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# SWALIS, KaRADOC and HOMARDS: a suite of airborne radars to support satellite earth observation missions.

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**Abstract**—This communication presents the different airborne radar systems which are developed at IETR (*Institut d'Électronique et des Technologies du numÉrique*). In close collaboration with CNES (*Centre National des Études Spatiales* and IFREMER (*Institut Français de Recherche pour l'Exploitation de la MER*), IETR has been designing airborne radar sensors to support satellite missions, both in the upstream phase and in the calibration/validation phase. These sensors are both tested and became operational with the PIMA platform, an airborne platform managed by the University of Rennes. Thus, this communication describes the SWALIS, KaRADOC and HOMARDS radars and the corresponding satellite observation missions. In our case, these missions are especially dedicated to the oceans and continental waters management. Finally, the results obtained are presented in relation to the aims of these satellite missions.

**Index Terms**—Airborne Radar System, Remote sensing, Radar reflectivity, Normalized Radar Cross Section, hydro and ocean measurements, doppler estimation

## I. INTRODUCTION

Over the last 50 years, investigations using radar and optical sensors, whether spaceborne and/or airborne, have shown that variations in backscatter and Doppler frequency of the surface of ocean waters are a function of wind and currents [1], [2]. It is fundamental to understand the mesoscale and subscale mechanisms of ocean surface currents in order to measure the impact the thermal regulation of the Earth. In the current context of global warming, it is a vital importance to identify and monitor in real time the surface freshwater resources. The world-wide observation of the Earth's water is carried out by many satellites by measuring the different phases of the water cycle through the on-board sensors. We can cite nadir altimeters dedicated to the ocean level measurement (Jason-1, -2 and -3 [3]–[5], Altika [6], ENVISAT [7]) or satellites

that provides information on the glaciers movement (ICESat-1 and -2 [8], CryoSat-2 [9]). This paper is concerned with measuring the distribution and behaviour of water (oceans and continental waters) at the Earth's surface. This is fundamental to provide information for synthesising the evolution of large-scale systems [10].

When choosing a satellite mission, there are two important phases for this mission which are called early and calibration/validation phases. On the one hand, during the early phase, an airborne experiment is proposed to create the same measurement conditions as the satellite is supposed to have. In case of radar satellite, an airborne radar system is described to provide radar measurement close to those of the satellite system (frequency, local incidence angle, etc.). Thus, the acquired experimental data make possible to validate the concept devised for the measurement of a geophysical parameter. On the other hand, the last phase is dedicated to the validation and the calibration of the satellite measurements. During this phase, the airborne radar measurements check that the measurements taken by the satellite are consistent with the ground truth measured during the sensor paths (airborne and satellite). Consequently, calibration coefficients are calculated to fit satellite measurements with airborne data.

This communication describes the different radar sensors which are developed at IETR in close collaboration with CNES and IFREMER in the frame of these early steps and calibration/validation operations. The first two sections of the communication are dedicated to SWALIS (Still Water Low Incidence Scattering) and KaRADOC (Ka RADAR for Ocean measurements). For each sensor, a brief description of the satellite or concept mission is given and the main results we obtained are described. The third section deals with

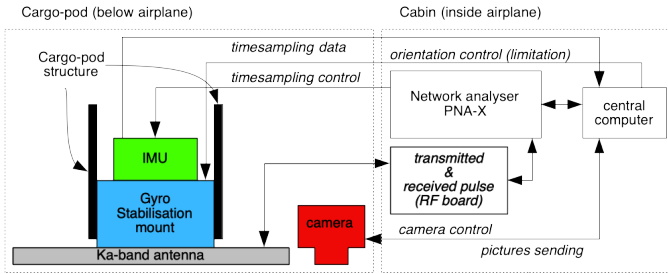


Fig. 1: SWALIS description.

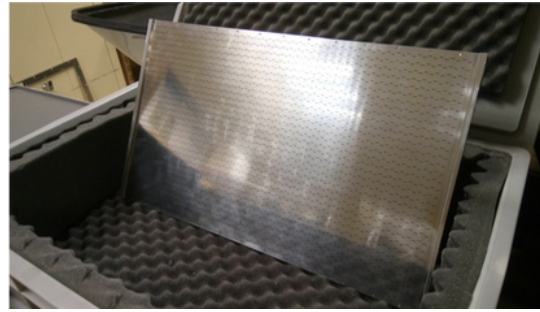


Fig. 2: The SWALIS leaky-wave antenna.

