Compatibility Tests Between the Mars Vehicle System Test Bed and RIMFAX Radar Antenna Prototype for the Mars 2020 Mission

Edward Gonzales, Edward.C.Gonzales@jpl.nasa.gov
Elizabeth Cordoba, Elizabeth.C.Cordoba@jpl.nasa.gov
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, United States

Svein-Erik Hamran, Svein-Erik.Hamran@ffi.no
Forsvarets forskningsinstitutt
Kjeller, Norway

***Abstract*—NASA's Mars 2020 rover will carry a wideband (150 MHz to 1200 MHz) ground penetrating radar—RIMFAX, contributed by FFI of Norway—to survey the subsurface geology of Mars. RIMFAX will take radar soundings while the rover drives across the Martian terrain, which presents possible compatibility issues between rover and radar operations. In order to study this risk, a prototype RIMFAX antenna was attached to the flight-analogous rover Vehicle System Test Bed (VSTB) in a mechanically representative location. The prototype antenna collected spectral and time-domain data across a variety of driving operations in order to assess the radar sensitivity to rover-generated noise. Conversely, the prototype antenna was driven while an engineering-model UHF antenna used for rover telecom measured received in-band power to ensure that the rover hardware was not at risk of damage. Evaluation of the data by the instrument science team showed that while rover noise was apparent to the receiver, data post-processing would yield >40 dB margin to the science requirements. Similarly, power levels received by the UHF antenna were well below damage thresholds.**

I. INTRODUCTION

NASA's Mars 2020 rover will carry a suite of new and upgraded scientific instruments to Mars in support of the mission's scientific objectives to determine the habitability of Mars, look for signatures of existing or once-existent life, cache samples of Martian material for possible future return to Earth, and develop technology in preparation for future human exploration.

Among these new instruments is the Radar Imager for Mars' subsurFace eXperiment (RIMFAX) ground penetrating radar (GPR) provided by Forsvarets forskningsinstitutt (FFI) in Norway. RIMFAX seeks to understand the subsurface geology of Mars down to 10 meters below the surface. As the rover traverses the Martian surface, the instrument will transmit frequency modulated continuous wave (FMCW) pulses from 150 MHz to 1.2 GHz and measure the characteristics of the reflected waveforms [1].

The wide operating frequency range of the RIMFAX instrument presents a potential EMC challenge in that RIMFAX can be susceptible to rover emissions as well as interfere with the operations of other rover systems as a result of its radar transmissions. The Mars 2020 rover, which derives heritage from the Mars Science Laboratory (MSL)—or Curiosity—rover currently on Mars, contains many electrical subsystems in the form of flight computers, avionics, cameras, power converters, and motor controllers. These subsystems and their interconnecting harnesses constitute a significant RF noise source that may interfere with radar operations. Conversely, a secondary concern arose that since RIMFAX will be a new RF transmitter on the rover, existing rover subsystems may not have demonstrated compatibility with the new resulting environment. Additionally, part of the frequency band used by RIMFAX overlaps with that of the rover's sensitive Electra UHF radio. Although rover operations will preclude concurrent operation of RIMFAX and Electra, concern arose about possible damage to the UHF radio while powered off if received power exceeded 0 dBm at the receiver center frequency.

Both FFI and JPL proposed risk reduction tests in order to determine if a GPR, as proposed, could meet its science requirements without risk to rover systems. FFI provided a prototype RIMFAX antenna for JPL to use for these risk reduction tests. JPL engineers determined that the most representative noise source for characterization was the rover Vehicle System Test Bed (VSTB), which contains engineering model (EM) or flight-spare versions of hardware flown on the MSL rover.

This paper will also briefly describe a radar figure of merit called System Dynamic Range (SDR) that is used to quantify the impact of noise to radar performance. So long as SDR remains above 100 dB for the RIMFAX radar in the rover electromagnetic environment, science objectives are not expected to be limited by noise.

