Interactive comment on “Radio frequency interference mitigating hyperspectral L-band radiometer” by Peter Toose et al.

Anonymous Referee #1
Received and published: 6 September 2016

General comments

The authors points out that RFI is a problem for spaceborne radiometers operating in the protected band and that the equipment that they have used for this paper can be useful in field campaigns aimed at calibrating/validating such satellite missions. However, the instrument used here (1400-1550 MHz) has a significantly wider passband compared to the spaceborne instruments (1400-1427 MHz). The reason for this difference is not clearly stated. Also, it is not clear if/how this difference affects RFI detection within the protected band.

The authors describe how RFI are detected. Though it is important to specify also how the mitigation is implemented. My guess is that once a sample is considered as RFI affected it is removed, so that the output is the average of all the RFI-free channels. But this is not stated in the text.

The calibration is well described.

Some questions remain on the detection algorithm.

It is generally a good paper. The authors put quite a lot of effort in the validation of their results on both simulated and actual measurements. A minor revision is needed before it is suitable for publication.

Specific comments

Introduction

R1-C1: The name of the mission is “Aquarius/SAC-D”, and it was launched jointly by NASA and CONAE. Aquarius is the name of the main instrument.

P1 L28-29 – changed text to – ‘The *NASA Aquarius instrument on board the Argentine SAC-D spacecraft*, acquired L-Band observations between September 2012 to July 2015 (Lagerloef et al., 2013)’

R1-C2: Soil moisture is the objective for SMOS and SMAP, not for Aquarius.

P1 L31: – changed text to – ‘In addition *to monitoring soil moisture and sea surface salinity*, these missions also provide useful measurements for cryospheric applications…’

R1-C3: Reword for clarity. ITU regulations allow spurious emissions in the protected band, as long as they are sufficiently weak.

P2 L10-14 – changed text to – '…has regulated that the frequency allocation of 1400-1427 MHz be dedicated to passive remote sensing from space and radio astronomy research and that all other emissions within this band be prohibited *or limited to maximum permitted emission power levels (ITU, 2012)*. Illegal sources, in-addition to spurious and harmonic emissions and other unwarranted transmissions, often violate these reserved *bands or exceed the maximum permitted emission power levels*, producing RFI.'

R1-C4: What do the authors mean by "avoid RFI"?

– response to reviewer – One further method of dealing with RFI while trying to conduct L-Band observations using airborne or ground-based instruments is simply to avoid an area known for RFI emissions. The authors acknowledge that the avoidance method is not an option for spaceborne sensors, and as such the term 'avoid' has been removed.

Section 2.1

R1-C5: It would be clearer if a block diagram were included as well.

– response to reviewer – This information is proprietary to Radiometrics Inc. and is not available for publication.

Section 3.3

R1-C6: P8 L19-20. This sentence is misleading. The natural thermal emission has a Gaussian distribution. However, when looking at it across frequencies one should expect a uniform distribution.

P9 Line 25-28 : - changed text to – '*This hyperspectral radiometer system assumes that the natural T_B of a scene is a Gaussian distribution and that the thermal spectra from the observed scene are a near constant T_B across the 1400-1550 MHz bandpass, with minimal observed variability due to the receiver's noise equivalent temperature difference (ΔT), calibration error and some small variance from within the scene (see Table 1.)*

R1-C7: Also, the dataset in Fig.3 is not a Gaussian distribution. It is the sum of two things: thermal noise (Gaussian) and RFI (not Gaussian). Please review the instances where a Gaussian distribution is mentioned.

P10 Line 12-13 : - changed to text – 'Fig. 3 illustrates the horizontal polarized TBs of one integration cycle of the ambient calibration target (251 K) shown in Fig. 2, *which is a sum of the natural thermal signal (Gaussian) and RFI (not Gaussian).'*

R1-C8: The authors state that the inflection point is representative of the mean if there are no RFI. Is it also representative of the mean for the dataset in Fig.3? If not, please review wording.