HOMARDS (Hydro-Ocean Measurements: an Agile RaDar System) through the required specifications by the targeted mission. The last section concludes this communication.

## II. THE SWOT MISSION AND SWALIS SENSOR

The SWOT mission [11], [12] is an international space altimetry mission involving NASA and CNES. The SWOT mission was launched on 16 December 2022 for a nominal duration of three years and is on an orbit with an inclination of  $77.6^\circ$  and an altitude of 891 km. Its repetition cycle is 21 days. The SWOT mission observes a topography of the oceans and surface waters that, until now, have been poorly imaged by radar satellites because of their small size. This capability is essentially due to the nadir targeting of SWOT (from  $0.6^\circ$  up to  $3.9^\circ$ ). Based on the pulse compression technique (across track) and SAR processing (along track), the SWOT mission offers a spatial resolution roughly around 20 meters (range resolution) and 2.5 meters (azimuth resolution) respectively. The sensor KaRIN (Ka-band Radar interferometer [13] [14]) embedded in SWOT is an interferometric synthetic aperture radar providing a centimetric resolution in height [15].

The airborne AirSWOT sensor has been designed by the NASA and has produced results that accurately reproduce water surface elevation [16]–[18]. In the same way, IETR and CNES propose to design an airborne radar sensor SWALIS that provides radar reflectivity at Ka-Band in near-nadir conditions.

### A. The SWALIS sensor

The main objective of the SWALIS airborne radar system is to carry out backscatter measurements (amplitude of the normalised backscatter coefficient of a rough surface:  $\sigma_0$ ) at small incidence angle to characterise areas of hydrological interest [15]. These measurements are used to study the following topics: roughness of hydrological surfaces, 'dark water' conditions, contrast between water areas, banks and covered areas [19]. The SWALIS sensor is placed in our airborne platform of PIMA (Plateforme d'Ingénierie Multimodale Aéroportée) [20]

1) *Main SWALIS description:* The SWALIS system is divided into 2 parts: the first one is located in the cargo-pod under PIMA and the second one is inside the aircraft cabin. In Fig. 1, we describe all the elements of the acquisition system and the links between the different parts. A PNA-X network analyser is used to generate and to receive a Ka-band signal. The transmitted waveforms are suitable for the

intended missions: pulse duration, pulse repetition time, carrier frequencies and transmitted power.

In addition, the characteristics of the sampling procedure (sampling period, sampling duration and delay, number of pulses per burst) are set by the central computer. A pulse is characterised by a transmission frequency and a burst which consists of a  $N$  number of pulses at the same frequency. It is worth to notice that we reach the expected range resolution through the thin mainlobe of the antenna: a transmitted chirp is also not useful.

Moreover, the PNA-X transmits the acquired radar data to the central computer and simultaneously sends a command to retrieve attitude data from the antenna via a logic card. This attitude data is supplied by an inertial measurement unit.

Finally, the central computer also manages the camera control which is installed inside the cargo pod. The purpose is to take photos of the terrain during the experiment.

2) *Data acquisition:* The signal waveform corresponds to that of a pulse signal of duration  $\tau$  and repetition frequency  $f_R = 1/T_R$ . The capabilities of the acquisition system determine how the radar data is acquired and stored. The choice of IF frequency for the input filter applied to the sampler sets the limits of the noise floor and the length of the recordable pulse. The PNAX offers several methods for measuring the pulse. We choose the 'pulse profile' available mode with the PNA-X.

3) *Antenna:* We use the leaky-wave antenna technology which allows it to be steered as a function of frequency. The physical characteristics of the antenna are as follows: 480 mm (in the H-plane, i.e. perpendicular to the direction of flight)  $\times$  270 mm (in the E-plane, parallel to the direction of flight)  $\times$  16mm thick, 32 waveguides oriented perpendicular to the E-plane, 80 slots described along each waveguide following the H-plane (see Fig.2). Two access ports are available for transmitting or receiving RF signals. The angle  $\theta$  is the angle of mainlobe steering in the antenna H plane. In addition, the aperture angles as a function of frequency in the E plane and the H plane are  $1.6^\circ$  and  $1.25^\circ$  respectively. The measured antenna gain is approximately 36 dBi.

