Analysis of RFI issue using the CAROLS L-band experiment
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Abstract—In the present paper, different methods are proposed for the detection and mitigation of the undesirable effects of Radio frequency interference (RFI) in microwave radiometry. The first of these makes use of kurtosis to detect the presence of non-Gaussian signals, whereas the second imposes a threshold on the standard deviation of brightness temperatures, in order to distinguish natural emission variations from RFI. Finally, the third approach is based on the use of a threshold applied to the third and fourth Stokes parameters. All of these methods have been applied and tested, with the CAROLS radiometer operating in the L-band, on data acquired during airborne campaigns made in spring 2009 over the South West of France. The performance of each, or of two combined approaches is analyzed with our database. We thus show that the kurtosis method is well suited to detect pulsed RFI, whereas the method based on the second moment of brightness temperatures seems to be better suited to detect continuous-wave RFI in airborne brightness temperature measurements.

Index Terms—RFI, radiometry, L band, CAROLS

I. INTRODUCTION

In recent years, various studies have revealed the substantial influence of Radio-Frequency Interference (RFI) in microwave radiometry. In fact, this type of noise can corrupt measurements, thereby introducing a significant deterioration to the database quality. In some regions of the world, it can in some cases render the data simply unusable. In an effort to circumvent this significant problem, RFI detection and mitigation have been widely studied theoretically [1], [2], [3] at different frequencies and for different spaceborne platforms [4], [5], [6]. At L-band, RFI have been studied and presented in a small number of papers [7], [8] and very few works were done on L-band airborne radiometric measurements [9]. In [1], authors have compared different strategies to detect pulsed RFI, while [2], [3] evaluated theoretically different algorithms based on statistical criterias.

In [8], the authors have shown the ability of an ADD (Agile Digital Detector) to detect and remove RFI from microwave measurements. The ADD performance was experimentally verified under controlled laboratory conditions and in the field, near to a commercial air traffic control radar. In [7], the authors tested a double detector based on kurtosis, which is linked to the non Gaussian nature of a signal, under equivalent conditions (on ground and in the laboratory).

In the last paper [9], the authors report RFI experienced during airborne CoSMOS campaigns; they tested RFI detection using the kurtosis parameters, and compared this method with a new approach based on a RFI indicator making use of the same 3rd and 4th Stokes parameters. They showed that the latter indicator, used alone, may provide a good alternative for RFI suppression. Alternatively, it could be used as a complementary improvement to the kurtosis method.

With the advent of various satellite radiometers operating in the L band (1400-1427 MHz, a protected frequency band), which are designed mainly for soil moisture estimation over the full terrestrial surface, this particular problem of measurement perturbations is becoming increasingly significant. Indeed, at these low frequencies, the soil moisture fraction has a negative dependence of approximately -1K / % on brightness temperature, with the exact value depending upon soil type, vegetation cover, surface roughness and other factors [10]. For example, The MIRAS radiometer, onboard SMOS [11], launched in November 2009, has been designed to measure soil moisture with a radiometric error requirement of less than 2K, depending on the nature of the target and its location within the instrumental field of view. The retrieval error performance is predicted to be lower than 4 %. Small levels of RFI, of only a few Kelvin, can thus cause the soil to appear to be dryer than in reality. Such an outcome can, in turn, be interpreted as a lower past rainfall or higher evaporation rate. No hardware has been provided with the SMOS instrument to provide real-time estimations of RFI. Furthermore, the same difficulty will be encountered with the future Aquarius [12] satellite, the SMAP [13] one will then benefit of actual studies to mitigate RFI effects on satellite images.

The ultimate objective of the present study is to enable natural surface emissions, interpreted for the purpose of soil moisture measurements, to be correctly estimated. For this, we made use of airborne measurements acquired in the L-band with CAROLS (Cooperative airborne radiometer for Ocean and Land Studies) [14], over different terrestrial areas including the South West of France, in which we identified the presence of strong RFI signals, particularly around the city of Auch, where a strong continuous-wave component of RFI was detected. We propose to test and compare different approaches, in order to identify and mitigate both forms of RFI (pulsed and continuous-wave) present in the CAROLS data.

