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SWALIS/KaRADOC Sensors: A Specific Calibration Procedure for Radar Systems for Hydrologic Remote Sensing Applications

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Abstract— This paper describes the radar sensors which are developed by the “Institut d’Électronique et des Technologies du PI numéRiques” (IETR) and the “Centre National des Études Spatiales” (CNES) to investigate the backscattering phenomena in near nadir conditions at the Ka band. These sensors have been previously addressed within the framework of the first campaigns we have conducted. In this communication, we propose rigorous calibration procedures we apply to our measurement campaigns.

Keywords— radar system, radar signal processing, back scattering phenomena, system calibration

I. INTRODUCTION

Under low incidence conditions, space remote sensing can be used to extract altimetry and behavioral data from areas with strong backscatter signal for these low incidence conditions. In addition, Ka-band measurements allow signal processing operations to achieve high resolution measurements. Within this context, a next space mission is the SWOT (Surface Water Ocean Topography) mission that will embed a cross-track interferometric synthetic aperture radar in Ka-band and with a range of incidence angle from 0.6° to 4.1° . In order to extract the most information from such a backscattering signal and under these conditions, it is fundamental to have the best knowledge of the backscattering properties of the illuminated surfaces. Thus, if measurements in basins allow to have basic information of cases under control [1], it is essential to have airborne data relating to surfaces as water-land transition.

Considering these expectations, the SWALIS sensor (Still Water Low Incidence Scattering) is developed for airborne radar measurements in Ka-band [2]. This radar must provide measurement data for the SWOT mission and nadir altimetry. The study areas illuminated by the SWALIS airborne radar are continental water surfaces.

In the same way, according to particular configurations, it is also possible to measure oceanic areas subjected to winds, currents or swell. Thus, in the framework of the European Space Agency (ESA) phase A/B1 SKIM (Sea surface KInematics Multiscale monitoring), CNES provides

the KaRADOC sensor (Ka RADAR for Ocean measurements) experiment built around the SWALIS experiment of SWOT. This experiment is developed to consolidate the method of measuring currents used for SKIM. We operated the KaRADOC sensor at 12° -incidence angle for the DRIFT4SKIM campaign organized in Nov. 2018 [3].

To make the measurements physically interpretable (and more specifically for the SWALIS sensor), it is necessary to perform sensor calibration operations. This calibration step is fundamental for relating received power to RCS value [4]. The model we propose is based on the use of many canonical targets which are considered to simulate a large area.

This article is organised as follows. The first part is dedicated to a brief description of the SWALIS and KaRADOC sensors and also focuses on the power budget for introducing the calibration step. In the second part, we explain the calibration procedure we develop to relate the received power values we measured to σ values. We close the paper by concluding about the high potential of this radar system measurement.

II. SWALIS/KARADOC SYSTEMS DESCRIPTION

As a reminder, the SWALIS sensor is embedded on the IETR PIMA airborne platform [5], which allows for large operating agility. Thus, SWALIS has shown its ability to perform radar measurements at near nadir in the Ka band [6]. Similarly, its ability to perform measurements in scanning mode (multi-incidence) very quickly during an acquisition flight allows measurements at several angles of incidence on the same area [2]. Finally, the very small aperture of the antenna provides backscattered power values of very localized areas on the ground in order to recover the size of a pixel in the framework of SWOT. All these operating characteristics have been largely exhibited in [6]. It is worth to note that many improvements are made either for SWALIS or KaRADOC radar. The greatest enhancement is about the sensitivity level so that to reach a sufficient signal-to-noise ratio. We particularly propose to isolate the transmission part from the reception one

during the reception time duration for improving the sensitivity level. A new RF design for the SWALIS system and achieved by CNES is based on the use of a Solid State Power Amplifier (SSPA) and on the use of a Single Pole Single Throw (SPST) switch to protect the low noise amplifier (LNA) before the PNA-X received port. For the KaRADOC radar, the choice is for isolating the transmission part with a power SPST and the LNA is protected by using a limiter device [3].

The first step for evaluating the SWALIS (or KaRADOC) capabilities is to estimate the power budget of the RF part so that we are able to estimate the received power value for the chosen canonical target. In addition, the calibration step is supposed to compensate for any frequency-dependent behavioural variations of the RF block.

III. SWALIS/KARADOC CHARACTERISATION

A. Power balance

We briefly describe the RF module shown in Fig. 1 which is designed by CNES RF team.