4) *RF front-end:* We use a pulsed amplifier for the transmitting part and a low-noise amplifier protected by an analogue switch (SPST) on the receive side. In addition, we add a circulator so that the antenna can be used for both transmitting

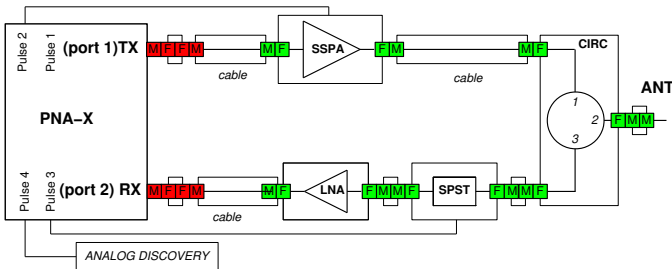


Fig. 3: Simplified diagram of the SWALIS RF module

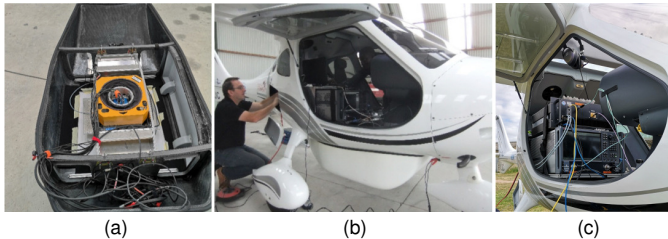


Fig. 4: Setting up the overall system (a) cargopod, (b) integration in the aircraft, (c) RF part in the cabin.

and receiving. The schematic diagram of the RF module and the PNA-X controls are shown in Fig. 3. This RF segment is made up of a pulsed power amplifier (SSPA) controlled by the Pulse 2 signal and which operates for the duration  $\tau$  of the transmitted signal, a circulator (CIRC) allowing transmission from port 1 to port 2 during transmission of the wave and reception of the return of this wave from port 2 to port 3 during the radar receiving time and an analogue switch (SPST) protecting the receive part of the RF module.

5) *The gyro-stabilisation system:* The gyro-stabilisation system is used to stabilise the antenna regardless of the aircraft's movement, keeping the axis perpendicular to the plane of the antenna in the Nadir direction ( $\pm 0.1^\circ$  during a burst period). Furthermore, on a measurement trajectory (currently limited to a few kilometres), the beam must remain at angles of incidence of  $\pm 0.5^\circ$ . The choice therefore is on the SOMAG CSM130 reference (Fig. 4(a)).

6) *The Inertial Measurement Unit:* In order to geo-reference the measured radar data, we associate an inertial motion unit (IMU) with the stabilisation platform to estimate the position and attitude of the antenna. The inertial unit used is an EKINOX SBG INS (model N) and provides information at a frequency of 200 Hz. This unit records all the position data from the SWALIS antenna (raw GPS data and GPS data) as well as attitude (roll, pitch and yaw) and speed (north, east and vertical) during flights. In addition, data acquisition is synchronised with each burst. In our case, we assume that the aircraft's attitude is stable for the duration of a burst (approximately 100 ms).

7) *System installation:* The system is installed both in the aircraft's cargo pod (the antenna, the inertial unit and the destabilization platform -Fig. 4(a)) and in the cabin (the RF segment, the central computer and the PNA-X - 4(c)).

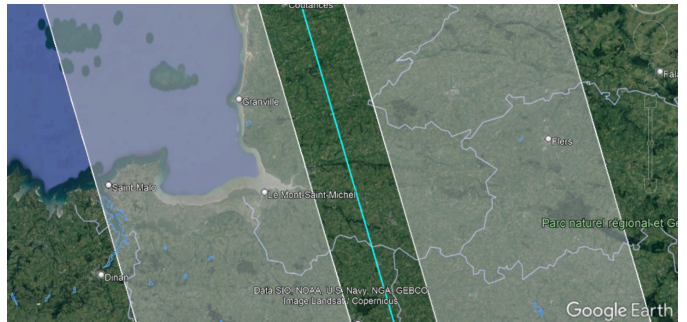


Fig. 5: SWOT Cal/Val orbit: Descending orbit over MSM area. The blue line represents the satellite trajectory and the grey one, the KaRIN swath on either side of the trajectory.

