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Airborne GNSS-R polarimetric multi-incidence data analysis for surface soil moisture estimation over an agricultural site

Mehrez Zribi, Vincent Dehaye, Karin Dassas, Pascal Fanise, Michel Le Page, Pierre Laluet, Aaron Boone

Abstract— The objective of this study is to propose a mapping of surface soil moisture (SSM) using airborne measurements based on the GLObal Navigation Satellite System Reflectometry Instrument (GLORI), a polarimetric instrument. GNSS-R measurements were acquired at the agricultural Urgell site in Spain in July 2021. In situ measurements describing the soil moisture and roughness and the vegetation cover leaf area index were then obtained simultaneously with flight measurements. An analysis of observable copolarization (right-right) reflectivity Γ_{RR} and the cross-polarization (right-left) reflectivity Γ_{RL} behaviors as a function of incidence angle is proposed, as is normalization of the reflectivity function of the incidence angle. The sensitivity of reflectivities is then proposed as a function of surface soil moisture. An empirical model with two variables, soil moisture and the normalized difference vegetation index (NDVI), based on the principle of the tau-omega model is then considered for the inversion of GNSS-R reflectivity Γ_{RL} and estimation of soil moisture. This model is calibrated and validated by a threefold cross-validation approach. A mapping of SSM at 100 m resolution is created with data from the studied site and three acquired flights.

Index Terms— surface soil moisture, GNSS-R, inversion, GLORI, airborne

I. INTRODUCTION

Surface soil moisture is a key parameter in understanding the function of the soil–vegetation–atmosphere interface. It is also an essential parameter in the management of water resources related to irrigation [1]–[4].

Over the past thirty years, microwave remote sensing has shown great potential for estimating and monitoring this parameter [5]–[7].

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M. Zribi, V. Dehaye, K. Dassas, P. Fanise, M. Le Page, and P. Laluet are with the Centre d'Etudes Spatiales de la Biosphère (CNES/CNRS/INRAE/IRD/UPS), 31401 Toulouse cedex 9, France (e-mail: mehrez.zribi@ird.fr, Vincent.dehaye@univ-tlse3.fr, karine.dassas@univ-tlse3.fr, pascal.fanise@ird.fr, michel.le_page@ird.fr, pierre.laluet@univ-tlse3.fr), and A. Boone is with the CNRM-Université de Toulouse, Météo-France/CNRS, Toulouse, Occitanie, France (e-mail: aaron.a.boone@gmail.com).

Various operational products have been offered in recent years, ranging from the scale of an agricultural plot to the scale of several kilometers.

In this same context, GNSS-R measurements have also shown great potential for characterizing earth surface states [8]–[11] and, particularly, surface soil moisture [12]–[21]. These measurements started first with in situ or airborne campaigns, illustrating good precision in the estimation of soil moisture and vegetation cover biomass at the same level as other active or passive microwave techniques [14]–[15], [22]–[24].

These studies mainly analyze data acquired in right–left (RL) polarization. During the Land Monitoring with Navigation Signals (LEIMON) campaign, with acquisitions in Italy, the sensitivity of Γ_{RL} signals to SSM was between 20 and 30 dB/(m³/m³). This result was confirmed during the GNSS Reflectometry Analysis for biomaSS monitoring (GRASS) campaign carried out in Italy, with a sensitivity confirmed to be on the order of 20 dB/(m³/m³) and a determination coefficient between the ground moisture measurements and the GNSS-R reflectivity polarization ratio equal to 0.86. Reference [14] also demonstrated the potential of GNSS-R data to estimate SSM during airborne measurements with the light airborne reflectometer for GNSS-R observations (LARGO) instrument at a Spanish site. An empirical model relating soil moisture, surface temperature, a vegetation index and reflectivity is proposed. This study was restricted to soil moisture levels below 0.15 m³/m³. The high sensitivity of reflectivity to SSM was also retrieved during campaigns carried out in southwestern France with the GLORI airborne instrument in 2015 [24]. The potential of GNSS-R was later confirmed by satellite receivers with early work with the Technology Demonstration Satellite (Techdemosat) [25]–[29], followed by numerous results from the Cyclone Global Navigation Satellite System (CYGNSS) constellation, which was launched in 2016 [30]. Reference [29] analyzed the relationships between TechDemosat data and SSM. The sensitivity of GNSS-R signals to soil moisture remains on the same order of magnitude as airborne measurements (~38 dB/(m³/m³)). The sensitivity of TechDemosat data to SSM is also observed in [26] with a 7 dB dynamic due to changes in SSM. With CYGNSS, the potential of GNSS-R satellite data was quickly highlighted for monitoring flooded areas, monitoring biomass, even at very high levels, and finally monitoring soil moisture [31]–[41].

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Reference [31] identified a strong correlation between temporal variations in *SSM* and *CYGNSS* signals. A bilinear regression model is thus proposed for the estimation of soil moisture. Trilinear regression including vegetation, roughness and *SSM* is proposed for the inversion of reflectivity at a quasiglobal scale [32]. Regression calibration is developed independently for each pixel. These cited studies are generally developed with the observable Γ_{RL} . Despite the high potential of these GNSS-R data, the interpretation of the measurement behavior is still a subject of research. Indeed, the angular effects, as well as the particularities of the two polarizations (right–left), RL and (right–right) RR, for different land surface contexts, are not yet fully understood, particularly for refining the inversions and better decorrelating the effects of soil moisture, vegetation, and possibly other factors. In this context, theoretical simulators are very useful for understanding all these multiconfiguration behaviors [42]–[43]. Numerous studies have also proposed confirming the potential of GNSS-R polarimetry, showing very encouraging results for the estimation of surface characteristics such as vegetation, soil moisture, and flooded areas [44]–[48].

The objective of this study is to propose new airborne measurements using real data to refine this understanding. This process involves analyzing polarimetric multi-incidence GNSS-R airborne data over an agricultural site with the goal of mapping *SSM*.

Section II presents the airborne and in situ data acquired at the study site in Spain and the observables measured by the GLORI instrument. Section III describes inversion modeling to estimate soil moisture. Section IV presents the discussion. Finally, Section V concludes this article.

