, accelerometers).

Onera has developed its own Graphic User Interface. Its purpose is to centralize the SETHI system controls and commands on the operator's display. This interface is easily reconfigurable to accommodate any type of payload.

[2]PolInSAR: Polarimetric Interferometric SAR

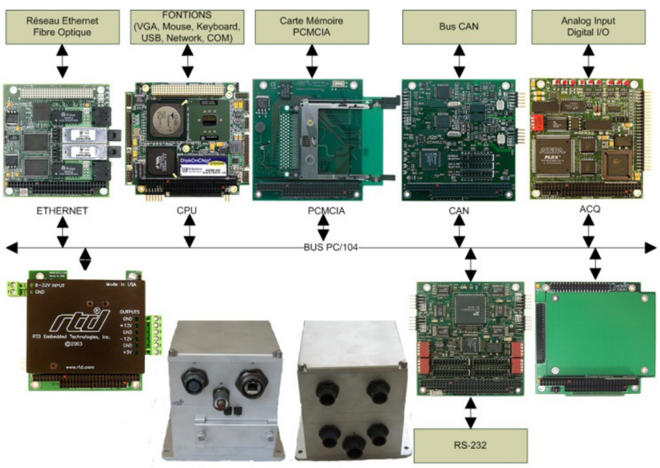

Fig. 3. Hardware architecture.

Fig. 4. Cutaway view of a SETHI pod.

C. *Payloads Integrated in Pods*

The SETHI pods are designed to carry heavy and cumbersome payloads of different kinds, ranging from VHF-UHF-band to W-band and/or optical sensors, with a wide range of acquisition geometries.

The useful length of the pod is 2300mm, its diameter is 530 mm and the maximum payload mass is 120Kg. The three first radar payloads developed for SETHI (P, L and X-bands) offer a full polarimetric capability, as well as cross and along track interferometry. Moreover, the X-band payload offers a very high spatial resolution (10cm class).

The aircraft has been modified to accommodate a fast link between the cabin and the pods. A set of cables, as generic as possible, assigned different functions (RF, control and command, synchronization) run through the wings for that purpose. RF cables show losses of less than 0.2 dB/m at 14 GHz and support a 500 W power at 18 GHz.

In order to offer a good flexibility level, the payloads can be oriented and moved during operation (e.g., it is possible to modify the line of sight between two acquisitions in the same flight). This flexibility is provided by four "motorized columns" for each pod, on which antennas of different types and sizes, typically horns or patch arrays, can be attached.

Fig. 5 and 6 present two examples of payload integration. As we can see, one of the most important challenges in the development was the integration of a large set of antennas into the pods.

Fig. 5. X + L bands and visible-band camera configuration.

Fig. 6. VHF/UHF-band configuration.

III. SETHI Development State and Future Upgrades

A. A Quick Synthesis of the SETHI Project

The interest in developing a flying lab dedicated to scientists and civilian applications, besides the full-spec military range, appeared clear at the turn of the Millennium. After a maturation phase, the SETHI project was officially launched in December 2004.

After two and half years of development, SETHI performed its first technological flight in August 2007. The EASA certification was obtained in October 2008, giving the SETHI system a worldwide capacity. This milestone was the most important one in the development process.

The first year of operational exploitation, 2009, was a very busy and successful year. SETHI was used in around ten experiment campaigns for different clients, performed more than 100 hours of acquisition flight and produced roughly 500 images. One of these campaigns, dedicated to biomass measurement in the tropical forest (See results presented in section IV), took place in French Guiana. The challenge of this experiment was the projection of the entire SETHI system, including the experiment and data exploitation teams.

This shows the ability of the SETHI to operate overseas in the first year of exploitation.

B. Future Capabilities Under Development

The SETHI project was conceived as an iterative project offering regular capacity upgrades. From the beginning, it was clear that the radar imaging capacity would be a first step only.

In order to understand complex problems, scientists need to collect a large spectrum of data, representing different points of view (shapes, spectral signatures, humidity, evolution over time – day/night, seasons, etc.) of a same object of interest.