TABLE I: SWOT path: date and time.

Date	SWOT path time
27 juin 2023	21:46:34 UTC+1
28 juin 2023	21:37:11 UTC+1
29 juin 2023	21:27:49 UTC+1

## B. Overview of results

In this communication, we present the results we have obtained during the Mont Saint Michel (MSM) campaign. This campaign has taken place during the calibration and validation phase of SWOT. The choice of this area is motivated by studying the backscattering phenomena of wet and dry sand. In this area, SWOT has a descending trajectory with an orientation of  $164^\circ$  as shown in Fig. 5. The bay of the MSM is at a local incidence angle of roughly  $3^\circ$ . The SWALIS tracks are chosen with respect to the SWOT times recorded in Table I. Taking into account the constraints of the PIMA plane (for Ultra-Light Motorised plane, flights during the night are not allowed), SWALIS flights above the defined areas approximately 1 hour before SWOT (the last flights take place 30 minutes before SWOT). The SWALIS measurement parameters are described in table II.

TABLE II: SWALIS: measurement parameters [21].

Parameters	Values
Transmitted power	-8 dBm
Pulse width $\tau$	1 $\mu$ s
PRF	4 kHz
IF filter	15 MHz
Sampling frequency	20 MHz
Carrier height	500 m
Number of samples per pulse	100
Number of pulses per burst	50

Firstly, we present on Fig.6 the picture after assembling all the pictures provided by SWALIS during the flights. Moreover, we describe the SWALIS  $\sigma_0$  measurements over 2 specific areas: wet sand area -green area- and less wet sand area (because above the sea level) -blue area. To carry out an analysis of the evolution of  $\sigma_0$  values along the SWALIS trace, we also have PIXC data for the areas which correspond to the  $\sigma_0$  values measured by SWOT. We apply an interpolation



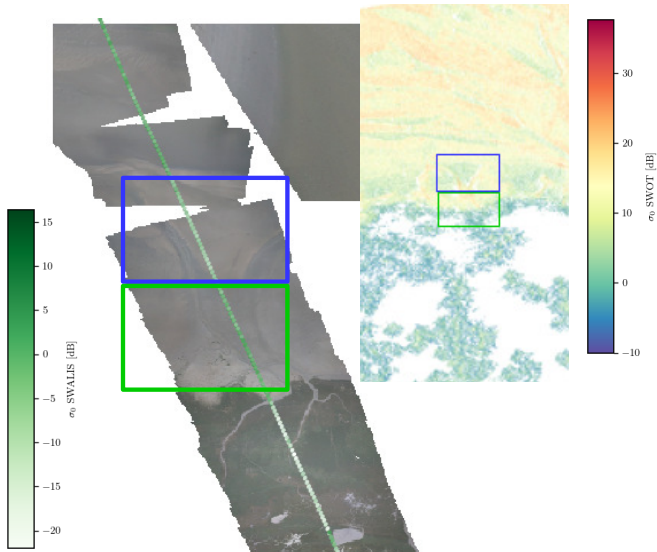


Fig. 6:  $\sigma_0$  measurements over the area (green and blue rectangles). On the left, the SWALIS pictures and the corresponding  $\sigma_0$  values and on the right, the SWOT PICX data.

