THE DETECTION AND MITIGATION OF RFI WITH THE AQUARIUS L-BAND SCATTEROMETER

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ABSTRACT

The Aquarius sea-surface salinity mission includes an L-band scatterometer to sense sea-surface roughness. This radar is subject to radio-frequency interference (RFI) in its passband from 1258 to 1262 MHz, a region also allocated for terrestrial radio location. Due to its received-power sensitivity requirements, the expected RFI environment poses significant challenges. We present the results of a study evaluating the severity of terrestrial RFI sources on the operation of the Aquarius scatterometer, and propose a scheme to both detect and remove problematic RFI signals in the ocean backscatter measurements. The detection scheme utilizes the digital sampling of the ambient input power to detect outliers from the receiver noise floor which are statistically significant, and flags nearby radar echoes as potentially contaminated by RFI. This detection strategy, developed to meet tight budget and data downlink requirements, has been implemented and tested in hardware, and shows great promise for the detection and global mapping of L-band RFI sources.

***Index Terms*—** Electromagnetic radiative interference; Radar data processing.

1. INTRODUCTION

The Aquarius/SAC-D sea-surface salinity mission, scheduled to launch in mid 2010 for a 3-year measurement campaign, includes both an L-band radiometer and scatterometer sharing a common aperture, and maps the ocean surface with three independent beams in a "push-broom" configuration. The scatterometer senses sea-surface roughness to provide a radiometric correction to the radiometer's measurement of ocean surface emissivity, thus allowing the estimation of salinity from the corrected brightness temperature [1]. Both sensors are subject to RFI in their respective L-band wavelengths (1400-1427 MHz for the radiometer, 1258-1262 MHz for the scatterometer), which must be considered in the design of the instruments. The mitigation of the RFI environment for the radiometer has been documented elsewhere [2,3]. Here, we estimate the level of difficulty posed by the RFI for the scatterometer, and describe the methods implemented for its detection and mitigation.

In order to meet the requirements levied on the scatterometer (~0.05 dB in power over 6 seconds of integration time), any non-radar-echo power into the antenna must be below about -145 dBW for a strong ocean backscatter signal, and -155 dBW for a weak ocean backscatter signal. How large a signal can we expect from terrestrial sources?

2. EXPECTED RFI ENVIRONMENT

In 2004, the Aquarius and Hydros [4] projects commissioned, with the NASA Earth Science Spectrum Management Office, an RFI environmental study to understand, quantify, and mitigate RFI generated by ground radars on the two orbiting instrument systems. Realistic beam patterns, orbit geometry, and instrument characteristics were used for modeling the Aquarius Instrument, both radiometer and scatterometer subsystems. A large sample of non-classified North American radars that transmit at L-band was included in the analysis. This yielded about 180 RFI sources, mostly air traffic control and air defense radars, with a wide variety of peak powers, pulse rates, scan rates, beam widths, and frequency-hopping characteristics, as shown in Table 1. Although all these sources are located on land, they can be seen by the Aquarius Instrument as soon as they appear over the horizon as observed from the satellite (approximately 3000 km distant). And although no main-beam to main-beam viewing occurs, the main beams of the RFI sources pass through the side-lobes of the three Aquarius antenna beams. The Aquarius main beams also view the side-lobes of the ground radars, but this always occurs over land, thus not affecting the ocean salinity measurements.

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Table 1. Most Numerous RFI Sources Used in Model

Radar name	quantity	peak power (KW)	average power (KW)	horiz BW (deg)	Scan Rate (RPM)	PRF 1 (Hz)	PRF 2 (Hz)	Pulse width 1 (µs)	Pulse width 2 (µs)
FPS-117	31	24.8	4	2.2	5	340	748	51	410
FPS-124	39	7	.14-.70	2.5	10	3000	1000	6.5	95
ARSR-1&2	40	4000	2.9-3.3	1.2	6	360		2	
ARSR-3	14	6500	3.3	1.1	5	310	364	2	
ARSR-4	42	65	3.3	1.4	5	216	72	150	151

Unlike the radiometer, which operates in a nominally protected RF band, the scatterometer operates in a shared radar band full of terrestrial sources. We assume that the modeled U.S. sources are typical of similar radars used worldwide, and that U.S. and foreign military radars, as well as mobile and marine radars, are rarely more powerful than these. Note that the average power levels of most of the radars are similar (3-4 KW), even though peak powers differ by several orders of magnitude.