– response to reviewer – No, the inflection point is not representative of the mean for this dataset because, the mean would be influenced by the RFI-affected channels. We clarify in the text:

P10 Line 14-16: - changed text to – 'The red dot in Fig. 3 is the inflection point *(251.9 K), representative of the mean T_B of the same scene without RFI. The mean value of the full spectrum in Fig. 3 (RFI included), is 255.2 K.'*

R1-C9: All the T_Bs above the inflection point are considered as RFI? This seems a very conservative approach. If this was the authors' intention, it is probably worth mentioning it explicitly in the text. Also, if only the measurements below the mean are used, the output will underestimate the natural thermal radiation. Can the authors comment on this?

– response to reviewer – Not all the T_Bs above the inflection point are identified as RFI, however, there is no way of identifying the exact number of contaminated channels because of the unknown nature/source of the RFI contamination and the potential for subtle RFI intrusions. This exact problem lead the authors to develop our RFI mitigation approach that identifies a single representative T_B value for each measurement as occurring at the point of inflection where the 2nd derivative of the 3rd order polynomial of sort-rank versus T_B goes from negative to positive, which agrees well with the mean T_B of an RFI-free scene of a natural thermal emission. The entire spectrum is used to identify the point of inflection, using the sort-rank versus T_B approach, but the values of each channel are not used in the calculation of the mean T_B of the scene because as the reviewer mentions, the T_Bs above the inflection point are contaminated by RFI (the exact number of channels and strength of RFI are unknown), and limiting the results to those channels below the inflection point would skew the mean TB too low. Our testing with synthetic data (Section 4.2) suggests that the agreement between the inflection point identified T_B and that of the mean T_B for a clean RFI-scene is maintained (to within 2 K), as long as the number of channels contaminated does not exceed ~9% of the spectrum. As the number of contaminated channels exceeds this percentage, the agreement degrades - See Figure 7.

P9-10 – changed text to – See response to reviewer R1-C14 where we clarify the inflection point approach for RFI mitigation below:

R1-C10: More commonly, RFI are identified as outliers above a threshold set to "mean +- N*standard deviations", possibly computing the mean iteratively. Did the authors also try to implement this approach and compare the results with the proposed approach?

– The authors developed this novel RFI mitigation approach because of its usefulness for separating out the subtle RFI contamination, receiver noise and calibration errors within the spectrum from the expected thermal signal. We think we have successfully demonstrated that our RFI mitigation technique works using both modelled and measured L-Band data. Comparing our results with the 'mean +- N*standard deviations' RFI removal method is beyond the scope of this paper.

R1-C11 : It is not a normal distribution if there are RFI.

P10 L19-21 – change text to – *'The inflection point T_B become less representative of the scene as the spectrum being analyzed becomes exceedingly non-normal…'*

R1-C11 : How do the authors cope with the cases of "extreme RFI contamination"?

P10 L21-23 – change text to – '…*due to over-whelming* RFI contamination, *which results in unrealistic TB values that are relatively easy to detect using a visual inspection of the spectrum and/or of the time series data plots.*'

R1C12: P8 L32-P9 L1. This is not clear to me. If only the protected band is considered and there are no RFI, then this method does not detect RFI? Maybe the authors meant that if only the protected band is considered and there are RFI, then this method does not detect them? –

response to reviewer - If the data to be processed is a uniform short-tailed distribution, then an error during the RFI mitigation processing can occur where the inflection point is identified outside the bounds of the spectrum. If this occurs during the RFI mitigation processing, the midpoint of the spectrum is chosen because it is a highly efficient estimator of the mean, given a small sample of a sufficiently uniform distribution.