II. TEST SETUP

The VSTB at JPL is housed in the "Mars Yard," which provides a Mars-like environment where in situ driving and instrument tests can be performed prior to uplinking commands to the actual rover. In order to perform any RF tests on the VSTB, an RF shielding tent was necessary to reduce the effect of numerous nearby transmitters within the RIMFAX operating band of 150 MHz to 1.2 GHz. Within this frequency range are the powerful nearby TV transmitters that service much of Los Angeles, cell phone base stations, and cell phones in close proximity to the rover (Fig. 1). The tent was also necessary to contain fields and prevent interference to nearby RF receivers when the RIMFAX antenna was transmitting. Therefore, a custom RF tent was designed and built to fit within the confines of the Mars Yard garage while also having sufficient space for the rover to make small driving motions: +/- 2ft forward and backward, +/-25 degree swivels. In order to maximize shielding effectiveness, aluminum plates were also necessary to cover the floor of the tent. Continuity between the bottom of the tent and the aluminum plates was ensured by placing weighted tubes along the periphery of the tent. The red trace in Fig. 1 shows that while the tent did not completely eliminate ambient noise, it significantly reduced it, yielding between 25 and 35 dB of shielding. While sufficient for the purposes of the test, shielding was limited by the pass-through of large rover support equipment, allowing for potential gaps in the tent-to-ground closure and allowing for a coupling path from the tent exterior to interior by common mode coupling of exterior RF signals.

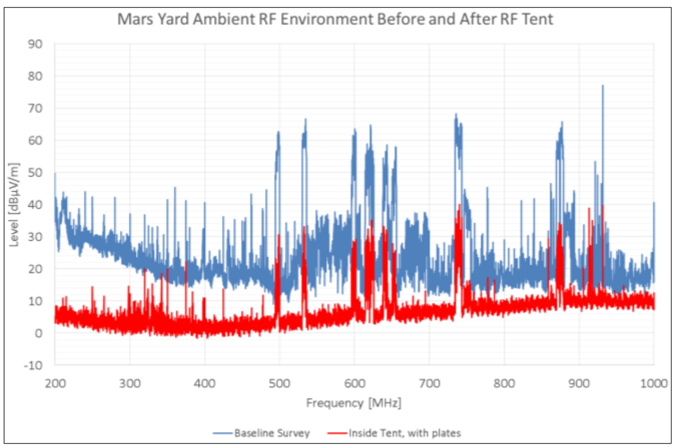


Fig. 1 RF environment in Mars Yard Garage without RF tent

The prototype antenna was mounted to the rover with a custom mounting plate (per direction from FFI that small holes could be drilled into the antenna with no effect to its performance) (Fig. 2). RF absorber was placed near the rear of the rover in order to mitigate the effect of reflections and standing waves.

When collecting data through the RIMFAX antenna (RIMFAX as victim), the spectrum analyzer was configured to capture data with parameters that most-closely emulated the RIMFAX electronics. A comparison of actual and achieved sounding mode parameters can be found in Table 1 and Table 2 respectively. Time domain scans were taken with a 2 GHz oscilloscope. As a control during RIMFAX-receive tests, a calibrated log-spiral test antenna for which gain parameters were very well known collected data under identical operating conditions. Data from this antenna was used to control for the effects of the test setup and provide a comparison to previously-conducted tests on the MSL flight rover.

The rover operated through a variety of drive modes in order to envelope the noise characteristics of various surface operations. The rover drove at

When transmitting through the RIMFAX antenna, a signal generator was connected directly to the antenna. The signal generator was set to transmit at the nominal transmit power of RIMFAX, +20 dBm (limitations from VSWR limited actual power to ~19 dBm). As with tests with RIMFAX as victim, transmit modes were matched as closely as possible to emulate the RIMFAX duty cycle, frequency, and sweep speeds. Due to limitations in the number of sweep steps in the signal generator, the transmitted sweep spectrum was highly discretized but allowed for a reasonable sampling of RF behavior over a wide band of frequencies.