The present paper is organized as follows: Section II presents our database, with a description of the CAROLS radiometer and CAROLS flight patterns. Section III discusses the three approaches proposed to detect and eliminate data contaminated with RFI. Section IV proposes an evaluation of the performance of each method. Finally, our conclusions are presented in Section V.
II. DATA PRESENTATION

A. CAROLS radiometer

The receiver, designed and built as a copy of the EMIRAD II radiometer from the DTU team, and adapted to the French ATR42 research aircraft, is a fully polarimetric correlation radiometer with direct sampling [15]: all four Stokes parameters describing the electric field are measured. Calibration is carried out using internal loads and a noise diode, which adds approximately 120 K to the radiometer input. This setup ensures frequent internal calibration capability, and allows the radiometer to calibrate any phase difference between the two input channels preceding the digital correlator. The receiver specifications were presented in [14].

The antenna system comprises two large, identical Potter horns and two bulky waveguide orthomode transducers (OMT), thereby achieving almost ideal antenna patterns and low losses. Each horn has an identical pattern and a 37.6 degrees half-power beam width (HPBW). The performance of the Potter horns is very satisfactory, with side and back lobes being suppressed by more than 40dB, while the cross-polar level is even smaller.

In order to correctly determine the correlation between the horizontal (H) and vertical (V) channels, the components used for each channel must be phase matched, with the two signals, corresponding to the V and H polarizations, thus arriving in phase at the receiver. The coaxial cables for each antenna were also chosen to be identical in type and length, for the same reason.

Each antenna was insulated, to minimize variations in its structure’s temperature. Indeed, our aim was to maintain both ports (horizontal and vertical polarizations) at the same temperature. The temperature of each OMT and horn was continuously recorded by means of thermistors.

The stability, accuracy and linearity of the radiometer were fully analyzed in the laboratory, and corresponded to the aforementioned specifications.

B. CAROLS flight plans

CAROLS radiometer flights were carried out with the French ATR42 operational research aircraft, operated by SAFIRE. The onboard instrumentation also included an inertial navigation unit combined with a GPS receiver, for aircraft attitude and position recording. One of the antennas was inclined to nadir (Nadir antenna), whereas the other one was positioned on the right side of the aircraft, and pointed at an angle of 32° (Slant antenna). Different types of flight were planned for the various campaigns carried out in 2008 and 2009. Several were planned to reach the ocean, by firstly overflying the different SMOSmania sites, which are meteorological sites in the South West of France, instrumented by Météo-France for SMOS algorithm ground-truth validation, then also overflying the ’Landes’ forest. Figure 1 illustrates the flight paths used in the South of France for the CAROLS 2008 and 2009 campaigns. As described in [14], most of the flights were dedicated to the study of the microwave signature of different land (SMOSmania and Nezer) sites, and of the Ocean in the gulf of Biscay. All flights followed approximately the same route, between Toulouse and Biscarrosse, and the aircraft always flew at a constant altitude of 3000 m over land.

C. CAROLS Measurements

For the purposes of the present study we selected one specific flight over the SMOSmania sites in the South West of France, flown on 27 April, 2009, of which we chose to analyze only one part: the return of the aircraft from Biscarrosse to Francalaz airport near Toulouse. At the western end of this flight, the over flown areas included various lakes, followed by the ’Landes’ forest, whereas at the eastern end, the continent was covered mainly by agricultural fields. We also selected measurements corresponding to the Slant antenna only. All measurements (4 Stokes parameters and kurtosis values) were originally sampled at 140 MHz, integrated every 1 ms and averaged over 40 ms periods, corresponding to the sampling frequency of the Inertial Unit of the aircraft.
For forested and agricultural areas, the Tb measurements led to values between 250 and 280 Kelvin, for the H and V polarizations; this range corresponds to the natural emission of the terrain, and is shown on the left side of Figures 2-a and 2-b. It should be noted that the first and second Stokes parameters correspond respectively to the sum and difference of the Tb values in the H and V polarizations. All of the above-ground transects were disturbed by interference, in both polarizations (see Figures 2-a and 2-b for the H and V measurements respectively), especially in the V polarization; pulsed sources appear clearly throughout the flight. Moreover, two point sources led to a strong perturbation of the measurements, in the vicinity of Auch and Toulouse (after 21:40 and near 21:55). These two brightness temperature peaks reached respectively 18000 K and 800 K, with the highest value occurring near to Auch. The measurements in the H polarization were also disturbed near to the ocean, probably due to military emissions from the Cazeaux base (right side of Figure 2-a).