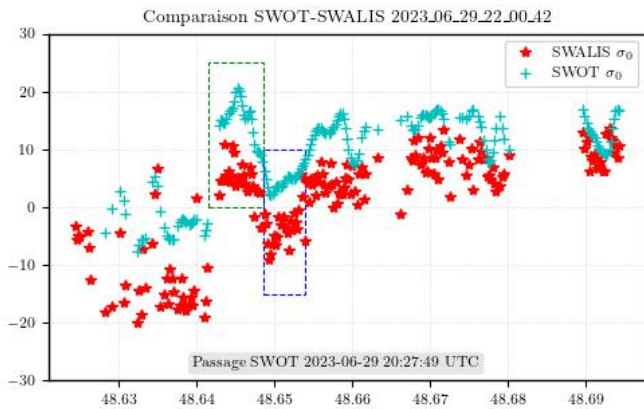


Fig. 7: Comparaison  $\sigma_0$  SWALIS et  $\sigma_0$  SWOT

operation along SWALIS longitude and latitude traces to compare  $\sigma_0$  values from SWOT and SWALIS at the same incidence angles. One of these comparisons is exposed in Fig. 7. We can see that the backscattering amplitude in the blue zone (exposed sand) is lower than in the green zone (wet sand). While the changes in  $\sigma_0$  values are comparable between SWALIS and SWOT, the absolute amplitudes are different. Nevertheless, the SWOT data are currently awaiting correction of the calibration coefficient for the  $\sigma_0$  value. Similarly, measurements are planned to refine the calibration coefficients of the SWALIS sensor [22].

### III. THE SKIM CONCEPT AND THE KARADOC SENSOR

The SKIM (Sea surface KInematics Multiscale monitoring) concept is planned to be a satellite mission. This is a new wide-swath multi-beam Ka-band radar [23] and designed to explore surface currents and wave spectra. The SKIM main instrument

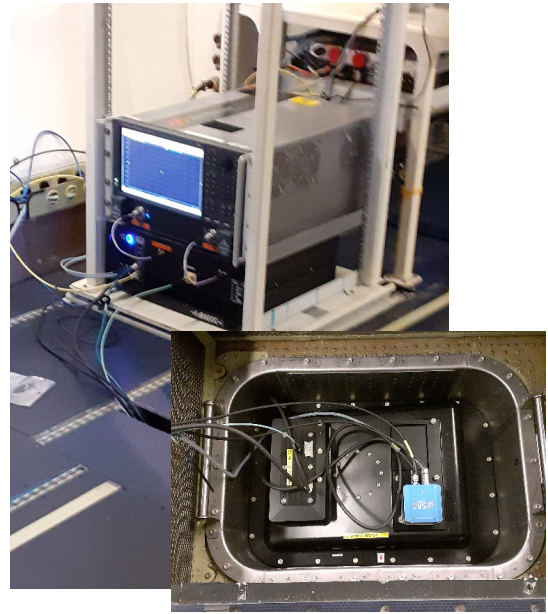


Fig. 8: KaRADOC installation inside ATR42.

is a Ka-band multibeam Doppler radar altimeter/diffusiometer. The pulse-pair Doppler technique [24] [25] gives a surface drift velocity representative of the upper metre of the ocean, after subtracting a significant wave-induced contribution. This concept provides unique and innovative measurements that would give a better understanding of transport in the upper layer of the ocean, permanently distributing heat, carbon, plankton and plastics.

#### A. The KaRADOC sensor

Like the SWALIS sensor, the KaRADOC (Ka RADar for Ocean measurements) sensor operates in the Ka band and carries out backscattering measurements. The KaRADOC sensor is an extension of the SWALIS sensor except that the RF front-end is based on a power amplifier which is isolated from the receiver part during the receiving slot time. Moreover, the KaRADOC antenna is a leaky-wave antenna as well but the expected incidence angles are close to  $12^\circ$  to enhance the doppler effect. Finally, KaRADOC is placed inside the ATR42 of SAFIRE agency (*Service des Avions Français Instrumentés pour la Recherche en Environnement*) (see Fig. 8)

#### B. Overview of the results

Measurement campaigns have been carried out to validate the SKIM concept [26]: Drift4SSKIM (November 2018 over the Iroise sea) and SUMOS (February 2021 over the Gascogne Gulf) campaigns. These campaign objectives were focused on demonstrating the sensitivity of airborne radar Doppler measurements to the contributions of ocean currents and waves. We focused on KaRADOC data which are easy to interpret considering the Doppler effect, due to the narrow radar beam of the antenna. Star-pattern flights were obtained in order to measure the ocean Doppler velocity  $U_{GD}$  under several illumination azimuth angles. From the data collected

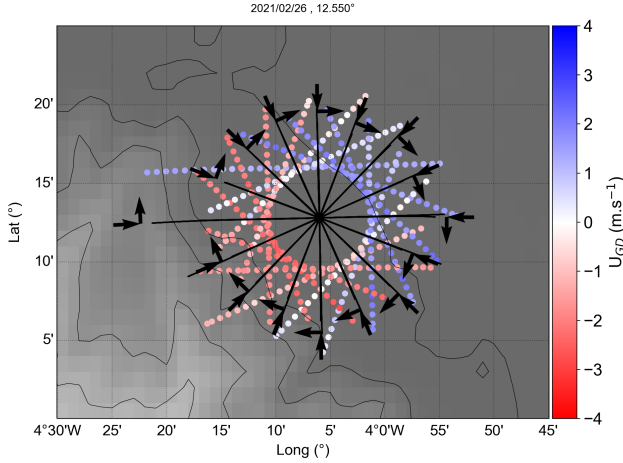


Fig. 9: Ocean Doppler velocity wrt. the azimuth direction of the flight track.

