RFI STUDY FOR THE SMAP RADAR

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ABSTRACT

The Soil Moisture Active/Passive (SMAP) mission has the scientific objective of measuring both soil moisture and freeze/thaw state from space. The mission will make both active radar and passive radiometer measurements at L-Band in order to retrieve soil moisture. Some studies, however, indicated that these measurements are susceptible to radio frequency interference (RFI) in several geographic locations. As SMAP is a global mission and its mission life is 3 years, it is crucial for SMAP to understand the RFI over the whole globe and its temporal behavior. There will be impacts to the instrument system design and ground data processing in order to mitigate RFI. In this paper, strategies and procedures for performing this RFI study will be presented, and some results utilizing the RFI observed in the ALOS PALSAR data are described. The nature of the observed RFI is characterized and suggests some bands are relative free of RFI. The SMAP radar system will use a 1 MHz bandwidth, which can be placed within these suggested "clear" frequencies. The ALOS PALSAR data covers 28 MHz within the 80 MHz allocated for active L-Band remote sensing. In addition, an initial analysis with UAVSAR data, which uses the entire 80 MHz allocation, indicates the relative severity of RFI over the whole band. An algorithm to remove RFI is suggested and its performance is shown for some data from ALOS PALSAR and UAVSAR.

1. INTRODUCTION

The Soil Moisture Active/Passive Mission (SMAP) is one of four missions recommended by the NRC Earth Science Decadal Survey for launch in the 2010-2013 time frame. The mission is now in Phase A. SMAP will measure and monitor the soil moisture and freeze/thaw state globally with high resolution. This mission will utilize both radar (active) and radiometer (passive) measurements to retrieve soil moisture and assess the freeze/thaw state of the surface. Both instruments will be operating at L-band due to the demonstrated sensitivity of this band to soil moisture. However, the L-band frequency is widely used for ground communications, Global Positioning System (GPS) and air traffic control systems, and there are already more than 100 terrestrial radars operating in just the United States. The signals from other resources or systems that interfere with the ground return echo of the SMAP system are regarded as radio frequency interference (RFI). Studies assessing the impact of RFI on radar and radiometer systems were conducted by several previous authors [1], [2], [3]. Some reports indicated that there was significant RFI in several geographic locations around the world. RFI could be a potential issue for the SMAP mission and has the potential to contaminate or corrupt its measurements. SMAP is a global mission and its lifetime is designed to be 3 years, it is crucial to study RFI over large extensive areas and for long duration in order to characterize its behaviour and impacts. The nature of RFI could drive the instrument design of SMAP, the selection of techniques for its mitigation, as well as the data processing algorithms. This study is thus significant for the success of this mission.

2. APPROACH AND RESOURCES OF STUDY

RFI is a phenomenon that is highly unpredictable. At any instance, the possible signals that would interfere with a remote sensing measurement are largely unknown. The terrestrial radars within the range of the instrument may be on or off. Many of them are scanning, and the pointing directions are unknown at a given time. The signals from urban areas can be similarly variable. Trying to investigate this issue with a theoretical approach seems unfeasible. A more concrete approach will be using data collected from previously or currently operating missions. Fortunately, the Phased Array L-band SAR (PALSAR) on JAXA's the Advanced Land Observing Satellite (ALOS) is an L-band radar system and is currently operating and collecting data over extensive areas of the globe. JERS-1 is another L-band radar system from JAXA, and it is the predecessor of ALOS PALSAR. However, because the RFI environment will change with time as new ground radars are built and other sources evolve, the data from the more recent ALOS PALSAR will be our primarily source of data for this study. In addition, PALSAR covers a wider bandwidth (28 MHz) than JERS-1 (15 MHz) for some data collection modes, and this will allow the study to cover larger percentage of the allocated bandwidth. The potential operating band of SMAP is 80 MHz, from 1217.5 to 1297.5 MHz, and so some bands are not covered by ALOS PALSAR. It is therefore desirable to get some information over these remaining bands. The newly developed UAVSAR system [4] is operating at the full 80 MHz, and its data can provide some insight about the RFI environment in the bands outside ALOS PALSAR. However, there are limitations associated with the data from UAVSAR as it is an airborne system and has collected data over limited areas, mainly in California.