D. Principal RFI sources

In the South West of France, we identified two main types of RFI: pulsed RFI and Continuous-wave RFI.

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As previously mentioned, the CAROLS radiometer also measures the third and fourth Stokes parameters ($T_3$ and $T_4$).

\[
T_3 = T_{+45^\circ} - T_{-45^\circ} = \frac{\lambda}{K Z} (2 \Re\langle E_V E_H^* \rangle)
\]
\[
T_4 = T_l - T_r = \frac{\lambda}{K Z} (2 \Im\langle E_V E_H^* \rangle)
\]

(1)

where $T_{+45^\circ}$ and $T_{-45^\circ}$ describe the brightness temperatures from an antenna system inclined at $45^\circ$ relative to the horizontal and vertical orientations, $T_l$ and $T_r$ represent the left-hand and right-hand polarizations respectively, $\lambda$ is the central wavelength of observation, $K$ is Boltzmann’s constant, and $Z$ is the impedance of the propagation medium (the air in our case). $E_V$ and $E_H$ are the V and H polarized electric fields; the measurements correspond to electronic counts corresponding to these fields, with internal calibrations allowing us to estimate $T_3$ and $T_4$.

Figure 2-a and 2-b illustrates the effect of RFI on these two measured parameters. The pulses in Tb correspond to positive or negative pulses in $T_3$ and $T_4$, which are presented in Figure 3-a and 3-b. Moreover, strong variations are observed in $T_3$ and $T_4$, corresponding to strong, local, continuous-wave RFI sources observed in the H and V polarizations, before 21:45.

The following comparisons are developed and illustrated, for the quantity Tb measured by the Slant antenna in the H polarization only, because the RFI effects were more significant on this antenna: its footprint is larger than that of the nadir antenna. The choice of H polarization is arbitrary, since the results are identical for the V polarization.
The first type of RFI is due to radars, air traffic control or military installations in particular (the sources were not clearly identified). The pulsed radar effects are shown on the left side of Figure 2 (a-b), resulting from the measurements made over the ‘Landes’ forest. The radar source appears to have been flown just after 21:30: inversion of the sign of the 3rd Stokes parameter indicates that the correlation between the H and V channels also changed sign.

Continuous-wave RFI were observed around some locations: very strong Tb values are shown on figures 2. We observe 3 peaks corresponding to places near Auch city and near Toulouse.

In order to analyze the origin of this strong, non-natural noise, we carried out time-frequency analysis of ‘quick data’, i.e. signals sampled at 139 MHz using a spectrum analyzer, recorded in the vicinity of Auch city. The resulting Fourier transform of the signal is shown in Figure 4. A high level of power density can be observed in the spectral band centered around 1427 MHz. On the right side of the figure, strong variations in the spectral power indicate non-natural emissions. Other variations may be due to different harmonics linked to fundamental frequencies such as that near to 1427 MHz.

Following a ground localization campaign to identify possible RFI sources in the vicinity of this city, we discovered that some companies are authorized to use antennas with a central bandwidth very close to the protected L-band. In Figure 5 we provide a map showing the location of these antennas in France; in this figure, the color is related to the difference between central frequency and 1427 MHz, and an arrow indicates the position of two antennas which could be RFI sources along the flight path.

III. RFI FILTERING

A. Kurtosis

The Kurtosis of a signal is the relationship between the fourth central moments $\mu_4$ and the square of the second central moment $\mu_2$:

$$\beta_2 = \frac{\mu_4}{\mu_2^2}$$

where for $q > 1$:

$$m_q = \frac{1}{N} \sum_{i=1}^{N} (y_i - m_1)^q$$

and $m_1$ is the sample mean ($y_i$, $i=1$ to N) mean. Kurtosis is equal to three if the signal is Gaussian type and will deviate from this value in presence of a non-Gaussian sources [16].

Natural radiometric noise being Gaussian and additional man-made noise (pulses and continuous-waves) being non-Gaussian, it is theoretically possible, by measuring them, to distinguish between RFI-free and RFI-contaminated signals.