Thus, it seems obvious to add an optronics capacity to SETHI. In the short term (by the end of 2010), a set of high resolution and hyperspectral cameras will be integrated in the nose of the existing pods.

For the longer term, Onera is starting to develop a new pod dedicated to optronics sensors, including visible, infrared, hyperspectral and laser sensors. This new capability, which will be operational by 2014, will offer a large set of data opening an enormous range of data analyzing to solve complex problems.

IV. Recent Significant Results

This section will illustrate some significant results obtained during the first two years of exploitation:

- High spatial resolution SAR image,
- Change detection in an urban area,
- Biomass measurement in the rain forest,
- Bi-static imaging,
- Innovative configurations (air-to-air imaging and circular imaging).

A. High Resolution SAR Image

For a long time, high spatial resolution was the *Holy Grail* of the SAR community.

In the 80s, the state of the art resolution was around 10 meters in X-band (3cm wavelength). At the end of the 90s this figure was reduced to 1 meter. Ten years later, the corner edge is around 10cm, i.e., 3 times the wavelength! The key drivers of this dramatic progress are the improvement in RF components (for example stability), carrier motion compensation (IMU and algorithms) and of course SAR processing (CPU and algorithms).

Fig. 7 shows an example of a high spatial resolution SAR image (10cm-class), the famous Millau viaduct in the south of France in X-band, taken with an incidence angle of 40°C [5].

B. SAR Imaging in Low Frequency Band

Over the last decades, the low frequency bands were progressively abandoned in favor of higher frequencies, which offer better resolution and are easier to integrate into the equipment.

Recently, the interest in low frequencies has resurfaced thanks to its capacity to detect targets hidden under foliage. In addition to this military or security application, low frequency bands are of interest for agronomy or forestry monitoring. Onera has developed a specific VHF/UHF band for SETHI, with a full polarimetric capacity airborne on the SETHI platform.

Fig. 8 presents a 1 meter resolution rural landscape image, which highlights how full polarimetric data is valuable for agronomy studies and crops monitoring.

Note that an electrical high power line is perfectly visible (Fig. 8 and 9) at the top of the image. The cables are visible

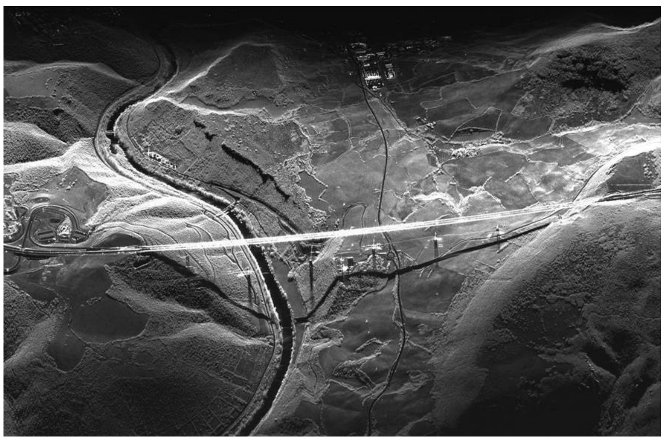

Fig. 7. High resolution image of Millau bridge.

Fig. 8. High altitude (25000 ft), large swath (8 km), low frequency and full polarimetric SAR image (the red lines at the top show the presence of high power lines, visible with Hh polarization).

continuously thanks to the long integration time, i.e., each object is observed under a wide view angle smoothing the classical specular effect obtained in higher frequency-band images.

C. Change Detection in Urban Area

One of the main difficulties in the surveillance domain is the enormous amount of available images and data. The bottleneck is now at the analysis level (saturation of the operators). Thus, an important effort must be done in data pre-processing algorithms and toolboxes able to facilitate image analysis [6].

In an experiment conducted in 2009, an urban area was imaged twice at times several days apart, using the same radar configuration. Thanks to a precise aircraft trajectory, an interferogram could be computed leading to a three-channel composite color. The green channel shows the intensity image for the first date, the red channel shows the intensity image for the second date and the blue channel shows the consistency between the two images. This composition distinguishes objects present in one image and not in the other, similar objects that have been replaced between the two dates and objects that remain still. An illustration, focused on a limited area of interest corresponding to a public car park, is given in Fig 10.