3. STUDY WITH ALOS PALSAR DATA

3.1 Properties of ALOS PALSAR Data

ALOS is Japan's new-generation Earth Observation satellite, launched in January 2006 by the Japan Aerospace Exploration Agency. ALOS PALSAR has the objective of global environmental monitoring, and its objectives and system design are given in [5]. PALSAR can be operated in five different observation modes, and the data from fine beam single polarization (FBS) mode will be used for this study. In this mode, the signal bandwidth is 28 MHz (the maximum bandwidth) among all possible modes, and the antenna look angle is 34.3^{o} which is very close to the SMAP measurement geometry. The relevant parameters of PALSAR in this mode are shown in Table 1. In addition, the corresponding design parameters for SMAP under the current design are attached for comparison.

Table 1 - Relevant system parameters of ALOS PALSAR and SMAP

Parameter	ALOS PALSAR	SMAP
Orbit	Polar, sun synchronous	Polar, sun synchronous
Altitude	691.65 km	670.00 km
Recurrence Cycle	46 days; 671 rev./cycle	3 days
Antenna Size	8.9 m x 3.1 m	6.0 m diameter (circular)
Center Frequency	1270 MHz	Tuneable within allocated band
Transmission Peak Power	2 kW	200 W
PRF	1500 – 2500 Hz	3500 Hz
Off-nadir Angle	34.3^{o}	35.5^{o}
Chirp Band Width	28 MHz	1 MHz
Swath Width	70 km	1000 km with conical scan

The orbit characteristics of ALOS PALSAR and the look angle in FSB mode are similar to SMAP, and so the slant ranges are similar for these two missions. The antenna areas are comparable to each other, and the difference in one-way antenna gain is estimated to be less than 2 dB. However, there is a factor 10 difference in the transmission power. This factor should be taken into account in evaluating the impact of RFI on the two systems. PALSAR operates in an exact orbit and it facilitates the temporal study of RFI. Some data covering the same area but separated by certain number of cycles were collected and the properties of RFI are compared. The PALSAR antenna always looks at the side looking direction and collects data along a strip of swath size 70 km. The SMAP antenna will scan conically around the nadir axis to achieve a wide swath of 1000 km. The RFI sources that influences the two systems conceivably have some variations, and we tried to minimize these differences by studying data over an extensive area approaching the swath size of SMAP.

3.2 Sites of Scientific Interest

SMAP has the objective to measure and monitor soil moisture and freeze/thaw state over the whole globe. The RFI study will be conducted for some selected sites for each continent. North America is the first to be studied, and the SMAP science team recommended some sites of interest in the United States, including Chickasha, OK, Ames, IA, Huntsville, AL, and Bakersfield, CA. To address the large swath size of SMAP, data within a square box of size 1000 km and centered on the requested sites will be collected and used for RFI study.

3.3 Analysis and Results from Chickasha, OK

The available ALOS PALSAR data over a particular site and its extended 1000 km box can be searched and acquired from the DAAC at the Alaska SAR Facility (ASF). After the L0 raw data are obtained from ASF, the frequency spectrum is evaluated and the properties of RFI are drawn from the spectral data. The steps in the resulting analysis are explained by example with data surrounding Chickasha, Oklahoma.

For this site, there are 35 data sets that PALSAR collected in FBS mode. The data are divided into 7 groups according to their geographical location, and they are shown in Figure 1. For each group, the geographic separation between data takes is less than 200 km in most cases. For groups with large separation among data sets, the spectra of the data takes are compared, and their features are found to be highly correlated. Therefore, one data take within each group is selected to be representative of that area, and more detail analyses are carried out.

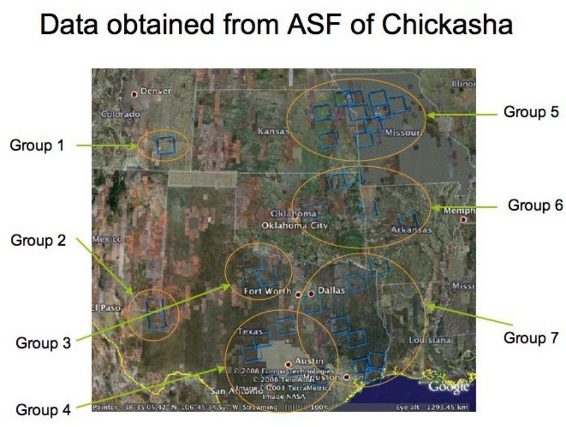

Figure 1 – Data takes of ALOS PALSAR in the area centered on Chickasha, Oklahoma, and the grouping of the data sets.