These radars exhibit short, high-power pulses at one or more pulse repetition frequencies (PRFs), with a main beam 1-2 degrees wide sweeping by a target every 6 to 12 seconds. Some radars frequency hop, either by pulse or by scan, within the range of 1220-1390 MHz. Thus, Aquarius may see RFI within the 60-150 ms envelope of the RFI main beam as it sweeps by Aquarius. During this interval, Aquarius will see peak power spikes every 1-14 ms, each lasting from 0.002 to 0.4 ms. Since the three Aquarius beams have receive windows of 1.8 to 2.3 ms and a PRF of 100 ms, Aquarius may very well see one or more RFI pulses within a receive window.

The RFI model uses average transmit power, rather than peak power, due to the 10 ms time resolution of the RFI simulation. Realistic radar heights, beam elevations, and terrain models were used in the simulation. Ground radar beam patterns were not available, so conservative assumptions were made for the ground radar side and backlobe profiles. In contrast, a detailed Aquarius instrument gain and beam pattern model was used for each of the three beams.

Figure 1 shows a 23-minute portion of the orbit, beginning over the Pacific Ocean and heading northward over Alaska. Aquarius looks towards the right, towards the continental U.S with its RFI sources. The RFI sources used in the simulation are shown with an X. Figure 2 show a time series of RFI power into the scatterometer's three beams. Several features stand out:

1. Over land, RFI is much higher than over ocean. The RFI peaks occur when the RFI sources enter the main Aquarius beam and traverse the moving ground footprint (it takes roughly 15 seconds for a target to cross the 3-dB footprint). These RFI features, with peaks up to –85 dBW, are not a problem for Aquarius' ocean measurements, as the instrument is viewing land at the time.

2. Over the ocean, the strongest RFI appears as "grass". This grass is typically 15-25 dB "high", and varies in strength with time and beam. The grass occurs as the strongest RFI sources are scanning by Aquarius. The grass can reach power levels of -105 dBW, although further from land it appears 10 dB weaker.

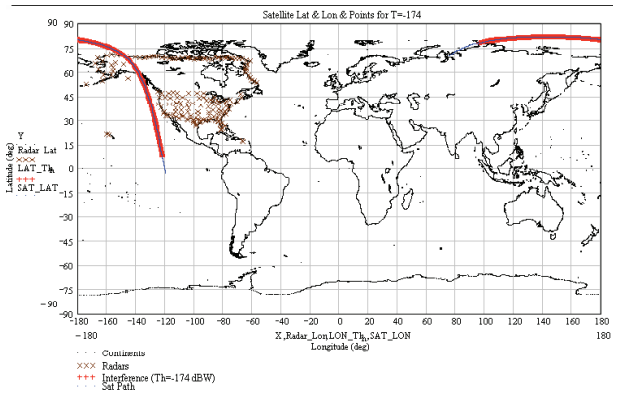

Figure 1. Model Aquarius trajectory and U.S. RFI radar sources.

3. Below the grass is a thick background of RFI "soil". This consists of the weaker RFI source main beams together with the RFI source backlobes. The soil can reach a level of -125 dBW, though it is usually lower.

4. The three radar beams see different sources at different times, but the overall power levels are similar. And in many cases, a strong RFI source affects all three beams at the same time.

5. Due to various approximations made in generating the simulation, the absolute predicted power levels are

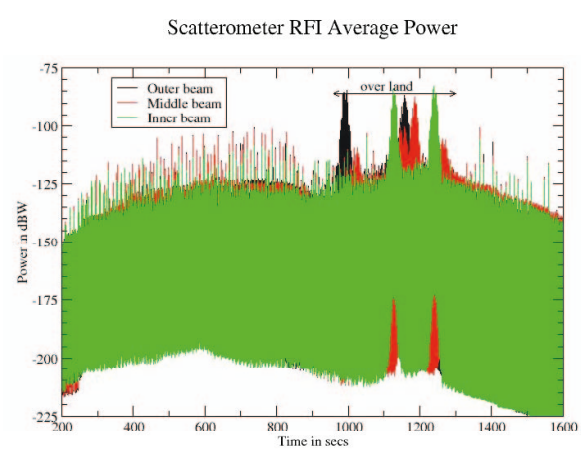

Figure 2. Predicted RFI power over model trajectory.

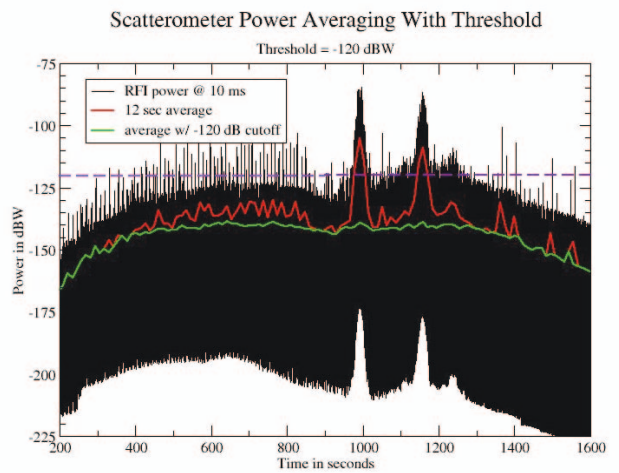

Figure 3. Effects of time averaging and outlier removal on RFI power.