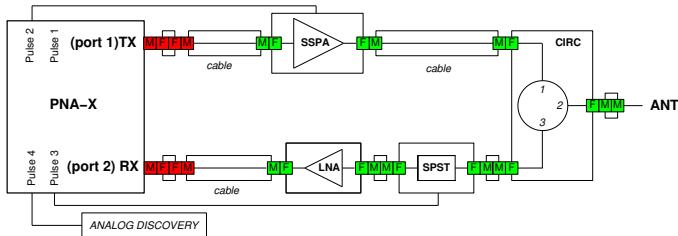


Fig. 1. Basic description of the SWALIS RF part

It consists of:

- a pulsed power amplifier SSPA (Quinstar - QPP - 30383740) controlled by the “Pulse 2” signal
- a circulator allowing the transmission from port1 to port2 during the transmission of the wave and the reception of the return of this wave from port 2 to port 3 during the radar listening time. The insertion loss between the different ports is about 1.5 dB
- a switch, used to isolate the reception part of the RF module during the transmission. It is controlled by the “Pulse 3”
- A low noise amplifier LNA (SPACEK - LABS - SL375 - 30 - 10) to amplify the signals during reception.
- The “Pulse 4” is used to monitor the inertial motion unit (IMU) for each beginning of measurement.

After laboratory measurements in [30-38] GHz, we obtain:

- a gain greater than 41 dB in transmission
- a gain greater than 28 dB in reception
- an isolation higher than 60 dB.

Thus, the high isolation characteristic makes possible to detect low received power and the lowest power value is imposed through the IF bandwidth of the PNA-X. In this paper, we consider a 15-MHz IF bandwidth that implies the lowest value β_{IF} of received power of -57 dBm.

The behaviour of all the radar system parts must be compensated during calibration phase, including the antenna.

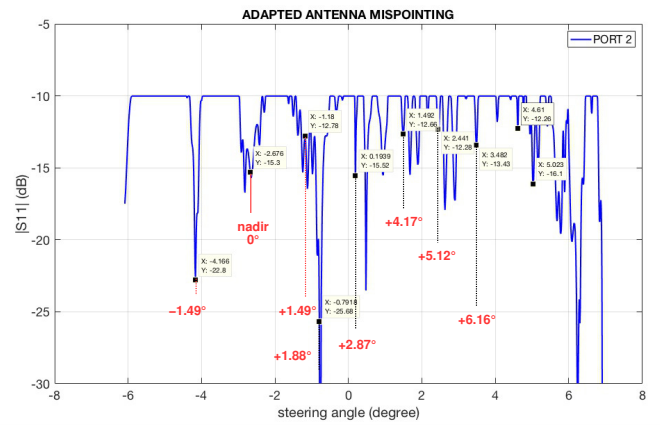


Fig. 2. $|S_{11}|$ vs. steering angle of the antenna. The expected incidence angles during the flights are given in red.

Table 1. Correspondence between the transmitted frequencies, the steering angles and the real incidence angles

f_i (GHz)	32.75	33.63	36.64	35.08	35.29	35.45	35.86
θ_{steer} ($^\circ$)	-4.23	-2.74	-0.77	0.15	0.46	0.97	1.77
θ_{inci} ($^\circ$)	-1.63	-0.14	1.83	2.75	3.06	3.57	4.37

B. Matched antenna

As described in [6], the SWALIS/KaRADOC antenna varies either in gain or in matching impedance. The measurement of this previous parameter (i.e. S_{11}) provides information on the choice of operating frequencies for which the antenna has the best match (lower than -10 dB) (see Fig. 2). For the calibration experiments, the chosen configuration corresponds to a nadir incidence (0°) surrounded by 2 equivalent incidence angles (approximately $\pm 1.49^\circ$). The other incidence angles are chosen for incidence angles covering a range up to 10° . We map the antenna’s off-axis angles to the frequency (as shown in Fig. 2) that helps us to choose the angle of -2.7° as the nadir reference angle. This new reference is obtained mechanically by inserting a mechanical shim on the antenna support to compensate for this angle. As described in Table 1, the correspondence of the offset angles with the illumination frequencies allows us to obtain the transmitted frequencies for the radar measurements as a function of the scanning incidence angle.

As the SWALIS (or KaRADOC) system measures power, it is necessary to link a power value to an equivalent RCS value. The measured power balance coupled with the ground calibration measurement conditions (measurement distance D_0 around 300 meters) gives us the expected power range at reception. In our case, this estimated power range is roughly between -55 dBm and -10 dBm (if the PNA-X transmitted power equals around -8 dBm), which requires RCS values between 5 m^2 and 4500 m^2 . The calibration procedure is necessary to relate the measured power to RCS target value.