In practice, the expectation operations in equation 2 are approximated using a finite number of samples. This approximation leads to uncertainties in the estimator, which have the same statistical origin as does the radiometer noise-equivalent delta-T uncertainty, associated with variance estimations. The error in estimating the kurtosis of a Gaussian distributed random variable, from a finite number of samples, N, has been previously studied [17]. The standard deviation of the estimator is given by:

$$N E \Delta \beta_4 = \sqrt{\frac{24}{N}}$$

In the case of the CAROLS data, the sampling rate was approximately 140 MHz, which means that 140 000 samples were integrated each 1 ms. This leads to: $N E \Delta \beta_4 = 0.013$.

$N E \Delta \beta_4$ was estimated using a small portion of CAROLS data without RFI and found to be equal to 0.017 (using $10^3$ data), with a mean Kurtosis value of 2.97, values stable during the flight, except during continuous-wave RFI.
Figure 6 shows the kurtosis distribution for H polarization data sampled at 1 ms. The mean kurtosis value is around 2.97 and the standard deviation (STD) is 0.05. In this case, it is clear that the usual kurtosis constraint is too restrictive, and that kurtosis values greater than 3 should be also considered.

In the present study, we tested different RFI flags (named F_K1 to F_K5), based on different kurtosis conditions. Two kinds of flag are possible, some based on an interval not centered on the mean Kurtosis value (F_K1, F_K4 and F_K5) as in [9], others centered on the mean value (F_K2 and F_K3) and defined by the standart deviation:

- F_K1: data in the [2.9-3.1] interval are kept, reference as a largely permissive condition;
- F_K2: data in the [2.97-2.97+NEΔβ4] interval are kept;
- F_K3: data in the [2.97-2.97+2NEΔβ4] interval are kept;
- F_K4: data in the [2.95-3.01] interval are kept;
- F_K5: data in the [2.95-3.00] interval are kept.

This last condition applied to the CAROLS data respects the theoretical. As a general rule, the F_K5 conditions are considered in kurtosis algorithm applications [9]. However, as shown in Table I, the application of this condition is restrictive, since only 72 % of the analyzed data remains unflagged. Moreover, the mean of the Tb measurements in H polarization is greater in this case than that resulting from F_K4. This mean (and justify the use of F_4 filter) that low Tb values were also eliminated, such that the F_K5 condition can be considered as excessively restrictive. The F_K2 was able to keep only 65 % of data which means that this condition is also very restrictive.

Figure 7 illustrates RFI elimination using the less restrictive F_K3 condition. Under these conditions, data exhibiting radar-pulse contamination is found to be completely eliminated. On the other hand, the continuous wave noise present in the vicinity of Auch city is not correctly eliminated: many Tb values as high as 300 K are not removed.

We compared the theoretical Kurtosis values in presence of continuous-wave RFI and measured values in the case of the strong RFI near the Auch city. In [18], authors have shown that Kurtosis should theoretically be:

$$\beta_2 = 3 - \frac{3 \text{INR}^2}{2(1 + \text{INR})^2}$$

where INR is the Interferer to Noise Ratio equal to:

$$\text{INR} = \frac{A^2}{2\sigma^2} = \frac{T_{rfi}}{T_{sys}}$$

where A is the amplitude of continuous-wave RFI, σ is the variance of the gaussian noise, $T_{rfi}$ is the RFI brightness temperature and $T_{sys}$ the system temperature without RFI.

Theoretical Kurtosis value should have been 2.73 ($T_{sys} = 414$ K and $T_{rfi} = 300$ K) when the radiometer was approaching the source. In our case, the RFI was not detected by the Kurtosis filters when approaching disturbed period; more precisely, Kurtosis remains between 2.9 and 3 when Tb measurements are between 300 and 600 K, which differs from theory. Unfortunately, we are not able to explain this difference between our measurements and theory; one hypothesis could be the presence of many RFI sources within an integration period, making data to appear to be Gaussian.

### B. Standard deviation of the brightness temperature (F_STD)

One very simple method for discriminating between RFI data and non-polluted data could be the use of a flag, based on the estimation of the brightness temperature standard deviation, also called pulse detector in [4]. This filter could be useful when RFI is only slightly perturbing signal, making useless a threshold on brightness temperature.