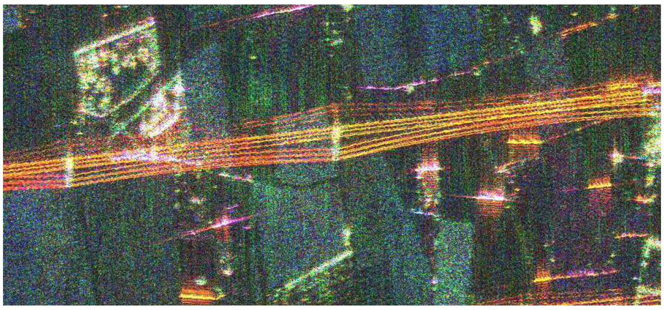

Fig. 9. Zoom on the high power lines.

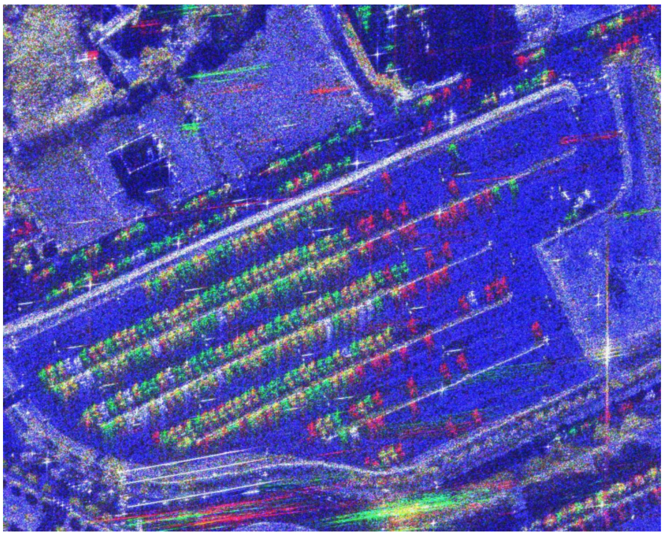

Fig. 10. Change detection example.

This representation illustrates the high potential of change detection using consistent images: Cars parked during the first flight appear in green. Cars parked two days later are presented in red. If the same place is occupied, the white color code indicates a same car parked in the same place; while yellow indicates two different cars parked in the same place.

This example shows the interest of the change detection technique to reduce the data volume. Onera is working on the development of in-house automatic change detection algorithms.

D. Biomass Measurement in the Rain Forest

Biomass measurement is a growing application linked to climate change prediction. In order to better understand the global carbon cycle, it is essential to measure the biomass density in tropical forests, a main component of the terrestrial carbon pool and also a carbon source due to deforestation.

Following the United Nations Convention on Climate Change, the BIOMASS mission, a P-band[3] SAR mission dedicated to monitoring forests at global scale, was selected by the European Space Agency (ESA) for further study and possible implementation. BIOMASS aims to quantify the forest biomass, as well as the extent of forested and deforested areas and to outline flooded forests on a global scale.

During phase 0, biomass retrieval algorithms have been developed and validated for a biomass range of up to 300 t/ha. The methods are based on combining SAR intensity and SAR Polarimetric interferometry (PolInSAR), which provide estimates of biomass and canopy height respectively. One of the important findings of the BIOSAR 2007 airborne campaign in the boreal forest was that for the P-band, the temporal consistency remains high after 20-30 days. The result indicates that forest height can be retrieved with good accuracy using interferometry at P-band at a time interval compatible with a single radar concept in a repeated pass mode. Reversely, in

[3]P-band: around 400 MHz (VHF/UHF band)

the L band, the loss of consistency after 20-30 days implies, for example, the use of two satellites for the height retrieval.