(a) Corner reflector (at 8 m height) (b) Radar antenna (at 15 m height)
Fig. 3. Calibration measurement set-up

C. Calibration procedure

The SWALIS system makes radar measurements and records the power received on the PNAX. It is therefore necessary to perform a calibration operation in order to be able to link this measured power to a radar equivalent surface (RCS) value using a calibrated target. Taking into account the conditions of measurement (duration of the pulse), it is necessary to make the measurement outside. The chosen site is the MERISE station (MontErfil station for RadIo and remote SEnsing) located at Monterfil (Ille et Vilaine) on which is a tower of about fifteen meters height. Moreover, we place a trihedral corner reflector at a distance D_0 far from the radar. This distance D_0 between the platform of the tower on which the radar is placed (at 15 meters height) and the calibrated target (at 8 meters height) is measured with a laser rangefinder and is equal to 351 meters. Moreover, for the frequency $f = 30$ GHz, the width $2r$ of the Fresnel ellipsoid [7] is equal to: $2r \approx \sqrt{\lambda D_0} = 1.88$ m. Regarding the topology, it is largely sufficient for considering the Fresnel ellipsoid free.

The measurement setup is described in Fig. 3. The antenna is steerable in azimuth and elevation angle by servo stepper motors. It is also equipped with a digital laser pointer sight to point the target.

The calibration procedure we operate is considered in a particular context. Indeed, the calibration must allow to link the power measured by the SWALIS system to a power backscattered by a surface (σ_0 in m^2/m^2). The first step of calibration is to link a calibrated target characterised by a known RCS value (σ) and a received power amount. Afterwards the correspondence between the value of σ_0 and the received power is then made by considering the area illuminated by the antenna. During the calibration, the measurement must consider the minimum power β_{IF} measurable by the PNA-X and imposed by the chosen IF bandwidth filter. This power corresponds to a value of σ equals σ_{IF} . The power $\beta_{i(ENV)}$ (at frequency f_i) corresponding only to the environment is related to an equivalent area of σ_{ENV} .

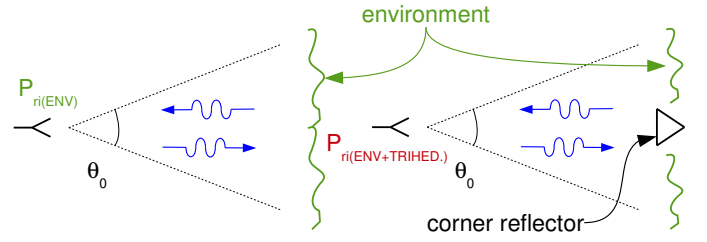


Fig. 4. Configuration for SWALIS calibration (with and without corner reflector) considering the measurement environment

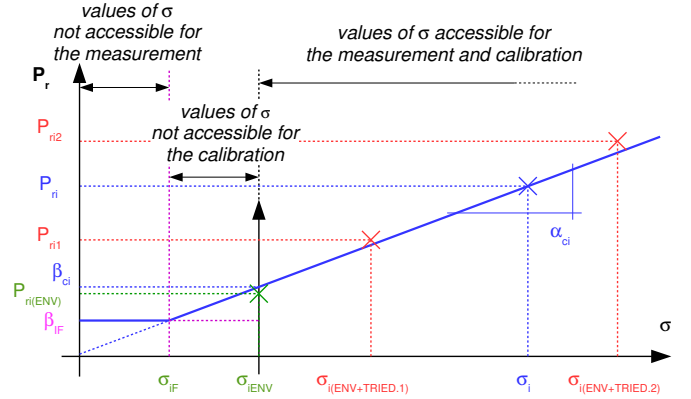


Fig. 5. Calibration principle

The power P_{ri} of the signal reflected from the trihedral into its environment is measured for each value of frequency f_i . Fig. 4 describes these two aspects of the measurement (environment and environment with the corner reflector).

The calibration is a procedure based on the radar equation and is established for a frequency f_i and a distance D_0 . In operational conditions, we have the relation describing the received power P_{ri} :

$$P_{ri} = \alpha_{ci} \cdot \sigma + \beta_{ci} \quad (1)$$

The variable β_{ci} is the sum of the environmental feedback $\beta_{i(ENV)}$ measured at frequency f_i and the minimum threshold β_{IF} measurable by the PNA-X and imposed by the chosen IF filter. Fig. 5 describes the calibration principle. In this figure, we see that it is not possible to access RCS values that are below σ_{IF} (the sensitivity threshold RCS of the SWALIS sensor). Moreover, for values between σ_{IF} and σ_{ENV} , it is not possible to perform calibration measurements. The calibration curve accessible during the calibration operations is described in blue (thick solid line). For each corner reflector, we measure the received power P_{ri} . A linear regression operation allows us to obtain the coefficients α_{ci} and β_{ci} .