P10 Line 25-26 - changed text to – *'In instances where a narrow spectrum is employed and the scene is RFI-free, the midpoint of the spectrum is chosen to represent the mean of the scene, rather than the inflection point.'*

R1-C13 : In case the latter is correct: I would expect the band 1427-1550 MHz to be even more contaminated than the protected band, since it is allocated to active applications. How does RFI contamination outside the protected band affect the performances on the proposed approach? –

response to reviewer – The reviewer is correct, the frequency of observed RFI is higher outside the protected band, however, this higher frequency of observed RFI outside the protected band does not affect the performance of the RFI mitigation approach, as long as the percent of contaminated bandwidth does not become exceedingly large (see section 4.2). However, if a persistent and broadband RFI signal is observed outside the protected band, the RFI mitigation can be applied to a smaller bandwidth (for example: 1400-1475 MHz). The advantage of initially observing over a larger bandwidth is to increase the chance of observing RFI-free channels incase the protected band is contaminated, but as a result, we will record more frequent (legal) RFI occurrences outside the protected band.

P9 Line 21-25 - changed text to – *'The advantage of observing over a larger bandwidth increases the likelihood of observing RFI-free channels, but also results in the recording of more frequent (legal) RFI occurrences outside the protected band. However, this higher frequency of observed RFI outside the protected band does not affect the performance of the RFI mitigation approach described herein, as long as the percent of contaminated bandwidth does not become exceedingly large (see section 4.2).'*

R1-C14 : After RFI is identified, how is it mitigated? Are the corresponding Tbs removed? Replaced by the mean?

– response to reviewer – The authors have tried to re-word/clarify the description of our RFI mitigation technique to better explain our methodology. Our RFI mitigation approach does not remove channels, or calculate a mean T_B based on channels identified as RFI-free. We simply use the T_B value present at the inflection point where the 2nd derivative of the 3rd order polynomial of sort-rank versus T_B goes from negative to positive to represent the scene T_B.

P9-10 Line 29-11 – changed text to – 'A simple but effective method of separating out the thermal *signal plus the receiver noise and calibration uncertainty* from RFI-contaminated channels is to sort the *observed T_B spectra* in ascending order. The thermal channels sort to the low values, *with the spectra gradually increasing by several Kelvin due to the receiver noise, calibration errors and variability within the scene*. The RFI-contaminated channels are then identified where the brightness begins to rise out of the expected thermal spectrum. *However, it is challenging to identify the exact point at which the RFI begins this rise out of the expected thermal spectrum because of the unknown nature/source of the RFI contamination. This dilemma, lead the authors to develop an RFI mitigation approach that identifies a representative RFI-free T_B value for this spectrum*, using a 3rd order polynomial of *the sorted T_B spectra in ascending order*. The 2nd derivative of the slope of this cubic polynomial is derived. For a clean thermal spectrum with random noise, the mean value is a close approximation of the TB at the inflection point where the 2nd derivative goes from negative to positive. *For a spectrum contaminated with RFI, the mean value of the spectrum is skewed higher by the RFI affected channels, however, the T_B at the inflection point where the 2nd derivative of the 3rd order polynomial of sort-rank versus T_B goes from negative to positive is still representative of the mean value of the same scene without RFI (within ≈2 K for a spectrum contamination of up to ≈9%: See section 4.2), and therefore the T_B value at the inflection is used for subsequent analysis and is considered the RFI mitigated result*.'

Section 4.1

R1-C15 : P11 L11-12. Yes, generally sky calibrations are done pointing out of the galactic plane. The Moon should also be taken into account.

P12-13 Line 34-2 – change text to – 'The higher error in the sky measurements could be related to the fact that the sky emission might vary slightly depending upon the observed portion of the sky, *due to the variability in sky background temperatures measured while the antenna beamwidth crosses the galactic plane (1-3 K) and due to the potential contributions from the sun and moon (Delahaye et al., 2002; Le Vine et al., 2005).'*

Delahaye, J.-Y., Golé, P., and Waldteufel, P.: Calibration error of L-band sky-looking ground-based radiometers, Radio Sci., 37(1), 11-1 – 11-11, 2002.

Le Vine, D. M., Abraham, S., Kerr, Y., Wilson, W.J., Skou, N. : Comparison of Model Prediction With Measurements of Galactic Background Noise at L-Band. IEEE T. Geosci. Remote, 43 (9), 2018-2023, 2005

Section 4.2

R1-C16 : Figure 7. Can the authors add a line at Tb-mean = 252 K. It would be interesting to have also a plot of DeltaTb (Tb-mean – 250 K) against the percent of contaminated bandwidth. It would give a more general idea of the performance of this method. – DONE updated Figure 7.