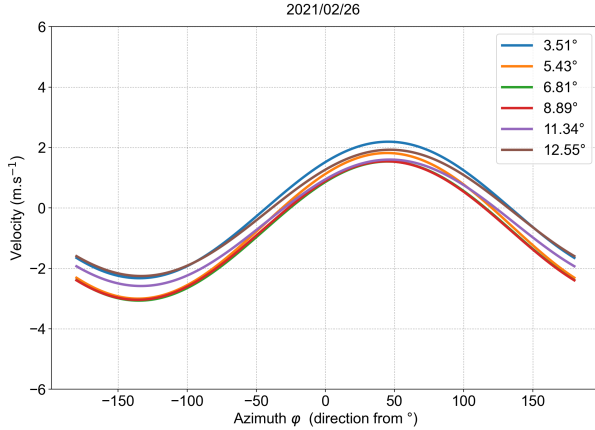


Fig. 10: Radial Doppler velocity estimation wrt. the azimuth direction of the flight track and for different incidence angles.

during the SUMOS field campaign, Fig. 9 describes the ocean Doppler velocity  $U_{GD}$  estimated for each of the star-pattern flights. These estimations are derived from the radar signal divided by the sine of the incidence angle as a function of observation location ( $12.55^\circ$  incidence angle) after platform motion compensation. We can note the dependence on observation azimuth. Moreover, Fig. 10 shows the compilation of the fits obtained for the different incidence angles. Note the very good agreement between fits of the radial Doppler velocity obtained at different incidence angles: the data can be explained as the projection along the line-of-sight of a well-defined vector, independent of the observation incidence angle.

Based on the SKIM concept, these results demonstrate the efficiency of KaRADOC to provide very accurate radar data to derive the radial velocity from the sea surface.

TABLE III: HOMARDS main parameters.

Parameter	Value
Pulse bandwidth	320 MHz
-3 dB elevation beamwidth	$1.5^\circ$
-3 dB azimuth beamwidth	$1.5^\circ$
Incidence angle	$60^\circ$
Pulse length	$1 \mu s$
Range resolution	0.468 m
Ground range resolution	0.541 m
Nominal platform altitude	500 m
Nominal antenna footprint surface	$14.17 \text{ m}^2$

#### IV. THE ODYSEA CONCEPT AND HOMARDS SENSOR

The 'wind work' term describes the energy transfer between atmosphere and ocean and has an influence on the ocean dynamics. The sudden increase of the wind work can not be observed by existing satellite due to the broad range of the wind work phenomena. To this end, the ODYSEA (Ocean Dynamics and Surface Exchange with the Atmosphere) [27] concept is dedicated to the estimation of the amplitude of wind work in the global ocean. Several achievements are required for a sensor that would be able to provide radar measurements under ODYSEA conditions. In this case, a radar measurement as SKIM described, would provide the Doppler data. The derived velocity combines accurately currents and wave under constraints of range resolution, local incidence angle and incident wave polarisation [28].