II. DATABASE AND METHODS

A. GNSS-R Airborne data

The GLORI instrument described in [23] is derived from the conventional GNSS-R (cGNSS-R) family. It is a low-cost, 4-channel, highly versatile GNSS-R receiver built using mainly commercial off-the-shelf components. Measurements of direct and reflected GNSS signals are realized by two hemispherical GPS L1-L2 dual-polarization active antennas, named the zenith antenna, which is mounted on the upper part of the aircraft fuselage, and the nadir antenna, which is mounted on the lower fuselage of the aircraft (Fig. 1). The polarimetric instrument allows simultaneous acquisition of left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) and a complete analysis of the polarization effect on land surface characterization. Measurements are realized with the French research aircraft ATR-42. The received signals are then filtered to reduce out-of-band noise, which can saturate the front end. The radio frequency (RF) signals are fed into a 4-channel L-band front end, which ensures direct IQ downconversion, 2-bit signal decimation, and serialization to a USB 2.0 interface. Raw data signals are acquired with a standard PC. All computations, signal tracking, and retrieval of observables are performed after the flights. The main technical specifications of the instrument are presented in [23].

The GLORI campaigns are realized over the Urgell site in Catalonia, Spain (Fig. 2). It is an agricultural area composed of

two parts, the first of which uses intensive irrigation. The irrigation water comes from the Pyrenees through the Urgell canal. Three different irrigation methods can be identified: i) flooding, which is still dominant in this region and is used for multiple crops, including fruit trees (apple and pear orchards) and cereals; ii) sprinkler irrigation (pivot, ramp, and integral), which is mainly used for alfalfa and cereal crops (maize, barley, and wheat); and iii) localized irrigation (mainly drip irrigation), which is mainly used for vegetables. A second part of the area is rainfed. The climate is in the Koppen–Geiger zone, a cold, semiarid climate bordering the Mediterranean Sea. It has mild winters, very dry and warm summers and two rainy seasons in autumn and spring. The GLORI campaign was spread over a period of one week (TABLE I) and linked with simultaneous, collocated ground-truth measurements.

In parallel with the GLORI GNSS-R airborne acquisitions, various in situ measurements were made on these sites (roughness, soil moisture, and leaf area index) to validate the GLORI data and optimize the inversion algorithms.

B. In situ and satellite data

Intensive, collocated ground-truth measurements were recorded at the same time that the flights were made over the twenty-four reference fields (8 maize, 4 bare soils, 6 alfalfa, and 4 apple trees). The in situ measurements made at the reference fields (Fig. 2) were designed to determine the soil moisture, roughness, and vegetation characteristics. These measurements are realized in the context of the LIAISE international project [49].

1) Soil moisture

On each of the dates listed in Table I, approximately 20 handheld thetaprobe measurements were made in each reference field (irrigated or nonirrigated) at a depth of 5 cm. The samples were taken from various locations in each reference field within a four-hour time frame of the concurrent airborne acquisitions. The thetaprobe measurements were calibrated with gravimetric measurements recorded during previous campaigns [50]–[51]. In the context of a homogeneous agricultural field, these in situ measurements should allow a mean accuracy better than $0.02 \text{ m}^3/\text{m}^3$.

2) Soil roughness

The soil roughness was characterized with a 1-m pin profiler exhibiting a pin spacing of 2 cm using six roughness profiles (3 perpendicular and 3 parallel profiles with respect to the interrow tillage direction). These profiles were digitized to calculate statistical parameters of the soil roughness, namely, the root mean square of the height (H_{rms}) and correlation length (L_c) [52]. H_{rms} varied between 0.4 and 1.84 cm, and the L_c value varied between 4 and 12.18 cm.

3) Leaf area index (LAI)

Vegetation cover measurements were performed to characterize the leaf area index (LAI). The LAI is defined as the total one-sided area of leaf tissue per unit ground surface area. According to this definition, the LAI is a dimensionless quantity. For each test field, ten hemispherical digital images were used. These were processed by analyzing the canopy gap fraction to retrieve this vegetation parameter. The

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measurements were applied 2 times during the intense experimental period. During all measurement campaigns, the computed LAI value ranged between 0 and 3.42. The highest values of LAI were observed mainly in irrigated test fields. Table II shows the ranges of all acquired in situ measurements over reference fields.

4) Sentinel-2 data

After the launch of Sentinel-2 (S-2) A and B on 23/06/2015 and 07/03/2017, respectively, optical data became free and open access with a spatial resolution varying between 10 m×10 m and 60 m×60 m and a revisit time of up to 5 days in 13 spectral bands at visible and mid-infrared wavelengths. In the present study, we used S-2 surface reflectance products downloaded from the Theia site (<https://www.theia-land.fr/>), already orthorectified and atmospherically corrected with a mask of clouds and shadows owing to the MAJA algorithm.

On each acquisition date and using red visible and near-infrared bands with center wavelengths of approximately 665 and 833 nm, respectively, we calculated the $NDVI$ and averaged this index for each reference field as expressed in the following (1):

$$NDVI = \frac{R_{NIR} - R_{Red}}{R_{NIR} + R_{Red}} \quad (1)$$

where R_{NIR} and R_{Red} are the surface reflectance in the two bands, near infrared and red visible, respectively.

C. GNSS-R data processing

1) Observables

Different observables were obtained from the GLORI measurements. The direct and reflected GNSS signals, $u_{d,r}$ and $u_{r,r}$, respectively, were cross-correlated with pseudorandom noise (PRN) code replicas $a(t)$, resulting in direct and reflected complex delay Doppler maps $Y(\tau, f)$, which are considered to be the fundamental observables in the GNSS-R measurements. The cross-correlated signals can be written in the following form:

$$Y(\tau, f) = \frac{1}{T_i} \int_{T_i} u_{d,r} a(t - \tau) e^{i(f_c + f)t} dt \quad (2)$$

where T_i (= 5 ms in the present case) is the coherent integration time. For the direct signal, τ corresponds to the signal propagation delay from the transmitter to the receiver, f_c is the GPS L1 frequency, and f corresponds to the Doppler shift resulting from the velocity of the aircraft relative to that of the GNSS satellite.