Technical corrections
P1 L27. Capitalize moisture - DONE
P3 L11. Capitalize CPU - DONE
P3 L18-19. Replace "Ten microsecond 1024 (512 horizontal and 512 vertical channel)" with "Ten microsecond 1024 channels (512 horizontal and 512 vertical)" - DONE
P4 L28. Replace "out" with "of". - DONE

P5 L29. Replace "observed" with "made". - DONE
P6 L2. Please remember to update the status of this paper if possible – Still in review as of October 17th 2016
P6 L2-4. Sentence is not clear, please reword. – response to reviewer – The purpose of this sentence was to highlight that the L-Band radiometer system was moved between multiple locations many times, highlighting the unique portability of the system, as well as the ability to successfully mitigate changing RFI sources between sites.

P7 Line 2-7 - changed text to – 'These temporally continuous measurements *recorded in the same location*, were augmented with monthly visits *to multiple sites with varying soil conditions and potentially changing RFI contributions*, across the Kenaston/Brightwater Creek soil monitoring network *85 km south of Saskatoon* (≈51.3° N; ≈106.5° W). Between October 23rd, 2014 and April 24th, 2015, 16 three-target calibrations were measured between these two research sites…'

P6 L11. Correct "durging" - DONE
P7 L22. Remove "1)" - DONE
P8 L6. Remove "2)" - DONE
P8 L6-7. Reword. Suggestion: the optimization results for the coefficients are used as first guess to run : : :

P9 Line 8-9 - changed text to – 'Secondly, the optimization results for the coefficients T_ND (0°C) and Offset(0°C) from the first post-processing step, are used as a first guess to run the inversion model again, …'

P8 L11. "science-ready". - DONE
P8 L17. Anterrieu 2011 is a software approach, not hardware. – Removed reference
P8 L21-22. Please reword

P9-10 Line 31-5 – changed text to – 'The thermal channels sort to the low values, *with the spectra gradually increasing by several Kelvin due to the receiver noise, calibration errors and variability within the scene.* The RFI-contaminated channels are then identified where the brightness begins to rise out of the expected thermal spectrum. *However, it is challenging to identify the exact point at which the RFI begins this rise out of the expected thermal spectrum because of the unknown nature/source of the RFI contamination. This dilemma, lead the authors to develop an RFI mitigation approach that identifies a representative RFI-free TB value for this spectrum,* using a 3rd order polynomial of *the sorted TB spectra in ascending order.*'

P9 L14-19. Summarize this paragraph and refer the reader to section 4.2 where all the details should be included (e.g. why below 2 K is OK) – response to reviewer – The authors feel that the methods section is the more appropriate section to describe the assessment criteria. The authors have added the following reference to the results section 4.2 to re-direct the reader to section 3.4 for more details on how/why the 2 K assessment criteria was chosen.

P13 Line 10-11 - change to text – 'If the RFI mitigation results were within 2 K, of the mean 250 K of the synthetic spectrum, then the RFI mitigation approach was considered successful *(See section 3.4 for successful assessment criteria).'*

Interactive comment on Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-27, 2016.

Interactive comment on “Radio frequency interference mitigating hyperspectral L-band radiometer” by Peter Toose et al.

Anonymous Referee #2

Received and published: 3 October 2016

Review of paper GI-2016-27 Toose et al. "Radio Frequency interference mitigating hyperspectral L-band radiometer"

General

The authors describe an L-band radiometer system designed for ground based or airborne experimental studies on microwave remote sensing. The calibration and RFI mitigation method of the system are described. Examples of calibration accuracy and RFI mitigation are demonstrated by means of actual measured data. The limitations of the method regarding broadband RFI mitigation are acknowledged. The paper is well written and generally to the point. The described system is to my knowledge a unique piece of equipment, and many of the features incorporated in its design may be useful when planning for similar future systems (surface based or satellite). In this regard, the authors could add a block diagram of the system to improve the description of the hardware. The study should be of interest to the remote sensing community. I recommend publication in GI after the following minor comments have been addressed:

Minor comments

R2-C1: P2 lines 5-17. The authors could add some discussion regarding the sensitivity of the different spaceborne sensors (SMOS, SMAP, Aquarius) to RFI. SMOS is the most vulnerable due the applied imaging technique, and also because during design of SMOS, the RFI problem at L-band was not seen as acute. With SMAP, some precautions and mitigation steps could be undertaken (see Bradley et al., 2010; Misra et al., 2013). These could be acknowledged and shortly discussed.

– response to reviewer – The authors have added a brief description of the RFI detection/mitigation strategies employed by these three spaceborne L-band radiometer instrument/missions to our introduction section.

P2-3 Line 16-5 - changed text to - ‘*A* number of different hardware and processing approaches have been explored and implemented *for handling RFI intrusions for a variety of L-Band radiometer systems* (Guner et al., 2007; Forte et al., 2011; Pardé et al., 2011; Misra et al., 2009). *The SMOS mission was the first L-Band spaceborne mission launched in several decades, and thus was the least prepared for dealing with the prevalence of RFI contamination. Anterrieu and Khazâal (2011), and Khazâal et al., (2014), developed post-launch methods to flag SMOS snapshots as RFI-contaminated, by identifying outliers in temporally averaged Level L1a data, and by evaluating the kurtosis for each snapshot. These methods simply identify RFI contaminated data with no mitigation applied, and were developed specifically for SMOS due to the unique SMOS hardware and software architecture, which does not archive the radiometric signals at their highest temporal resolution, limiting standard approaches for detecting RFI contamination (Anterrieu and Khazâal, 2011). The prevalence of L-Band RFI was well-acknowledged prior to the launch of the Aquarius instrument, and thus the radiometer was designed with RFI mitigating capabilities. Le Vine et al., (2014), describe the rapid sampling ‘glitch detection’ algorithm employed by* *the Aquarius L-Band instrument that differs from SMOS by rapidly sampling the scene many times in the time required for the antenna to move half the width of an image pixel, so that potentially those samples corrupted with RFI could be identified by comparing these measurements to preset thresholds. If the samples exceed the thresholds, they are flagged as RFI and are not included in computing the mean of all measured samples for an image pixel. The recently launched SMAP mission employs a more advanced RFI mitigation technology that was not available to previous generation spaceborne L-Band radiometers, involving both space-flight instrument hardware and ground-based processing algorithms. Piepmeier et al., (2014), describe the hardware and processing algorithms of the SMAP radiometer that outputs the first four raw moments of the receiver-system noise voltage in 16 frequency channels for measuring noise temperature and kurtosis, as well as cross-correlation products for measuring the third and fourth Stokes parameters. The ground-based processing algorithms utilize several detectors to identify RFI in the frequency, time, statistical, and polarization domains measured by the instrument. These detectors are then utilized to remove the contaminated time / bandwidth portions of the observation. Therefore, the Aquarius instrument and SMAP radiometer have the ability to flag RFI affected samples, as well as mitigate the influence of RFI, and provide a measure of the level of RFI contamination.'*

R2-C2: Section 2.1, lines 10-20: could you add a block diagram of the radiometer? This would support the text which is now a bit hard to follow.

– response to reviewer – This information is proprietary to Radiometrics Inc. and is not available for publication

R2-C3: P3, lines 24-26: "Because of filter roll: : :are utilized" the sentence is a bit too complex and difficult to grasp. Please revise & clarify and maybe split in two.

P4 Line 24-27 – changed text to – *'To reduce the effects of spectral leakage from adjacent bands of strong RFI*, *the channels near the edges of the* 200 MHz receiver bandwidth are not used for analysis, and instead only 385 channels and ≈150 MHz bandwidth (1400 to 1550.5 MHz) are utilized.'