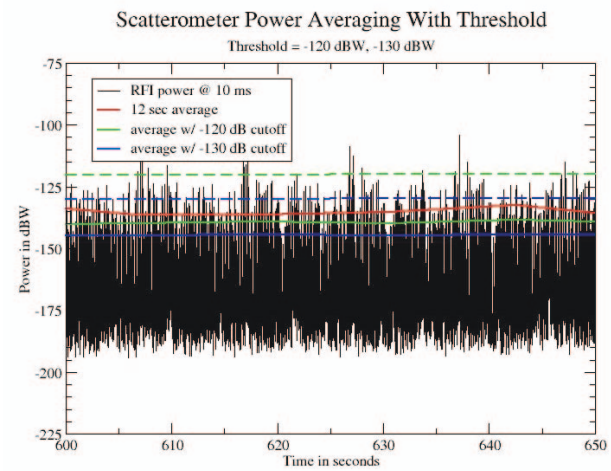

Figure 4. Closeup of RFI "background" showing effects of time averaging and outlier removal on average RFI power.

probably accurate to no better than 5 dBW, but the relative power levels should be more reliable.

Since any RFI over -145 to -155 dBW will impact the recovery of surface roughness and the brightness temperature correction, it is clear that even the background RFI at -125 dBW will be a problem for the scatterometer.

3. RFI MITIGATION AND INSTRUMENT DESIGN

We employ several approaches to detect, mitigate, and remove RFI from the scatterometer data. The first is the simple time-averaging of the measurement data on the ground. Aquarius data collected at the instrument pulse repetition interval (PRI) of 10 ms will be averaged down to intervals of 5.76 seconds in order to reduce thermal noise and scintillation. This averaging by itself tends to reduce the mean RFI power of the continuous fluctuations noted above by at least 10 dB.

A second approach is to attempt to flag any RFI with a level above the receiver noise floor of -130 dBW, and remove any contaminated echoes before generating the 5.76-second average described above. Figure 3 illustrates the effects of time averaging the RFI power, both with all the data used in the average and with only data below a cutoff threshold used. (This figure shows one sample analysis with a 12-second average and a -120 dBW cutoff.) Figure 4 shows a closeup of the RFI "grass" and background, with various cutoff thresholds. By excluding all RFI with average power greater than -130 dBW and time averaging for 6-12 seconds, the average RFI power can be reduced, even over land, to a level of -145 dBW. This level of residual RFI power is acceptable for strong ocean returns, but is still about 10 dB too high for weak ocean returns. Unless more complex RFI detection and excision is implemented, there is a chance that the brightness temperature corrections for a relatively smooth ocean will be degraded near low-level RFI sources.

Unfortunately, we do not have the bandwidth to downlink measurement data at the digital sampling rate of 16 MHz, which would give us tremendous flexibility in detecting and removing RFI using ground algorithms. We are instead averaging the received power over the ~2 ms receive windows onboard, and downlinking these values. Yet the digital sampling hardware allows a simple method of flagging those 2-ms pulses for RFI contamination.

We have implemented a programmable threshold detection system in onboard logic [5] that can sense RFI peaks within a "noise-only" (no transmit) measurement and flag that measurement as contaminated. This system allows us to specify both the power level of RFI and the length of the RFI pulse to flag; as long as these two parameters do not allow receiver thermal noise to generate false positives, we can detect most of the RFI sources indicated as problematic in the RFI study. This concept is illustrated in Figure 5, where a sinusoidal low-level RFI signal is embedded in the Gaussian noise floor; with the correct detection threshold and trigger count, the RFI may be detected with very little processing overhead. No data are actually removed onboard, so all radar data can be reexamined on the ground for consistency with the flagging and characterization of the RFI signal. In addition to providing flags to mitigate the contribution of RFI to the radar backscatter measurements, we essentially have the ability to map RFI sources with diverse characteristics at 1260 MHz around the globe.