The geophysical analysis cannot be realized directly from complex waveforms. Incoherent integration is then added to reduce the speckle noise from reflected signals. This step is illustrated by (3):

$$\langle |Y(\tau, f)|^2 \rangle = \frac{P_t^2 P_r G_t \lambda^2}{(4\pi)^3} \iint_A \frac{Gr(\vec{\rho})}{R_0^2(\vec{\rho}) R^2(\vec{\rho})} \sigma_{pq}^0 \chi^2(\vec{\rho}, \delta\tau, \delta f) d\vec{\rho} \quad (3)$$

where P_t and G_t are the satellite transmit power and antenna gain, respectively, λ is the signal wavelength, $Gr(\vec{\rho})$ is the receiving antenna gain, $R_0(\vec{\rho})$ and $R(\vec{\rho})$ are the distances from the specular point to the transmitter and the receiver,

respectively, σ_{pq}^0 is the polarization-dependent bistatic radar coefficient, and χ is known in the radar terminology as the Woodward ambiguity function (WAF) and accounts for the radar pulse characteristics.

$Y(\tau, f)$ is referred to as a delay Doppler map (DDM), corresponding to the average value of the GNSS power scattered by the surface as a function of delay and frequency.

Finally, we consider the apparent reflectivity based on the calculation of the relative power of the reflected signal compared to the direct signal.

For a polarization pq , the apparent reflectivity Γ_{pq} can be expressed as the ratio of the reflected $Y_{r,q}(\tau, f)$ to direct waveforms $Y_{d,p}(\tau, f)$.

In the case of GNSS-R, the right–right and right–left ratios Γ_{RR} and Γ_{RL} represent the co and cross-polar reflection coefficients. Assuming that f is aligned with the Doppler frequency shift of the direct signal, the apparent surface reflectivity Γ'_{pq} can be obtained as:

$$\Gamma'_{pq} = \left| \frac{Y_{r,q}(\Delta\tau, f)}{Y_{d,p}(0, f)} \right|^2 \quad (4)$$

where $\Delta\tau$ represents the difference in delay between the direct and reflected paths.

In GLORI data processing, the apparent reflectivity Γ'_{pq} is calculated in a way that allows for the separation of coherent and incoherent components using the interferometric complex field (ICF), corrected using the differences in noise and antenna gain between the direct and reflected channels [23].

2) Processing steps

Four steps are considered to process the raw data (Fig. 3) and to generate different data products:

1. The first step is to calculate coherently integrated direct and reflected waveforms. The considered integration time is 5 ms. The direct GPS signal is acquired and tracked from the measurements of the zenith-pointing antenna, while the reflected signals measured by the nadir-pointing antenna are processed according to a master–slave scheme using the tracking parameters from the direct signal. From these measurements, in addition to metadata and information relating to decoded GPS messages, level 0 (L0) files are generated.
2. From the L0 level to the L0b level, the waveforms are precisely time-tagged from the GPS message, the waveform maxima are detected, and the waveform noise floor is computed.
3. From L0b to L1a, the corrected ICFs are computed for each polarization and coherent integration time step. Then, the ICFs are incoherently averaged (200 ms), and their standard deviation is estimated to be able to compute the apparent reflectivity. All useful information, such as attitudes and the relative position of the emitter, interpolated in the integration step in addition to calibration factors, such as the antenna radiation pattern, are stored in level 1a files (L1a).
4. L1a files are then aggregated into Level 1b (L1b) files for each flight. They include all of the calibration information in addition to other ancillary parameters. From the auxiliary

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data, the location and shape of the specular ellipses corresponding to the first Fresnel zone are also calculated.

Fig. 4 illustrates the processed signals for the different transects. As presented in the processing steps, illustrated areas correspond to specular points with calculated first Fresnel zones [9]. For each reference field, the measurements acquired by the GLORI instrument are averaged to obtain an estimate of the reflectivities. From the observed values, we note qualitative trends, particularly for the highest signatures on a small lake located west of the study site. This is obviously specular background with maximum reflectivity.

III. RESULTS

A. Normalization of the reflectivity function of incidence

Fig. 5 illustrates the variations in all the acquired GLORI reflectivity data over the Urgell site as a function of the incidence angle. As demonstrated in [23], the cross-polarization isolation is better than 15 dB at angles up to 45° from boresight (45° incidence angle) for both LHCP and RHCP ports. A cross-polarization performance of less than 15 dB is considered inadequate for polarimetric measurements [21]. In this study, analysis is proposed up to a 60° incidence angle because we do not observe any particular anomaly in data higher than 45° (cross-polarization isolation is still higher than 10 dB for considered angles). We observe weak variations for the case of Γ_{RL} and a stronger variation for the case of gamma Γ_{RR} . To better understand the effect of incidence angle on reflectivity, we propose this analysis according to the *NDVI*, with a window of 0.2 to allow the evaluation of trends. Concerning Γ_{RL} , we propose linear approximation of the observed variation function of the incidence angle.

$$\Gamma_{RL} = a(NDVI) + b(NDVI). \theta \quad (5)$$

where parameters a and b are functions of *NDVI*.

We consider the hypothesis of an identical *SSM* range for all *NDVI*s and incidence angles to avoid considering the effect linked to moisture levels.

Fig. 6 illustrates the linear approximations for each *NDVI* interval. We clearly observe a decrease in the b parameter and slope of the linear relationship with the *NDVI*. Indeed, on bare soils, an almost zero slope is observed, which decreases slightly with the *NDVI*. The slope parameter decreases from -0.014 to -0.048 dB/°. Initially, for bare soils, there is a slight effect linked to the Fresnel coefficient due to the generally low roughness, as illustrated in ground measurements. This effect increases with the development of the vegetation cover and the introduction of an attenuation effect that changes with the incidence angle. Regarding the behavior of the Γ_{RR} measurements as a function of the incidence angle, we propose an empirical relationship of the following form:

$$\Gamma_{RR} = \alpha(NDVI). (\cos\theta)^{\beta(NDVI)} \quad (6)$$

where the α and β parameters are functions of *NDVI*.

Fig. 7 illustrates the approximations of these relationships for different *NDVI* classes. A decrease in the angular effect is

observed with increasing *NDVI*. The difference in reflectivity levels between 0 and 50° for almost bare soil (*NDVI*=0.2) is approximately 11 dB and reaches a value close to 8 dB for an *NDVI* equal to 0.8. The largest differences between signatures of the different *NDVI* classes are observed at low incidence angles. These differences decrease to almost zero for angles close to 50°, as illustrated in Fig. 8. These strong angular trends for Γ_{RR} show the importance of considering the incidence angle in the analysis of these data. This also highlights a much greater potential to monitor the dynamics of the vegetation cover for low incidence angles.