The questions that remain to be addressed in phase A concern the overall performance of the retrieval algorithms in tropical forests characterized by high biomass density (>300 t/ha) and complex structure. Thus, it was decided to conduct a flight campaign in high forest density regions, to verify the robustness of the height and biomass retrieval algorithm.

The TropiSAR experiment in French Guiana, was conducted by Onera to provide feedback on the performance of a P-band SAR to measure the biomass and canopy height of a tropical forest with high biomass density.

The main TropiSAR objectives were the following:

- To provide temporal consistency measurements in the P and L bands over tropical forests, for time periods compatible with spaceborne missions (typically 20-30 days).
- To assess the performance of methods transforming P-band SAR intensity and interferometric measurements into forest biomass and forest height.
- To assess uncertainties in in-situ methods, for biomass estimates and tree allometry for the tropical forests under consideration.

The above objectives have been addressed through a set of coordinated ground and airborne SAR and lidar acquisitions performed at the Nouragues and Paracou stations, two long-term experimental research sites located in the lowland rain forest in French Guiana.

During the TROPISAR experiment, performed in August 2009, a large dataset was collected, providing a valuable basis for further evaluations of the forest biomass and height retrieval procedures [7], [8].

E. Bi-static Imaging

Bistatic SAR imaging of a very asymmetric configuration is an interesting technique for both military and civilian applications. Indeed, an illuminating radar standing off at a safe distance may be combined with a low cost, possibly unmanned, air vehicle using a passive radar receiver operating at a closer range. A practical civilian application could be the high resolution remote sensing of dangerous disaster areas (fire, chemical of radioactive hazard) with small unmanned aircraft. For low frequency-band sensors, another advantage is a significant increase in the target-to-clutter ratio, allowing a better performance in foliage penetration applications.

In the bistatic SAR mode, the key challenge is that the transmitter and the receiver are remote systems without any interconnection and a fine synchronization between the two (limited clock drift and jitter free clock) is absolutely necessary for the SAR image formation process [9].

The simplest and most efficient way to achieve synchronization between the remote airborne radar systems is to use GPS receivers. All GPS receivers produce a signal called 1-PPS, which is a pulse generated at each GPS time second change. Some GPS receivers offer a 10MHz reference clock, synchronized to the 1-PPS signal. Such a type of GPS disciplined oscillator is the solution for the phase synchronization problem.

Hence, the 1-PPS signal in combination with the GPS disciplined 10MHz oscillator (using high quality OCXO[4]) allow both airborne SAR systems to become consistent and synchronized.

Moreover, such configurations are strongly non-stationary in the sense that the transmitter to receiver distance and relative orientation vary. This makes the task of frequency domain processing, and especially its motion compensation, much harder. Specific SAR processing has been developed for this application, providing self-testing before image synthesis and forecasting phase errors in the resulting image depending on terrain elevation features.

Onera has now acquired great experience in bistatic imaging. The first airborne bistatic campaign was conducted with the DLR (Germany) in 2003, which successfully tested time invariant configurations (same velocity on parallel tracks). Then, in the following years, more sophisticated configurations will be performed in different frequency-bands (from VHF-UHF to X-band) and with different SAR systems from DLR and FOI (Sweden), and between two Onera systems (SETHI and the Stemme motoglider "Busard").

Fig. 12 and 13 illustrate the maturity of this technique [10]. The same scene is imaged in both pictures: Fig. 12 shows the bistatic image and Fig. 13 shows the monostatic image (reference). The image quality obtained in the bistatic image is similar to the reference. Moreover, a remarkable reduction of the specular reflections on the building edges can be observed in the bistatic image.

F. Innovative Air-to-air Imaging

During one of the bistatic campaigns, an opportunistic air-to-air inverse SAR imaging (of the receiver plane) was successfully experimented with in X-band. The Stemme motorglider, the receiving aircraft, was imaged in flight with 40 cm resolution. This successful imaging required advances in both the image synthesis algorithm (the apparent transmitter trajectory in the target frame is extremely uneven, due to target attitude fluctuation) and the autofocus algorithm (for retrieving both trajectory and attitude estimation errors).