Recall that we wish to flag RFI whose average power is -130 dBW. Since peak RFI power is at least 10 dB higher than this average, short-duration pulses with peak amplitude > -120 dBW must be flagged. These signals yield a 14-mV rms signal in the Aquarius analog-to-digital converter (ADC). The receiver noise floor at -130 dBW yields a 5-mV rms signal. Thus, a detection threshold set at 14 mV, or 7 ADC counts, is about 3 sigma above the noise. For a Gaussian noise floor, about 0.3%

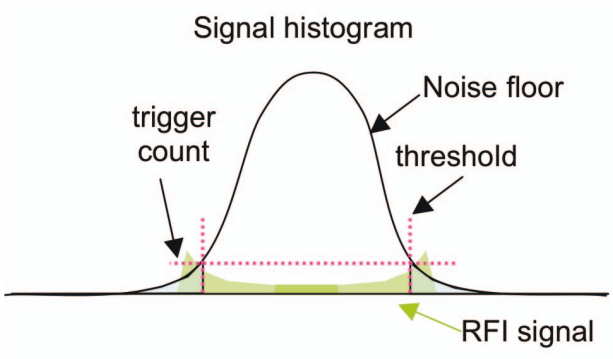

Figure 5. RFI detection model: sensing a low-level CW signal within a Gaussian noise envelope.

of samples will exceed this 3-sigma level. For a 2-ms receive window, less than 100 ADC samples should exceed this threshold. Since most RFI sources have pulse lengths of about 0.1 ms, or 1600 ADC samples, but only half the samples exceed the rms voltage levels, we set the trigger count at about ¼ this value, or 400 ADC samples. This provides sensitivity to shorter pulses with a negligible false-alarm rate. This nominal set of parameters (7 counts, 400 samples) is our default set of RFI detection parameters. Other sets – for example, one to detect the shortest but higher power RFI pulses we expect (9 counts, 16 samples) – may be commanded from the ground.

Another complicating factor is the sequencing of the scatterometer as it cycles through measurements for 3 beams, 2 transmit and receive polarizations, and a series of noise-only reference measurements. We have chosen to apply the RFI detection test only to the noise-only measurements so that radar echoes are not flagged as RFI, and to intersperse the noise-only measurements as closely as possible to the same beam and polarization echo measurements. This allows us to have an RFI detection window within ~10 ms of every ocean echo, enabling the excision of corrupted echoes from the ~6-second averages. If the RFI source exhibits pulse-to-pulse frequency hopping, than the utility of the RFI flag is reduced. Rather than allowing us to excise specific measurements, the flag allows us to map regions of the Earth with problem L-band RFI. All scatterometer data in these areas can then be viewed with caution as potentially contaminated with RFI. This global mapping ability is in-and-of-itself a useful capability of the Aquarius instrument.

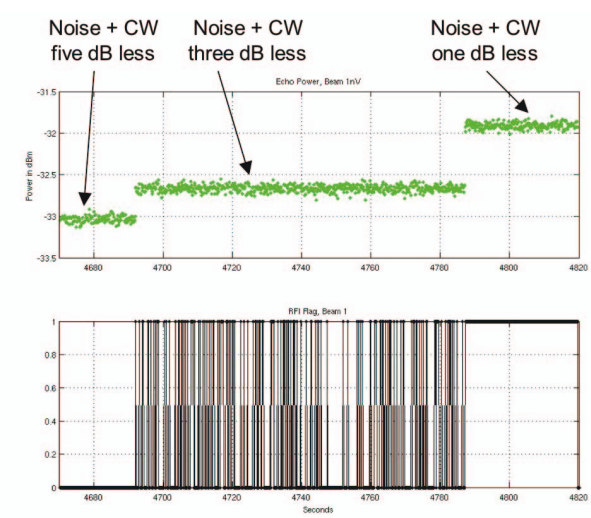

Figure 6. Signals (above) with increasing power trigger RFI flag (below).

Figure 6 shows an example in instrument testing where the RFI flag has been set off by small signals embedded in the noise floor. In this case, the added sinusoidal signal is stepped up in power from 5 dB below the noise floor to 1 dB below the floor. By studying the statistics of the RFI flag as a function of injected power, we can refine the statistics of our model for RFI detection.

4. CONCLUSIONS

We have implemented in the Aquarius scatterometer processing hardware a method to detect and flag problematic RFI. These RFI flags are downlinked along with all measurement data to the ground, for use in creating averaged measurements with the RFI removed. The detection parameters are programmable and can be revised and uploaded after launch to provide more or less sensitive flags for RFI, or to detect and map different types of RFI sources. Indeed, L-band global RFI maps may be a useful ancillary product from Aquarius.

The RFI flags generated by the scatterometer may be useful to the radiometer. Although RFI is expected to be less of a problem for that instrument (it operates in a protected RF band), encroaching or unlawful RFI transmissions may appear both in the scatterometer RFI flag and in radiometer data. Thus the RFI flag can be a warning to the radiometer.

5. REFERENCES AND ACKNOWLEDGEMENTS

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