The frequency spectrum of a single raw data line is noisy due to fading effects. To reduce the noise, the spectral power is averaged over 50 lines. This number is selected in order to balance the signal fluctuations and the temporal variability of RFI. It turns out to be close to the integration time of the SMAP SAR design. The whole data set is divided into sectors with each one containing 50 lines, and the average spectrum of each line sector is generated. The spectrum of the whole data take versus line sector number (or time) is plotted, and one example from Chickasha is shown in Figure 2. The temporal variation of RFI can be observed as we move along the y-axis.

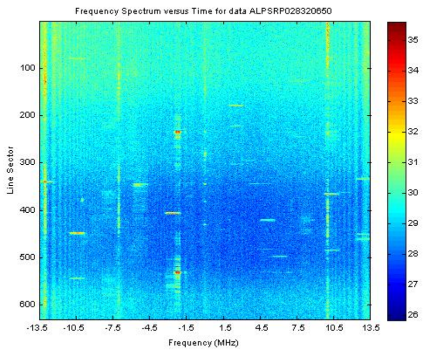

Figure 2 – Spectrum plot of ALPSRP028320650, the frequency coordinate is relative to the center frequency 1270 MHz

In the spectrum plot, some frequency bands have relatively high power and they are clearly RFI signals. It is worth noting that some RFI has short duration, but others last for the whole data take. The properties of RFI, such as the temporal variations and their time durations, will be presented in the next section.

To better locate the RFI bands, a threshold is derived from the spectrum of each line sector, and the frequency bin with power higher than this threshold will be flagged as RFI. The threshold is generated by two cycles of standard deviation evaluations. In the first cycle, all the useful frequency bins, removing the bins close to the DC regions and outside the chirp frequency band, are used in calculating the standard deviation (sigma). The bins with RFI will bias the sigma values, and they should be eliminated. Thus, the data which are outside 3 times the 1-sigma value are removed. After most of the potential RFI bins are taken away, the standard deviation of the remaining data is evaluated again. Then 3 times this new sigma will be set as the threshold for detecting RFI. The probability of detection with this threshold methodology will be discussed in the section 3.5. After RFI is identified in this way, the possible RFI free bands with bandwidth larger than 1 MHz are searched. The band is set to be larger than 1 MHz as SMAP will use chirp bandwidth 1 MHz. The result for the data take example of Figure 2 is shown in Figure 3.

After the RFI free bands for each line sector are derived, the probability associated with being “RFI free” for a particular 1 MHz band can be calculated from the data of all lines. The example for the data take sample in Figure 2 is given in Figure 4. From the plot, there are bands that have probability of being RFI free more than 80%, and they include 1265 - 1267 MHz, 1268 - 1269 MHz, 1271 - 1278 MHz, and 1282 - 1283 MHz.

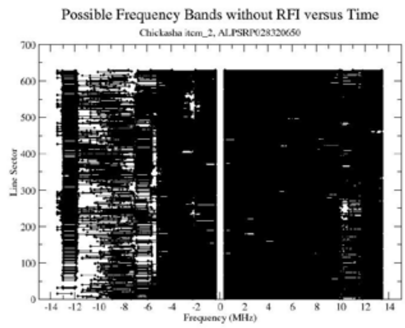

Figure 3 – Possible frequency bands without RFI for data take ALPSRP028320650

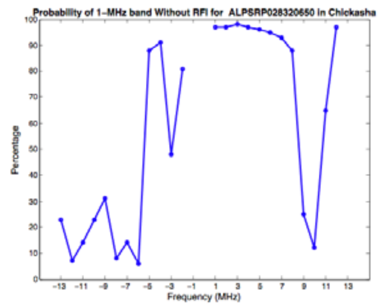

Figure 4 – Probability of 1-MHz band without RFI for data take ALPSRP028320650

The same analysis procedure is applied to the other representatives of all groups. The probability curves are generated for all selected data takes. They are shown as the dotted lines in Figure 5 for the data takes from Chickasha. The solid line is the average of all data takes, and again it shows some bands are RFI free for more than 80% of the time. They are 1266 - 1267 MHz, 1268 - 1269 MHz, 1271 - 1279 MHz, and 1282 - 1283 MHz.