The distance D_0 is the reference distance which is the one measured for the calibration: in our case, $D_0 = 351$ m. When we measure during a flight at the distance D_m , we obtain the power P_{rm} . The associated σ_m RCS is therefore calculated from the relation:

$$\sigma_m = \frac{P_{rm} - \beta_{s(IF)}}{\alpha_{ci} \cdot D_0^4} \cdot D_m^4 \quad (2)$$

This equation (2) is used to obtain σ_m from the values of α_{ci} obtained during the calibration step, the range distance D_m of the radar system during the measurement and $\beta_{(IF)}$ which corresponds to the minimum threshold value measurable by the measurement device PNA-X. Note that to find σ_m in flight conditions, the quantity $\beta_{(IF)}$ is used instead of β_{ci} because in this case of in-flight measurement, the whole environment is measured i.e. included in σ_m .

D. Calibration data processing

A burst is characterized by a succession of k pulses, at a chosen frequency f_i and also toward a measured scene. These successions of pulses are then integrated in order to recover a unique power corresponding to a frequency f_i and a scene. In the case of calibration, for a frequency f_i we have:

- the measured scenes are hypothetically identical (the same calibrated target),
- a single frequency per recording (record),
- an average of the powers received per burst (burst),
- a measured power per recording,
- 200 bursts of 200 impulses (i.e. 40000 pulses).

To a given recording, we associate the measurement of a canonical target for which we obtain a power measured at a given frequency. This measurement is carried out at a frequency value and therefore for an incidence angle. It is repeated for each frequency and for canonical target.

E. Determination of calibration coefficients

In our calibration experiment, the calibrated target is a corner reflector characterized by an inner edge a . The calibration procedure consists in determining for a given value of RCS of the corner reflector, the calibration coefficients (α_{ci} and β_{ci}) from (1). For each frequency $f_i = c/\lambda_i$, the maximum corner reflector RCS σ_t is given by $\sigma_t = 4\pi a^4/3\lambda_i^2$. The choice of the size of the corner reflector is made according to the power budget established with our SWALIS or KaRADOC system. In our case, we have 10 corner reflectors that make possible to reach RCS range values from 5.4 m² to 4464 m². We then measure the received power when the radio axis of the radar antenna points to the corner reflector under measurement. For each frequency and each corner reflector, we carry out a measurement time corresponding to about 200 by 200 bursts. As an example, Fig. 6 shows the received power versus each corner reflector RCS for 15 MHz IF bandwidth for frequencies given in Table 1. For each frequency f_i , we apply a linear regression operation to get the relationship between received power and σ value/ Corresponding to the measurement conditions previously described, the provided α_{ci} and β_{ci} coefficients are exhibited in Table 2. The same procedures are also applied with the measurements

IV. CONCLUSION

In this paper, we present a complete calibration procedure for airborne radar systems (KaRADOC and SWALIS) to be used for space missions such as SWOT. We link a measured power value to a corner reflector σ value. The next step is

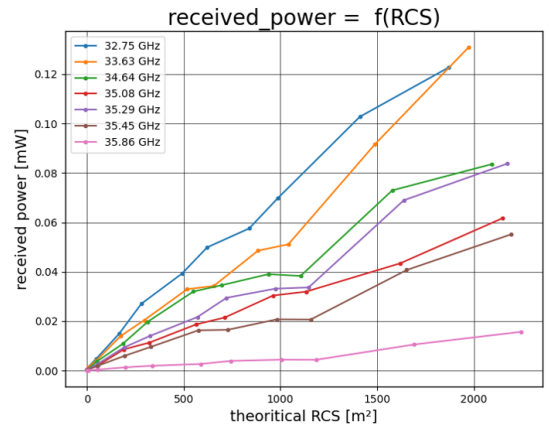


Fig. 6. Received power vs. the corner reflectors RCS (IF = 15 MHz)

Table 2. Calibration coefficients at the distance $D_0 = 351$ m for IF bandwidth of 15 MHz, $\beta_{s(IF)} = 19.9526 \times 10^{-7}$ mW.

freq. (GHz)	α_{ci} (mW.m ⁻²)	β_{ci} (mW)	β_{ENV} (mW)	Score (%)
32.75	6.969136e-05	0.003258	0.000408	99.27
33.63	5.571097e-05	0.001495	0.000457	97.46
34.64	4.112490e-05	0.003204	0.000469	94.83
35.08	2.662784e-05	0.002247	0.000264	98.79
35.29	3.740210e-05	0.000331	0.000326	95.26
35.45	2.178385e-05	0.001005	0.000236	95.29
35.86	5.320580e-06	-0.000142	0.000051	90.96

to relate the measured power value to the σ_0 value which is an essential characteristic in hydrological applications for example. Another work will focus on the measurement flights with SWALIS for Cal-Val operations to SWOT mission.

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