The HOMARDS (Hydro-Ocean Measurements: an Agile RaDar System) sensor is designed for supporting future satellite missions dedicated to the water monitoring. In our case, HOMARDS is designed for ocean Doppler measurements on high local incidence angle conditions (ODYSEA concept). The main configuration of HOMARDS is summarized in Table III that matches with the ODYSEA [28]) operating set-up. The most important modifications compared to the SWALIS/KaRADOC devices deal with the range resolution by modulating the transmitted pulse, the high incidence angle and the polarisation diversity. The main requirements for HOMARDS are: i. Compact system, ii. Custom waveform transmission, iii. Fast carrier frequency tuning, iv. Transmission/reception with dual-linear polarization. The HOMARDS is under development but many choices have been made (Fig. 11): i. the Control block including server, Human-Machine Interface, GPS, Inertial Motion Unit (IMU), Storage unit, Logical I/O unit, ii. the baseband block which generates the desired waveform under I(channel 1)/Q(channel 2) format with two Analog to Digital Converter (ADC) to record the V (vertical polarization) and H (horizontal polarization) channels, iii. the RF block for up/down conversion and transmitting/receiving RF signal (a calibration loop is implemented). The important part of HOMARDS is the antenna with dual-linear polarization providing a high directivity and a high steering direction (up to  $60^\circ$ ). Slotted antennas have been identified as the enabling antenna technology realized with an additive manufacturing (antenna dimensions:  $400 \times 400 \times 60$  [mm]).

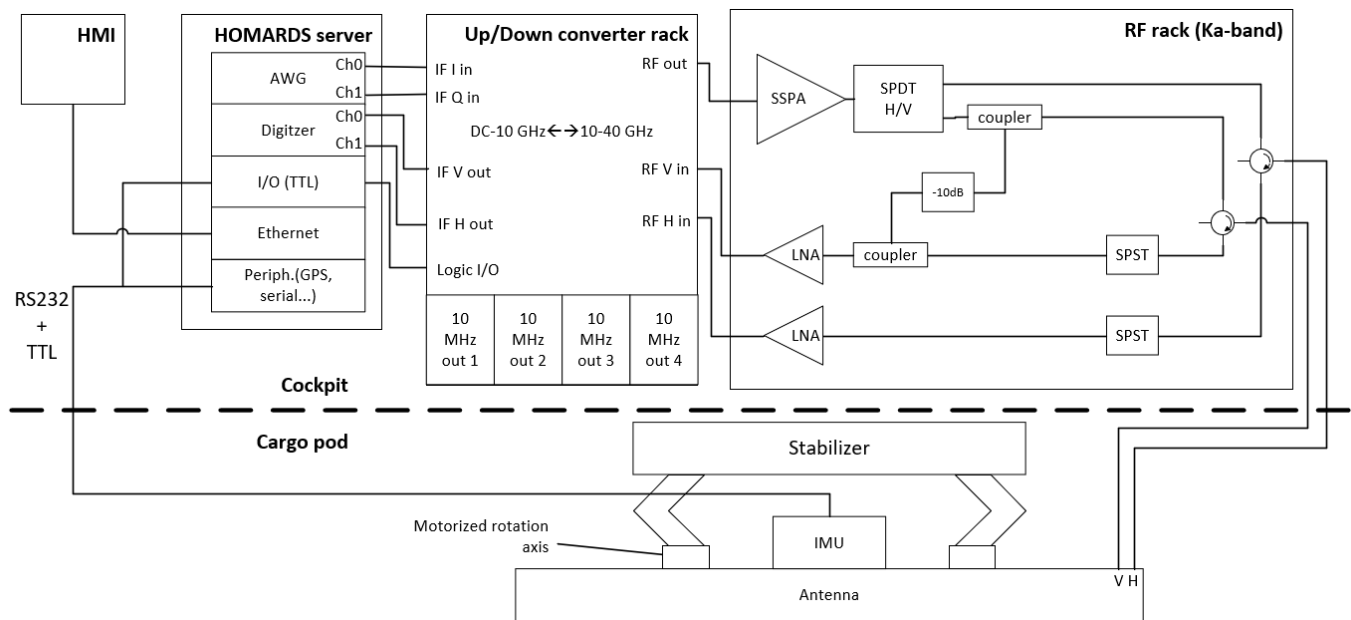


Fig. 11: HOMARDS blocks schematic.

## V. CONCLUSION

As a conclusion, this paper presents the range of radar sensors developed by the IETR in support of the SWOT, SKIM and ODYSEA space missions. One of these sensors is operational and the results are in the process of being validated (SWALIS), another is still in the process of exploiting the results (KaRADOC) and finally, the last is in the process of being implemented and the next measurements are planned for the beginning of 2025 (HOMARDS). Through the results we obtain, we demonstrate that these described sensors are suitable for supporting some specific satellite missions.