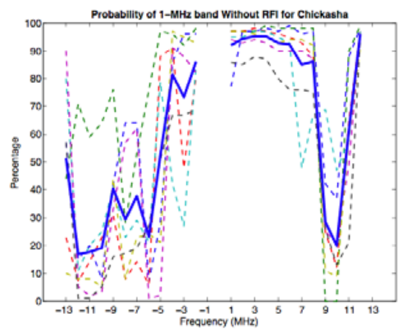

Figure 5 – Average probability of 1-MHz band without RFI for data takes in area centered on Chickasha, OK.

3.4 Results from PALSAR Data over North America Sites

Besides Chickasha, OK, some other selected sites have been studied, including Ames, Iowa and Huntsville, Alabama. Plots similar to Figure 5 are generated, and it was found that the band 1272 – 1279 MHz is RFI free for more than 80% for all these sites.

In this analysis, the 80% level is set as the probability that RFI is present. Another factor that we need to consider is the level of RFI that will degrade the SMAP measurements. From the spectrum plot, the power levels of RFI have large variations. Some of their levels are close to that of the ground return. And it is expect that their contaminations will not severely affect the accuracy of the measurements. Thus, if the band within 1272 – 1279 MHz is used, the percentage of harmful RFI will be much less 20%. This band may minimize the effect of RFI over the North America continent, but some other bands may be needed for other continents. Some international sites have been selected by the science team and this study will be carried out for these areas as well.

3.5 Characteristics of RFI

From the spectrum plot of PALSAR data (see Figure 2 as an example) some characteristics of RFI can be observed. Some RFI is consistently occurring throughout the whole data take, while some appear only in very short periods of time. Moreover, the bandwidth of the RFI can be narrow or relatively wide, from hundreds of kHz to a few MHz. In addition to the frequency domain, the properties of RFI in the time domain will be crucial too. This can indicate how many samples in a range line are affected and the relative power between RFI and the ground return. In Figure 2, the 1 MHz frequency subband at +10 MHz from the center frequency of PALSAR contains significant RFI over the whole data set. The raw data are filtered to isolate this band and are range compressed. The images of 1000 lines at the start and in the middle of the data take are shown in Figure 6.

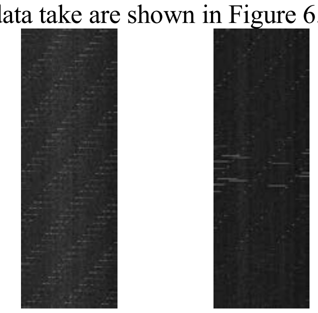

Figure 6 – Range compressed images of frequency filtered subband data. The selected 1 MHz subband is +10 MHz offset from PALSAR center frequency. The left image is for lines 1 to 1000, and the right image is 17701 to 18700.

The Figure shows that a single RFI source appears to exist in this subband and persists until line 3500 (about 2 seconds), only 1000 lines are shown for better visualization. The RFI shows up in every 5 range lines. With a PALSAR PRF of 1919.386 Hz for this particular data set, the PRF of the RFI is close to 400 Hz, in fact it is less as the consecutive appearance is shifted to later time. The pulse width of the RFI is very consistent and is about 64 μs.

In the middle of the data take, an RFI source with long pulse width, 72 μs, shows up for a short duration, less than 150 lines. Another RFI with short pulse width, about 6 μs, endures more than 2000 lines (or 1 second), and again appears in the data in every 5 range lines.

In Oklahoma and the United States in general, there are a set of terrestrial radars, the ARSR systems, operating in the SMAP allocated bandwidth, 1215 – 1300 MHz. The characteristics of these radio-location systems are documented [6]. The RFI characteristics derived from PALSAR data will be compared with the properties of ARSR systems. If RFI sources can be identified, the SMAP radar can be adjusted to operate in 1 MHz frequency band different from these sources.

The ARSR systems have powers ranging from 45 kW to 5 MW. The large variations of RFI power can also be observed from the range compressed images, some lines with a sequence of very bright RFI pixels and some relatively dim. In the case where the RFI power is at the same level as the ground return or lower, they cannot be separated by power comparison. Thus, the detection mechanism that was shown before will ignore some RFI. The SMAP system engineering team is developing a detection algorithm based on the statistics of the echo data, and the RFI and ground return should be differentiable as long as they carry different statistics. This algorithm will be used to determine the power distribution of RFI. With known RFI power distribution, the probability of detection of the current mechanism can be evaluated.