Based on these results, we propose normalization of the data to a single incidence angle of 20°.

$$\Gamma_{RL}(20^\circ) = \Gamma_{RL}(\theta) + b(NDVI)(\theta - 20^\circ) \quad (7)$$

$$\Gamma_{RR}(20^\circ) = \Gamma_{RR}(\theta) \left(\frac{\cos(20^\circ)}{\cos(\theta)} \right)^{\beta(NDVI)} \quad (8)$$

This normalization aims to clearly limit the angular effects, particularly for Γ_{RR} , and thus to characterize the effects due to land surface properties with higher precision. Hence, for each *NDVI* class, we apply the retrieved linear relationship for Γ_{RL} and the cosine relationship for Γ_{RR} . From normalized data, we finally propose a 100 m mesh to build maps of observables. For each mesh, we average all the measurements acquired with different PRNs. Fig. 9 illustrates the map of Γ_{RL} .

B. Sensitivity of reflectivity to surface soil moisture

Figs. 10 and 11 illustrate the Γ_{RL} and Γ_{RR} reflectivities over reference fields as a function of *SSM* ground measurements. An analysis of two vegetation classes, *NDVI*<0.4 and *NDVI*>0.4, is proposed to limit the effects related to vegetation cover. We first observe a sensitivity that decreases with the development of the vegetation cover. In the case of Γ_{RL} , this sensitivity decreases from 29.61 dB/(m³/m³) for the class with *NDVI*<0.4 to 9.86 dB/(m³/m³) for the densest class. These sensitivities are consistent with the results found in other airborne campaigns, such as GLORI'2015, LEIMON and GRASS. For the case of RR polarization, in the case of the two classes of vegetation, we observe extremely low sensitivities of reflectivity to soil moisture, with correlations that are very degraded (less than 3.12 dB/(m³/m³)). These results could be explained by the weakness of the RR signal over agricultural surfaces and by a higher vegetation effect with RR than with RL polarization. In conclusion, these results clearly illustrate a much greater potential for soil moisture monitoring using Γ_{RL} reflectivity data. In the following, the estimation of the moisture is limited to this last polarization.

C. Reflectivity semiempirical modeling

The reflectivity can be modeled by:

$$\Gamma_{pq}(\theta) = \Gamma_{pq}^{soil}(\theta). e^{-\frac{2\tau_p^{canopy}}{\sin\theta}} (1 - \omega_p^{canopy})^2 \quad (9)$$

where Γ_{pq} is the reflection coefficient for circularly polarized (pq) radiation, $2\tau_{pq}^{canopy}$ is the two-way vegetation opacity,

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$(1 - \omega_{pq}^{canopy})^2$ accounts for the two-way path of the GNSS signal, θ is the elevation angle and ω_{pq}^{canopy} is the single scattering albedo.

Various works have used the *NDVI* optical index as a proxy to describe the dynamics of vegetation cover and thus to estimate the optical thickness. In this study, the *LAI* in situ measurements only served qualitatively to situate the development of the covers. In the modeling of reflectivity, the *NDVI* seems the most suitable for the highest applicability of methodologies.

$$\tau_{pq} = c \cdot NDVI \quad (10)$$

where c is a constant applied to all vegetation covers.

The single-scattering albedo is neglected in the context of L-band measurements. Analyzed data are normalized as a function of incidence angle.

Equation (9) can then be simplified to:

$$\Gamma_{pq} = \Gamma_{pq}^{soil} \cdot e^{-2c \cdot NDVI} \quad (11)$$

The relationship between reflectivity (in dB) and soil moisture Mv is identified as linear in many works; hence, we consider the following approximation:

$$\Gamma_{RL}^{soil} = \gamma Mv + \delta \quad (12)$$

Therefore, by applying a logarithmic function to (11):

$$\Gamma_{RL} = \gamma Mv + \mu NDVI + \delta \quad (13)$$

where γ is the sensitivity of the reflectivity to soil moisture, μ is the sensitivity of the reflectivity to vegetation growth through the *NDVI*, and δ is a constant related to the roughness mean effect. α , β and δ are empirical parameters retrieved from the experimental data. The parameters γ , μ and δ are estimated by minimizing the sum of the squared differences between the simulated and measured Γ_{RL} data. In the context of mostly very smooth surfaces due to gravitation irrigation, it is not possible to establish an empirical relationship between the parameter δ and variations in roughness parameters.

D. Application of the proposed semiempirical model for soil moisture mapping

The inversion model is applied to the Γ_{RL} GLORI data. To calibrate and validate the proposed model, we use the three-fold cross-validation approach. Our database consists of 31 samples with airborne and ground measurements for reference fields. It is divided into three parts. In these sequential folds, the first was used for validation, and the two remaining folds were used for model parameterization. As in the case of the “repeated holdout” method, the overall accuracy is given by the average of the values obtained from all runs. The model is calibrated and validated 3 times. The calibration and validation steps are then applied to the whole database.

The calibrated parameters with statistics of comparison between the simulated model and the dataset used for the calibration are shown in Table III.

Thus, if we have the Γ_{RL} reflectivity and the *NDVI* level, the soil moisture is estimated using the following equation:

$$Mv = 0.067 \Gamma_{RL} + 0.35 NDVI + 0.85 \quad (14)$$

Fig. 12 illustrates the comparison between in situ measurements and estimates from Γ_{RL} data inversion. The retrieved *RMSE* is equal to $0.07 \text{ m}^3/\text{m}^3$. This reasonable precision illustrates the Γ_{RL} potential to retrieve soil moisture at a high-resolution scale.

A mapping of SSM is proposed from the Γ_{RL} map at 100 m resolution. The inversion model is thus used for each mesh considering the Γ_{RL} information and the *NDVI* calculated from the S-2 data. Three maps are proposed for the three proposed flights acquired on three dates, 22/07/2021, 27/07/2021 and 28/07/2021. The map corresponding to the second date is illustrated in Fig. 13. In all three cases, we first observe a clear contrast between the irrigated and rainfed zones, with higher moisture levels for the first one. This is obviously consistent with our field measurements and water resource use. In the nonirrigated part, we observe a certain homogeneity of the estimates due to the limitation of only rainfall effects and fewer variations in vegetation density.