In fact, as shown in Figure 8, for some types of RFI we observe a strong increase in the signal standard deviation (STD), based on the averaging of 400 samples at the original integration period of 1 ms, when it is compared to that of RFI-free data characterizing natural surfaces. This increase has an almost linear trend (Figure 8a), and a large quantity of data characterized by high Tb values (those above 300 being non-natural) are also characterized by high STD values (Figure 8b).

In view of these considerations, we consider that a criterion based on STD estimation could be useful for the detection of continuous-wave RFI.
Figure 8. Relationship between the mean Tb values and their STD in H polarization. All data are shown in (a), a zoom on the smaller mean Tb values is provided in (b).

Figure 9 shows the time variation of the STD values, with a zoom on the data acquired around 21:50, clearly showing that low STD values and RFI-induced peaks can be distinguished: the strong values are shown on the left and right sides of the figure, corresponding to the Auch and Toulouse continuous-wave RFI respectively. The peaks correspond to pulsed RFI as indicated on the Tb values. The threshold of 2 K, corresponding to the horizontal line in this figure, was chosen empirically, based on the number of samples and the STD value taken by natural emission during the flight (under 1 K).

Figure 10 illustrates the result after RFI elimination, using the F_STD filter. In this case, a large amount of pulsed signal is removed and Tb values showing the strong increase, the continuous-wave RFI, is almost completely removed too. However, at the beginning of the flight, near Biscarrosse, non natural emission is still remaining.

C. Filter based on T3 and T4 values (F_T3 and F_T4)

As can be seen in Figures 3-a and 3-b, $T_3$ and $T_4$ are strongly contaminated by RFI: over natural targets, these two Stokes parameters could be expected to be small in the L-band. Both types of RFI, pulsed and continuous-wave, can be seen together with the brightness temperatures in the two polarizations.

We propose to analyze different options, making use of these parameters to filter RFI-contaminated data. We considered an empirical threshold for both $T_3$ and $T_4$, chosen from RFI-free data, and then applied the filter to the Tb values in H polarization, based on this threshold. The two filters are:

- $F_{T3}$: threshold of $\pm 3K$
- $F_{T4}$: threshold of $\pm 3K$
Filtering method | Percentage of kept data (%) in H pol | H (K) |
---|---|---|
Without modification | 100 | 356.6 |
F_K1 | 94 | 253.5 |
F_K2 | 64.9 | 251.3 |
F_K3 | 89.7 | 252.3 |
F_K4 | 79.9 | 250.7 |
F_K5 | 72.9 | 250.9 |
F_STD | 77.5 | 246.8 |
F_STD_K | 70.4 | 246.7 |
F_T3 | 75.5 | 248.8 |
F_T3_K | 66.3 | 247.5 |
F_T4 | 62.5 | 247.8 |
F_T4_K | 54.8 | 247.7 |
F_STD_K_T3 | 62.8 | 246.4 |

**TABLE I**
RFI PERCENTAGES AND MEAN Tb VALUES IN H POLARIZATION, DEPENDING ON THE FILTER APPLIED TO THE DATA SET

Fig. 11. Tb measured along the flight track in H polarization. The black line represents unfiltered values, whereas the red points correspond to values filtered by the $T_3$ threshold $= [-3, 3]$ (filter F_T3).

Figure 11 illustrates the results of RFI elimination with a threshold on $T_3$ equal to ±3K: the pulsed RFI is eliminated, whereas the continuous-wave RFI is less affected than the previous filter: increasing values between 250 K and 300 K are still present in the data base. Despite that, it seems that the F_T3 filter is more adapted to the elimination of continuous-wave RFI compared to the use of the Kurtosis filters.

The F_T4 filter results were less than optimal for both RFI types: some pulses were not eliminated while natural emissions were eliminated in one specific place; moreover, continuous-wave RFI was not wholly eliminated.