R2-C4: P7 lines 18-19: 5 K is quite a crude approximation for sky TB at L-band. While this is fine for assessing the "sky contribution" via ground reflectance to observations of surface TB, for absolute calibration purposes one would prefer to use a precise value. The authors return to this subject in section 4.1. I would suggest calculating a precise value by means of a model of sky TB at L-band. If it is not possible for this study, the authors would need to provide more justification as to why 5K is suitable. One possibility would be to apply a range of realistic values in the calibration and analyze the effects.

– response to reviewer – A range of observed and modeled sky background temperatures have been reported in the literature. These publications agree on the 2.7 K cosmic background radiation, and differ slightly on the contribution of the atmosphere at L-Band (1.5-1.9 K) and 1-3 K for the contribution of the galatic background (smoothed by large beamwidth antennas). The authors believe that the following references provide justification on the use of the 5 K temperature of the sky for use in the radiometer calibration procedure:

1. Pellarin et al. (2016) reported the average background sky temperatures of 4.44 and 4.46 K (H, V) with standard deviations of 0.27 and 0.29 K for three years of sky observations at 1200 UTC at 135° relative to nadir in a westerly direction near Grenoble, France.

2. Delahaye et al. (2002) calculated the best calibration orientation for a sky-looking radiometer at medium northern latitude would be 0° in azimuth (northward) and an elevation equal to the radiometer's latitude. They found that the computed total sky noise contribution would be 6.6 K, with 24 hour variations of ±0.2 K and a maximum bias of ±0.6 K. Their results are valid for the whole year, assuming low to moderate solar activity and no rain.

3. Le Vine et al., (2005) compared modeled and measured background sky temperatures from multiple L-Band radiometers. The observed sky background temperatures were typically between 5 and 6 K, and varied an additional 1-3 K when crossing the galatic plane.

4. Lemmetyinen et al., (2016) report that using ≈ 5 K as the reference sky temperature, the ELBARA-II showed a standard deviation of less than 0.4 K at both polarizations while measuring the sky at zenith for the entire 6 year campaign.

P8 Line 18-20 – changed text to – 'The reference sky TB at L-Band was considered to be ≈5 K for *both* polarizations *based on previously published data from both measured and modelled sources* (Pellarin et al., 2016; Lemmetyinen et al., 2016; *Le Vine et al., 2005; Delahaye et al., 2002*).'

R2-C5: . P7 lines 29-30 ": : :leading to a difference of 10 K," difference in what? The measured TB (of the ambient target) I guess, but please specify for clarity.

P8 Line 30-32 – changed text to – 'The minimum and maximum observed T_{case} values were used as inputs (-18.1 and 23.5 °C), leading to a difference of ≈10 K (269.4 K versus 259.3 K) *in the calculated* T_B *of the ambient calibration target*, highlighting the importance of applying a temperature *correction to reflect changes in the environmental operating temperatures of the radiometers*.'

R2-C6: Figure 4: please use the same range in y-axes for H and V pol figures. This would highlight larger T_NDTC and Offset peaks at H-pol. – DONE

Is there any reason for this difference between the polarizations? Perhaps this is discussed somewhere but I missed it.

P11 Line 27-28 – changed text to – *'RFI intrusions can be polarization specific, as illustrated by the differences in the dashed-green line between the H-pol and V-pol plots.'*

R2-C7 : 7. P10 lines 11-15. "Using the results: : :over course of the campaign." Very long sentence and as a result quite difficult to grasp. Please revise.

P12 Line 2-5 – changed text to – '… the smoothed results for the coefficients T_ND (0°C) and Offset(0°C) are used as a first guess, to run the inversion model again. *A* set of new calibration coefficients for T_ND (0°C) and Offset (0°C), for each date of the 16 three-target calibrations*, are produced. These coefficients are used* to correct for sensor drift of the radiometer over course of the campaign (Fig. 5: red dots - for the 1451 MHz channel).'

R2-C8: Editorial 1. Figure 4: 'T' missing in y-axis label of T_NDTC (H-pol) vs. frequency - DONE

Interactive comment on Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-27, 2016.