## REFERENCES

- [1] B. Chapron, "Direct measurements of ocean surface velocity from space: Interpretation and validation," *Journal of Geophysical Research*, 2005.
- [2] A. Wineteer et al., "On the Surface Current Measurement Capabilities of Spaceborne Doppler Scatterometry," *Geo. Research Letters*, 2020.
- [3] S. Brown et al., "Preliminary validation and performance of the Jason microwave radiometer," in *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2003.
- [4] W.J. Bannoura et al., "NOAA Ocean Surface Topography Mission Jason-2 Project Overview," in *Proceedings of OCEANS*, 2005.
- [5] F. Maiwald et al., "Reliable and Stable Radiometers for Jason-3," in *Proceedings of IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 2016.
- [6] J. Richard et al., "Altika Instrument for Space Altimetry with Improved Performances and Ocean Sampling : Development Status and First Test Results," in *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2008.
- [7] Y.L. Desnos et al., "The ENVISAT advanced synthetic aperture radar system," in *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2000.
- [8] W. Xiaodong et al., "Retrieval of sea ice thickness of Ross Sea with ICESat/GLAS measurements," in *Proc. of IEEE International Conference on Remote Sensing, Env. and Trans. Engineering (RSETE)*, 2011.
- [9] J. Beckers et al., "Characteristics of CryoSat-2 signals over multi-year and seasonal sea ice," in *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2013.
- [10] GIEC, "AR6 Synthesis Report, Climate Change 2023,"
- [11] "SWOT Mission Overview," <https://swot.jpl.nasa.gov/mission/overview/>
- [12] S. Biancamaria et al., "The SWOT Mission and Its Capabilities for Land Hydrology," *Surveys in Geophysics*, 2016.
- [13] R. Fjortoft et al., "KaRIn - the Ka-band radar interferometer on SWOT," in *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2010.
- [14] R. Fjortoft et al., "KaRIn on SWOT: Characteristics of Near-Nadir Ka-Band Interferometric SAR Imagery," in *IEEE Transactions on Geoscience and Remote Sensing (TGRS)*, 2014.
- [15] F.T. Ulaby, "Microwave radar and radiometric remote sensing," 2014.
- [16] E. Altenau et al., "AirSWOT measurements of river water surface elevation and slope," *Geophysical Research Letters*, 2017.
- [17] E. Altenau et al., "Temporal variations in river water surface elevation and slope captured by AirSWOT," *Remote Sensing of Env.*, 2019.
- [18] Y. Yoon et al., "Estimating Flood Discharges in Reservoir-Regulated River Basins by Integrating Synthetic SWOT Satellite Observations and Hydrologic Modeling," *Journal of Hydrologic Engineering*, 2016.
- [19] S. Sherman et al., "Monopulse principles and techniques," 2011.
- [20] PIMA, "Plateforme PIMA (Plateforme Ingénierie Multimodale
- [21] J.-C. Koumi et al., "The SWALIS project: First results for airborne radar measurements in Ka band," in *Proceedings of the 17th European Radar Conference (EuRAD)*, 2020
- [22] J.-C. K. Koumi, "SWALIS/KaRADOC Sensors: Calibration Procedure for Radar Systems for Hydrologic Remote Sensing Applications," in *Proceedings of the 19th European Radar Conference (EuRAD)*, 2022
- [23] F. Arduin et al., "Measuring currents, ice drift, and waves from space: the Sea surface Kinematics Multiscale monitoring (SKIM) concept," *Ocean Science* 2018.
- [24] S.S. Abeysekera, "Performance of pulse-pair method of Doppler estimation," in *IEEE Transactions on Aerospace and Electronic Systems (TAES)*, 1998.
- [25] S.S. Abeysekera, "Efficient frequency estimation using the pulse-pair method at various lags," in *IEEE Trans. on Communications (TC)*, 2006.
- [26] L. Marié et al., "Measuring ocean total surface current velocity with the KuROS and KaRADOC airborne near-nadir Doppler radars," in *Ocean Science*, 2020.
- [27] T. Lee, "A satellite mission concept to unravel small-scale ocean dynamics and air-sea interactions: ODYSEA (Ocean Dynamics and Surface Exchange with the Atmosphere)," in *Proceedings of EGU*, 2023.
- [28] ODYSEA, "Ocean DYNAMics and Surface Exchange with the Atmosphere," <https://odysea.ucsd.edu/publications/>