### D. Double indices for RFI detection

From the results illustrated in the three last sections, the kurtosis and standard deviation approaches are seen to be complementary. In fact, the former method correctly detects radar pulses, but has difficulties to eliminate continuous-wave RFI noise, such as that observed in the vicinity of Auch. In the other hand, standard deviation approaches are well adapted to the detection of such continuous wave RFI sources, characterized by a strong increase in the value of this parameter. For these reasons, we propose the identification (and removal) of RFI based on the combination (referred to as F_STD_K) of these two methods: in this case, the F_K4 filter is first applied to the data, followed by the F_STD filter. We also tested the possibility of making simultaneous use of Kurtosis filters (F_K4), and $T_3$ and $T_4$ (F_T3 and F_T4).

Table I provides a summary of the outcome of various RFI filtering strategies, using the different combinations of the aforementioned filters. For each case, we compute the percentage of data retained, together with the mean brightness temperature over the whole transect for the H polarization. It can be seen that in the absence of RFI mitigation, the mean value of Tb is very high: 356.6 K. The application of different Kurtosis filters allows the mean value of Tb to be significantly reduced, with improving efficiency from F_K1 to F_K3. The F_K4 filter produces a higher mean value of Tb than F_K3, due to the low pass filtering of unaffected Tb measurements. It can be seen that the F_STD filter produces a very low mean value of Tb (246.7 K). This result should be considered in the light of the data shown in Figure 9, from which it is highly likely that only very small quantities of good data (without RFI) were rejected. Other filters also generate low mean values of Tb, however these are probably still affected by poor filtering of continuous-wave RFI (Figure 11, Tb ranging between 270 and 300 K, just after 21:40).

Although the combination of different filters allows pulsed RFI to be suitably mitigated, when this is not possible using one filter only (F_T3 or F_T4, for example), its effectiveness is not as good in terms of the mean Tb criterion, for the case of F_T3_K and F_T4_K, or the proportion of retained data criterion, in the case of F_STD_K_T3.

Finally, the last 6 of the filters listed in Table I provide quite similar mean Tb values (with differences lower than 2K), but are disqualified as a result of strongly differing quantities of non-rejected data. It should be understood that when a low percentage of data is kept, there is the risk of a considerable quantity of good data being rejected. This observation depends however on the thresholds chosen for the F_STD, F_T3 and F_T4 filters, and should thus be considered with caution. Nevertheless, in an effort to select an optimal filter, we note that the F_STD filter retains a large quantity of data, whilst producing a low mean Tb value.

**IV. Pulse detection**

Four filters were tested on a specific part of the flight without continuous-wave RFI but showing pulses. Results are shown on figure 12 where we plotted Tb values without filtering and Tb values after the use of F_T3, F_T4, F_K2 and F_STD filters respectively.
Fig. 12. Evaluation of the performance of different filters (F_T3, F_T4, F_K2 and F_STD) to eliminate pulsed RFI. Remaining Tb values variations are plotted depending on time.

In this case, F_K2 detects 399 pulses (F_K3, 2376), F_T3 detects 479, F_T4 and F_STD eliminate 1592 and 849 points respectively. F_T3 and F_T4 are missing some pulses, F_K2 and F_STD are eliminating the same pulses when F_K2 is keeping more data than F_STD. This point out the weakness of filters based on third and fourth stokes parameters concerning this kind of RFI.

V. DISCUSSION AND CONCLUSION

In the present study, different methods have been evaluated for the detection and elimination of RFI from CAROLS radiometric data. We applied this analysis to airborne Tb measurements acquired in the South West of France, characterized by the presence of strong RFI emissions due to two types of source in particular: air traffic control or military radars, and company antennas emitting a continuous and very high level signal. The first filtering technique is based on an algorithm using kurtosis values. The second and third methods are based on standard deviation or brightness temperature thresholds, or the third and fourth Stokes parameters. Our analysis of the resulting RFI corrections reveals that the two methods are complementary. In fact, the kurtosis parameter is well adapted to the correction of radar pulses. On the other hand, standard deviation analysis is better adapted to continuous noise sources characterized by an approximately Gaussian distribution, which are not easily detected with kurtosis. By using a low value for the standard deviation threshold, pulsed RFI can also be filtered using this method; in the CAROLS configuration, the filter F_STD is thus very competitive with kurtosis. However, depending on the integration time, kurtosis appears to have greater potential for the filtering of pulsed RFI. Nevertheless, as the threshold on standard deviation was chosen empirically and as position of emitters was not known, we were still not able to study the detection of small changes in Tb measurements due to small RFI.

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