IV. DISCUSSION

SSM maps are created from the three flights taken on three different dates. The second flight took place just after a rainfall event of 14 mm. This is observed in the temporal variation in SSM levels. Fig. 14 illustrates SSM distributions on the study site for the three dates. We observe a first dry date, 22/07/2021, with a very low moisture level percent. This was illustrated by approximately 32% moisture values below $0.1 \text{ m}^3/\text{m}^3$. 27/07/2021 illustrates a general increase in moisture following 14 mm of precipitation. Thus, the distribution of moisture values significantly changed, with a maximum moisture distribution of approximately $0.3 \text{ m}^3/\text{m}^3$. On the last date, in the context of high heat and temperatures close to 35° during the day, the drop in SSM was quite general, with a return of a higher percentage of low moisture levels below $0.1 \text{ m}^3/\text{m}^3$ (more than 25%). 28/07 is thus intermediate to the two extremes, a very dry first date and a relatively wet second date.

The proposed inversion approach makes it possible to map soil moisture. However, the sizes of the agricultural fields, which were generally less than 1 ha in the studied site, gravity irrigation of the plots with flooding and, finally, different types of land use affect the precision of the proposed inversion approach. Indeed, mapping at 100 m spatial resolution can include local heterogeneities that are difficult to consider. Despite this relatively complex context, the retrieved precision of approximately $0.07 \text{ m}^3/\text{m}^3$ remains reasonable to respond to thematic studies related to water resource management. The Γ_{RR} reflectivity is not considered for moisture mapping because of its low sensitivity to SSM. However, the limitation of the database and the drop in the data quality for high incidence angles with decreasing cross-polarization isolation excluded a finer analysis of different configurations and confronted the observations with theoretical modeling.

CONCLUSIONS

The objective of this study is to deepen the understanding of the behavior of GNSS-R measurements to propose a high-spatial resolution mapping of surface soil moisture. An airborne

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campaign using the GLORI instrument is proposed for the Agricultural Urgell site, which consists of two separated irrigated and nonirrigated areas. An analysis of the behavior of GNSS-R reflectivities for the two polarizations RL and RR and as a function of incidence angle is also proposed. The angular effect is demonstrated to be very weak for the case of Γ_{RL} . Linear modeling of this effect seems sufficient, with an effect linked to the development of vegetation cover. Thus, the slope of this relationship is between -0.014 dB° and -0.048 dB° for data ranging from an *NDVI* close to 0.2 to an *NDVI* close to 0.8. Regarding reflectivity in RR polarization, the angular effect is much greater, particularly for low incidence angles. A cosine function with two calibrated empirical parameters seems suitable to describe this relationship. For the polarization RL, the angular effect increases with the development of vegetation cover. Normalization of the reflectivity is thus proposed as a function of the incidence angle. As demonstrated by other studies [14]-[15], [29], reflectivity illustrates high sensitivity to *SSM*. For RL polarization, the sensitivity decreases from $29.61 \text{ dB}/(\text{m}^3/\text{m}^3)$ for the class with *NDVI*<0.4 to $9.86 \text{ dB}/(\text{m}^3/\text{m}^3)$ for the densest class (*NDVI*>0.4).

A simplified tau-omega model is then proposed to describe the relationship between the measured signals and the two variables *SSM* and the *NDVI* of the vegetation. After calibration of the three parameters describing the model with a 3-fold cross validation approach, the validation allowed good precision for Γ_{RL} , with an *RMSE* of $0.07 \text{ m}^3/\text{m}^3$. Moisture maps were thus created at a spatial resolution of 100 m for each airborne acquisition, illustrating strong differences between irrigated and nonirrigated areas, as well as temporal variations related to precipitation events. In the context of the future launch of the European Space Agency's HYDROGNSS mission, these measurements should be enriched by other acquisitions covering new configurations, particularly with the L5/E5 configurations, to analyze their contribution to the monitoring of land surface states. Consolidation of cross-polarization isolation for high incidence angles is certainly useful for global analysis of RR polarization potential.

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Mehrez Zribi is a Research Director with Centre National de Recherche Scientifique (CNRS). He received the B.E. degree in signal processing from the Ecole Nationale Supérieure d'Ingénieurs en Constructions Aéronautiques, Toulouse, France, and the Ph.D. degree from the Université Paul Sabatier, Toulouse. In 1995, he joined the Centre d'Etude des Environnements Terrestre et Planétaires Laboratory/Institut Pierre Simon Laplace, Vélizy, France. Since October 2008, he has been with the Centre d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse. His research interests include microwave remote sensing applied to hydrology, microwave modeling for land surface parameters estimations and finally airborne microwave instrumentation. He has published more than 150 articles in refereed journals. He is currently director of CESBIO.

Vincent Dehaye is a research engineer at CESBIO. He received a MSc degree in Aerodynamics, Energetics and Heat transfert at ISAE-ENSMA in 2019. Since 2021 he is working on data processing for the GLORI campaign in Catalonia (2021).

Karin Dassas was born in Paris, France in 1974. She has been graduated from the "Ecole Nationale Supérieure de Géologie" in 1997, which corresponds to 5-year university degree (Master's degree) in Earth Sciences combined with Engineering Sciences. She also received a master's degree in computer science from Sorbonne University (former called Université Pierre et Marie Curie).

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After having worked for a few years as a geophysicist for para-petroleum companies, she joined the IAS (Institut Astrophysique Spatiale, Orsay, France) in 2004 as CNRS (Centre National de la Recherche Scientifique) research engineer where she mainly did satellite data processing (L1 L2 L3 level), control-command and also on-board software for astrophysical space missions such as Planck, Herschel, Bepicolombo, JUICE. For her last mission at IAS, she was in charge of the MAJIS OBSW (Moon And Jupiter Imaging Spectrometer On Board Software) till 2021, when she joined the observation systems team at CESBIO (Centre d'Etude Spatiale de la Biosphere, Toulouse, France). She is currently working on GNSS-R data processing for airborne and satellite measurements.