The imaging aircraft was flying at 160kt and an altitude of 1700m (5500 ft), while the target aircraft crossed the swath at

[4]OCXO: Oven Compensated Crystal Oscillator

Fig. 11. P-band PolInSAR image on the rain forest – Paracou site.

Fig. 12. Bistatic SAR image.

Fig. 13. Monostatic SAR image of the same scene (remark the important specular reflections on the building edges).

90kt and an altitude of 300 m (1000 ft), with a heading angle at 125° from that of the imaging aircraft.

In the image focused on the ground (Fig. 13), the target aircraft is completely invisible, since its image is strongly smeared on the azimuth due to the along-track component of its own velocity and its radar cross section (RCS) is low (it is mainly a composite material aircraft).

Using the appropriate processing, the target aircraft appears clearly in Fig. 14.

G. Innovative Circular SAR Imaging

Another innovative SAR mode is to use a circular configuration to extract a Digital Elevation Model (DEM) using radargrammetric techniques [11], [12]. This type of configuration is well suited to urban areas; the complementarity between the different viewpoints is used to remove layover and shadow areas.

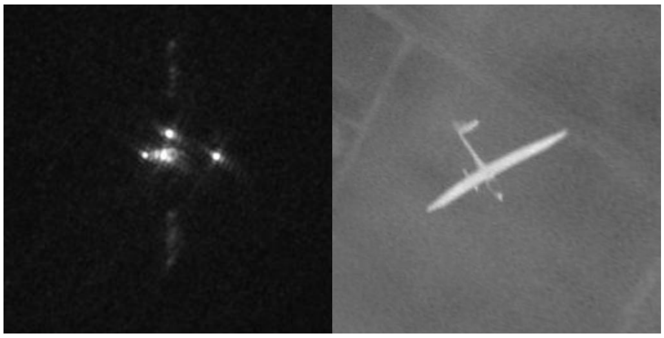

Fig. 14. Air-to-air ISAR image of the motoglider (left) ; photography of the motoglider for comparison (right).

The output DEM (Fig 15) is dense and displays the main characteristics of Nimes downtown (narrow streets, trees, inner yards, etc.).

This circular configuration could be highly valuable for specific applications, such as disaster response or security concerns in a dense urban area.

V. Conclusion

The main objective of the SETHI flying lab was to offer a powerful and valuable test bench for scientists and researchers. After the two first years of operation, the results validate the concept and the overall performance of the system. Thus, we could say that our objective has been fulfilled. SETHI has collected a large amount of varied data under different conditions and for different applications.

The next step is to include the development of the optronics capability, which will increase the interest in this flying lab allowing radar and optronics complementarity, a significant improvement expected by scientists to address complex problems.

Acknowledgments

The authors thank all of the SETHI team members involved in the design, operation and data exploitation of the system.

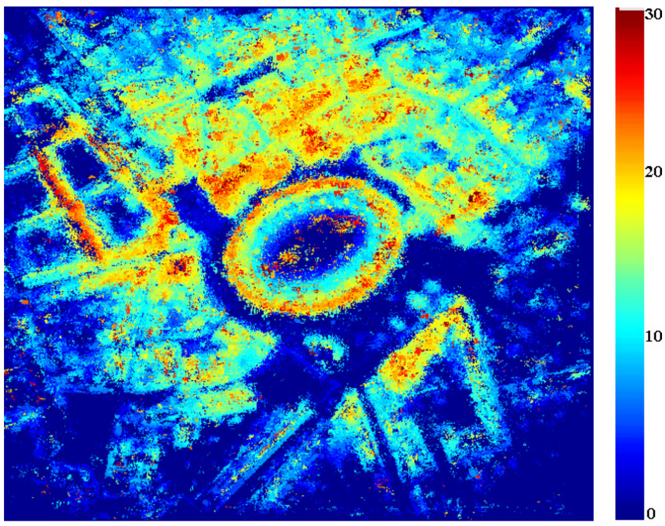

Fig. 15. Circular SAR image of the centre of Nimes (France).

Fig. 16. Nimes Roman arena.

Fig. 17. The SETHI team.

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