4. UAVSAR DATA ANALYSIS

4.1 Information of Other Bands

The FBS data from ALOS PALSAR has a bandwidth of 28 MHz -- from 1256 to 1284 MHz. It does not cover the whole 80 MHz bandwidth that SMAP can utilize. It would be helpful if the RFI characteristics in the other portions of the allocation could be examined. However, there is no spaceborne remote sensing system that is operating in this entire band.

The newly developed JPL airborne UAVSAR operates at L-band and uses the full 80 MHz bandwidth. Recognizing that it is an airborne system, the RFI environment will be different from a spaceborne one, however the data may provide us some insight into the properties of RFI over the whole band, or the relative frequency of RFI in different bands. In Figure 6, a frequency spectrum plot of one UAVSAR data take is shown.

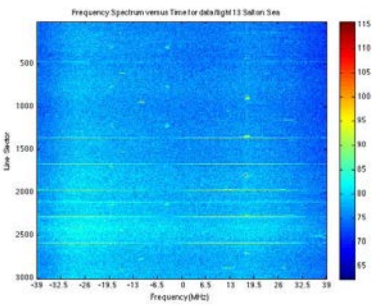

Figure 6 – Spectrum plot of data take from Flight 13 over the Salton Sea, the frequency band is relative to the center frequency 1257.5 MHz.

From data sets that clearly include some RFI effects, most of the RFI is found within the ALOS PALSAR band, and they happen intermittently in most cases. Up to now, UAVSAR has mostly collected data over California. When its flights are extended to other area, they will provide additional information to characterize the behaviour and properties of RFI.

5. ADJACENT LINE REPLACEMENT ALGORITHM FOR RFI REMOVAL

Besides the detection of RFI, some methodologies to remove RFI are considered. In SAR processing of the GeoSAR system, a range line will is replaced by an adjacent line if some pixels in that line have power larger than a threshold for RFI detection. This algorithm is modified and the replacement will not be a whole range line, but only certain range bins with power higher than the RFI threshold. This algorithm is a potential candidate for SMAP, and some evaluations are performed with PALSAR and UAVSAR data. As the integration time of SMAP is 35 ms, corresponding to about 120 pulses for a PRF of 3500 Hz, unfocused SAR processing will achieve good approximation to the best resolution.

5.1 Evaluation of Adjacent Line Replacement Algorithm

For PALSAR data, the raw data is frequency filtered with a specified subband of 1 MHz bandwidth. Then, the data are range compressed, and the unfocused SAR image is generated. The unfocused SAR aperture size is 100 lines and it gives the resolution 350 m for PALSAR system, emulating the SMAP parameters. The mean power of each data block is evaluated and the RFI threshold is set to be 3 times (4.7 dB) of the mean power. In image formation with RFI removal, all pixels in a particular range bin are considered. If the power of a pixel is higher than the threshold, it will be replaced by the pixel of next line. The comparison with and without RFI removal for a PALSAR 1 MHz subbanded data take from Figure 2 is shown in Figure 8.

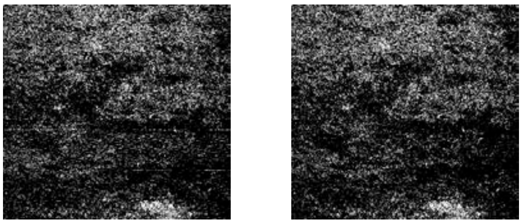

Figure 8 – Comparison of unfocused SAR images from PALSAR without and with adjacent line replacement algorithm. Left is without removal, and right applies the removal.

The RFI showing up as stripes in the upper right corner are removed as indicated by a comparison of the two images. Moreover, some clear bright horizontal lines disappear in the image with removal.

For UAVSAR, the same algorithm is tested with the data from flight 09001 imaging the Rosamond area in California. From the range spectrum, RFI is clearly indicated. The improvement with the removal algorithm can be observed from in the images in Figure 9.

Figure 9 – Comparison of unfocused SAR images from UAVSAR without and with adjacent line replacement algorithm. Left is without removal, and right applies the removal.

The bright lines near the center of the left image indicate strong RFI. Owing to its high power, the array of corner reflectors is dim and difficult to identify. With removal, the high power RFI streaks disappear and the corner reflectors are clearly observed.

From these tests, the potential improvement associated with this algorithm is demonstrated. Some other algorithms are also under considerations and their performance will be evaluated in future studies.

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