Pascal Fanise was born in 1979 in Paris, France. He received the M.Sc. degree in electronic engineering from the university of Paris XII. Since 2010, he has joined the Centre D'etudes Spatiales de la Biosphère (CESBIO). He is currently a instrumentation engineer and a technical manager for several ground-based and airborne instruments. He is focused on microwave radiometer systems and is currently responsible of the design for the hardware architecture and experiment for GLORI reflectometer.

Michel Le Page is an Engineer with the Institut de Recherche pour le Développement (IRD). He holds a technical degree in computing, a Msc in Urban Geography and a PhD in Remote Sensing. He has more than 30 years of experience in Remote Sensing and GIS. He joined the Centre d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse in 2006. His research interest is the use of optical, thermal and microwave earth observation time series for water management, including irrigation management, drought monitoring, integrated watershed modeling, and the development of end-user applications. He has published more than 50 articles in refereed journals.

Pierre Laluet is a PhD student at the Centre National de Recherche Scientifique (CNRS). He received a Master's degree in Water Sciences at the University of Rennes 1, France, in 2019. Since 2020 he is doing a PhD at the Centre d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse. He is working on the estimation of agricultural flows by combining remote sensing and hydrological models.

Aaron Boone is a Research Director with Centre National de Recherche Scientifique (CNRS). He received a B.S. degree in Meteorology from Northern Illinois University, Dekalb, IL, USA, and a M.S. degree in Meteorology from the Florida State University, Tallahassee, FL, USA. He worked in the Mesoscale Atmospheric Processes Branch of NASA-GSFC, USA, from 1992-1997, and then went on to earn a Ph.D. degree specializing in Hydrometeorology from the Université Paul Sabatier, Toulouse, France. He has been with the Centre National de Recherches Météorologiques, Météo-France, since 1997, except for a stay at the Centre d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse from 2002-2003. His main research interests include land-atmosphere-hydrology interactions and land surface modeling. He has published more than 110 articles in refereed journals.

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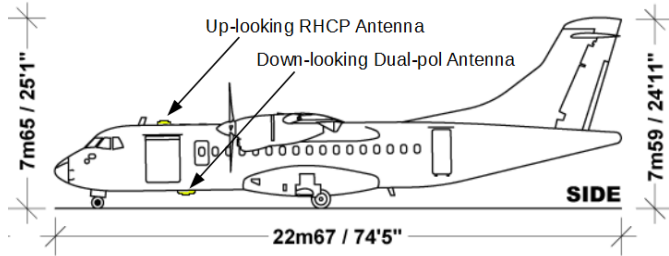


Fig. 1. GLORI antenna locations on ATR-42. Dimensions are in millimeters.

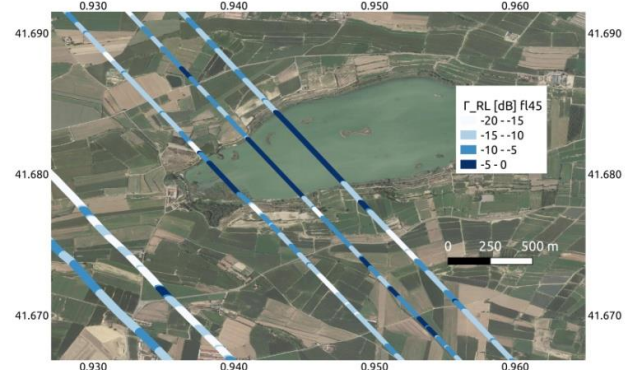


Fig. 4. Γ_{RL} measurements over the Urgell site. The aircraft altitude is ~ 1100 m, and the measurement temporal resolution (incoherent averaging time) is 200 ms.

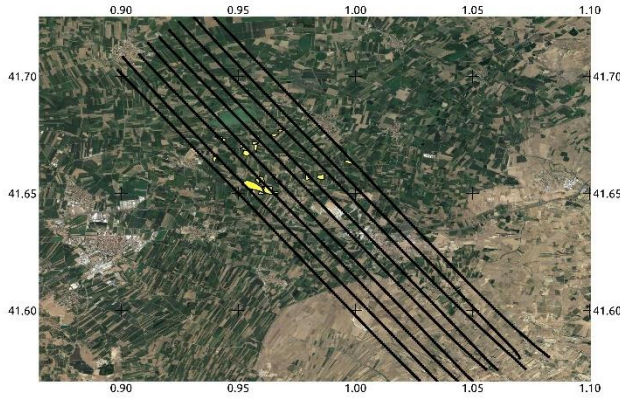


Fig. 2. Location of the GLORI flights in the Urgell Basin, with reference fields in yellow.

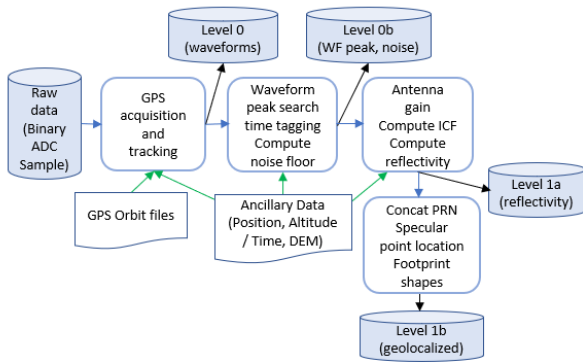
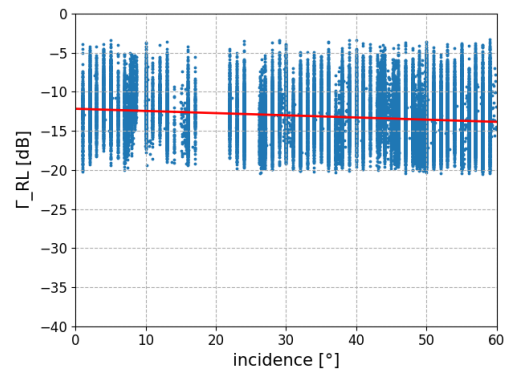
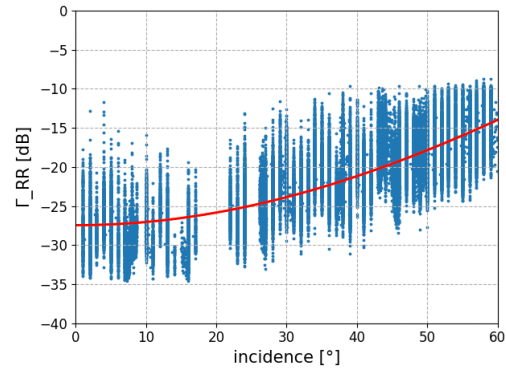


Fig. 3. Processing Block Diagram



(a)



(b)

Fig. 5. Illustration of GLORI reflectivity data over the Urgell site as a function of incidence angle: a) Γ_{RL} and b) Γ_{RR}

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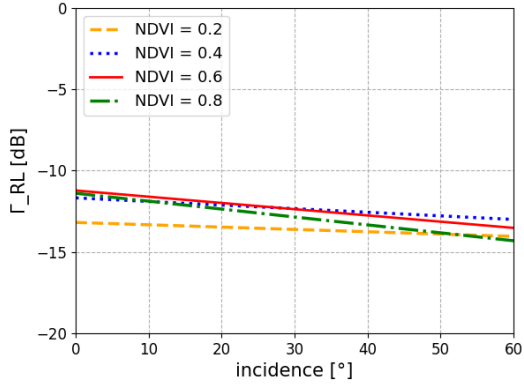


Fig. 6. Illustration of empirical fitting relationships between Γ_{RL} and incidence angles for different $NDVI$ classes

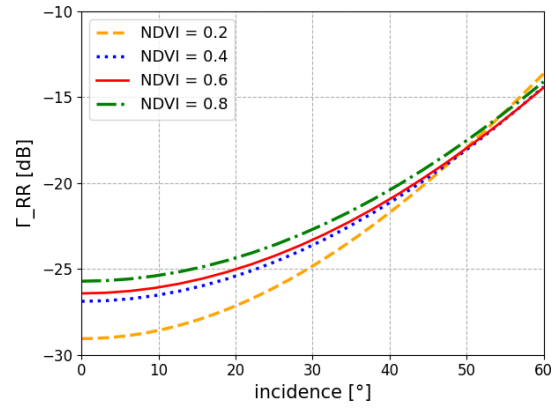
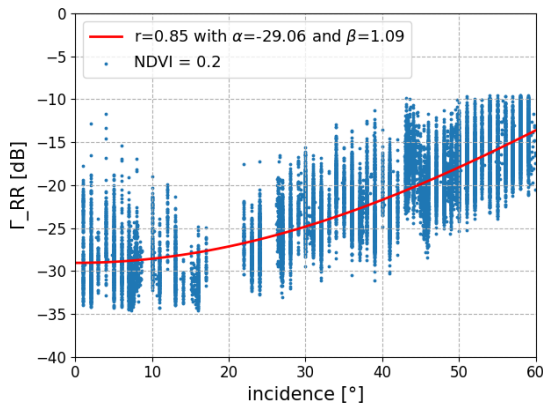
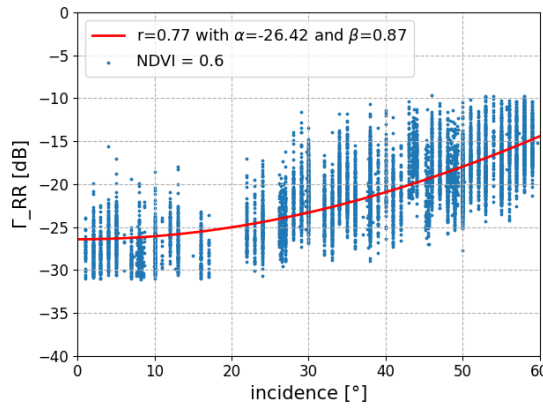


Fig. 8. Illustration of empirical fitting relationships between Γ_{RR} and incidence angles for different $NDVI$ classes



(a)



(b)

Fig. 7. Illustration of the Γ_{RR} variation function of the incidence angle for two $NDVI$ classes: (a) $NDVI = 0.2$ and (b) $NDVI = 0.6$

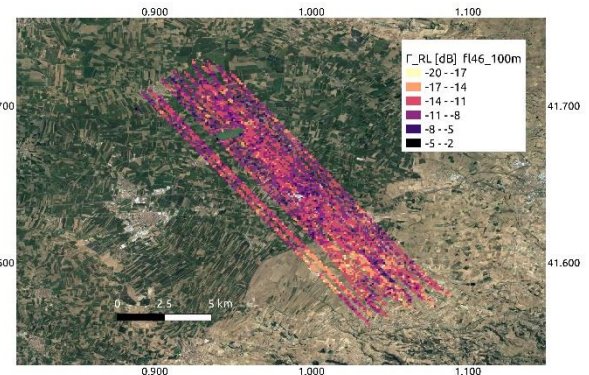
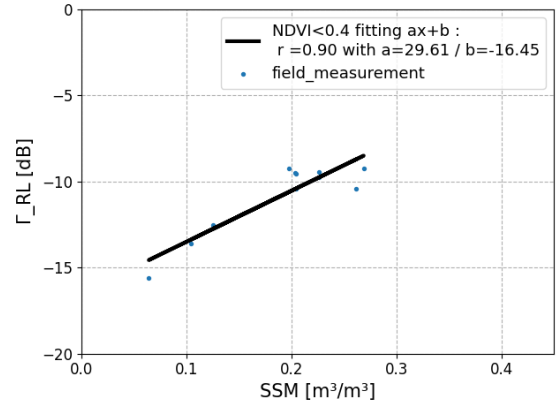
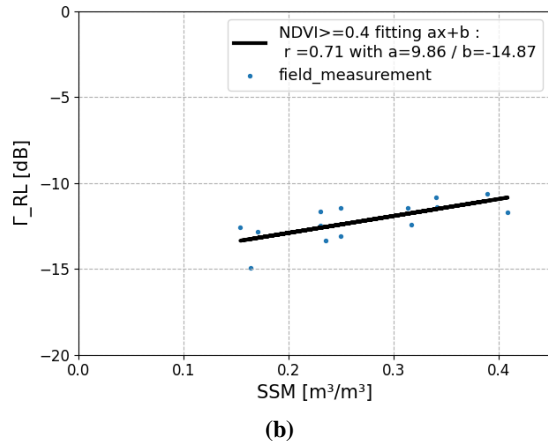


Fig. 9. Map of Γ_{RL} over the studied site



(a)

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(b)

Fig. 10. Analysis of Γ_{RL} sensitivity to soil moisture for two vegetation classes, a) $NDVI < 0.4$ and b) $NDVI > 0.4$

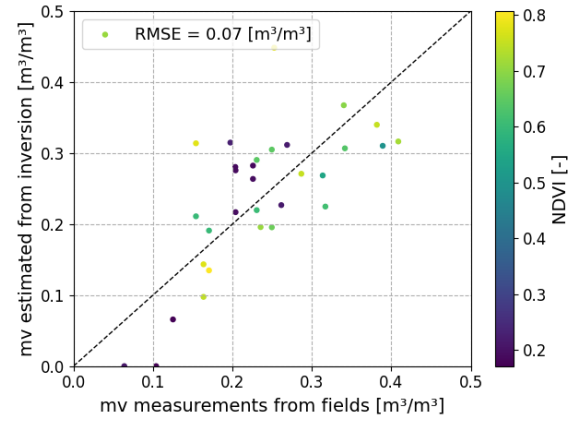
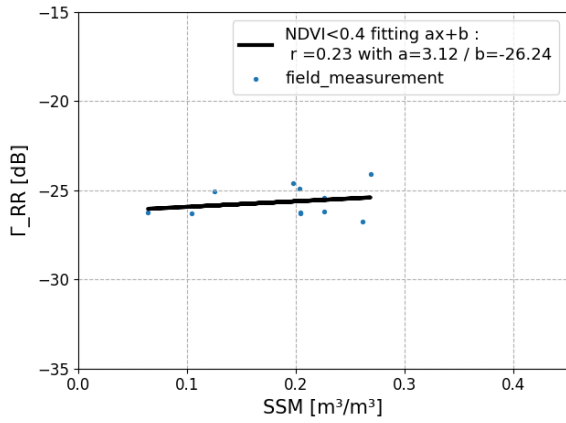
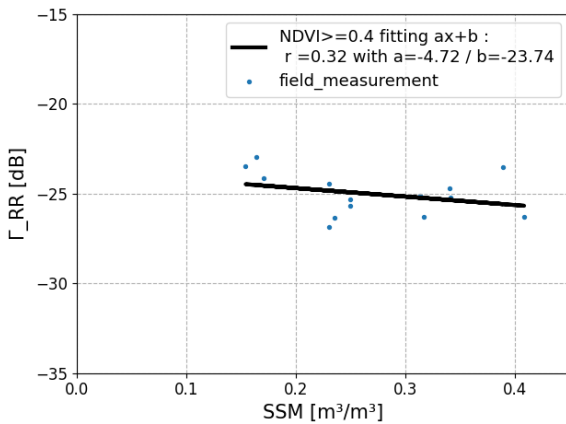


Fig. 12. Intercomparison between ground measurements and estimated soil moisture from Γ_{RL} data inversion



(a)



(b)

Fig. 11. Analysis of Γ_{RR} sensitivity to soil moisture for two vegetation classes, a) $NDVI < 0.4$ and b) $NDVI > 0.4$

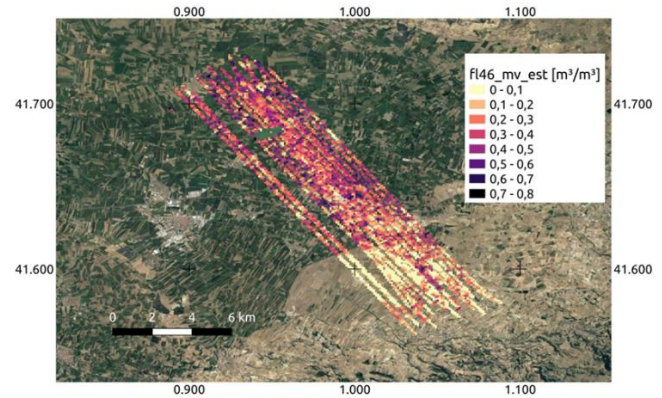


Fig. 13. Map of SSM retrieved from the Γ_{RL} inversion on 27/07/2021, with a spatial resolution equal to 100 m

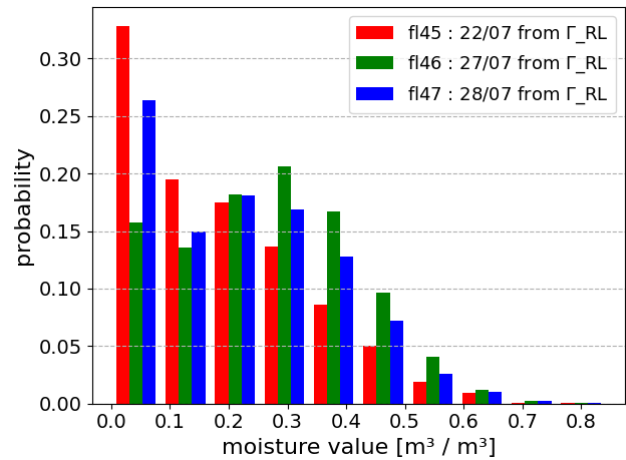


Fig. 14. Illustration of soil moisture level distributions over the Urgell site for three analyzed flights.

TABLE I
Summary of the GLORI campaign characteristics

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TABLE II
GROUND MEASUREMENTS DURING GLORI CAMPAIGNS

	<i>Hrms</i> (cm)	<i>Lc</i> (cm)	<i>M_v</i> (m ³ /m ³)	<i>LAI</i> (m ² /m ²)
22/07/2021	[0.4-1.84]	[4-12.18]	[0.06-0.34]	[0-3.14]
27/07/2021	-	-	[0.12-0.40]	-
28/07/2021	-	-	[0.1-0.43]	[0.14-3.42]

Flight id	Date	Start (UTC)	End (UTC)	Flight Duration
45	22/07/21	10:38:10	14:50:05	04:11:55
46	27/07/21	10:23:54	14:28:32	04:04:38
47	28/07/21	10:23:45	14:27:36	04:03:51

TABLE III
PARAMETERS OF THE CALIBRATED INVERSION MODEL

	γ	μ	δ	RMSE (dB)
Γ_{RL}	14.9	-5.3	-12.7	1.3