Applicable rover telemetry was collected when appropriate. 8 Hz power bus telemetry was taken during RIMFAX-transmit events to evaluate the effect of the RIMFAX on the rover. Additionally, during tests where the RIMFAX prototype antenna were transmitting and the rover was driving, 512 Hz telemetry was collected from the rover's motor controller to evaluate the health of the mobility systems. Mobility systems were of special interest given the operational concurrency of the rover motors and RIMFAX soundings along with the close proximity of some motors to the RIMFAX antenna. In order to determine the effect of radar soundings on nearby Hazard-Avoidance Cameras (HazCams) that may also operate concurrently, rear HazCam images were taken during transmit events and analyzed for anomalous data.

The risk of RIMFAX transmissions coupling excess power into the nearby UHF antenna was evaulated by placing a breadboard (prototype) UHF antenna in a representative location near the rover. The UHF antenna was then connected to a receiver scanning in the general range of the Electra UHF radio (400 MHz to 500 MHz).

The VSTB was configured to emulate surface mode operations that were similar to those during MSL self compatibility testing, for which there is data to compare and so differences in emissions profiles can be attributed to test setup.

TABLE 1. ACTUAL RIMFAX SOUNDING MODE PARAMETERS (TABLE BY FFI)

RIMFAX Sounding Modes					
Mode Name	**Frequency band (MHz)**	**Sweep time (ms)**	**Sweeps averaged per sounding location**	**Samples after downsampling**	**IF BW (kHz)**
Shallow Sounding	150-1200	1.0	100	1450	725
Deep Sounding	150-450	2.5	40	1250	250
Deep Sounding Ex 2	150-450	20	5	3500	87.5

TABLE 2. ACHIEVABLE RIMFAX PARAMETERS WITH RECEIVER

Test Receiver Settings					
Mode Name	**Frequency band (MHz)**	**Sweep time (ms)**	**Sweeps averaged per sounding location**	**Samples after downsampling**	**IF BW (kHz)**
Shallow Sounding	150-1200	10	10	1401	500
Deep Sounding	150-450	10	10	1251	300
Deep Sounding Ex 2	150-450	20	5	3501	50

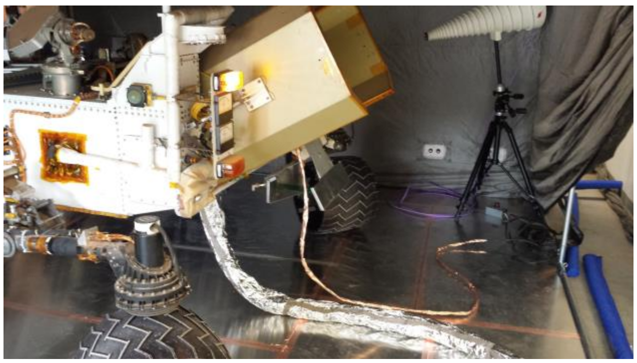


Fig. 2 RIMFAX antenna mounted on VSTB. External log-spiral antenna used as control shown on right.

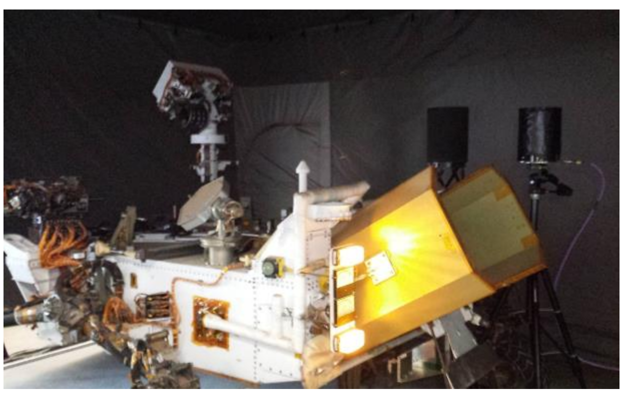


Fig. 3 UHF breadboard antenna (far right black cylinder) adjacent to mock-UHF antenna for RIMFAX transmit test

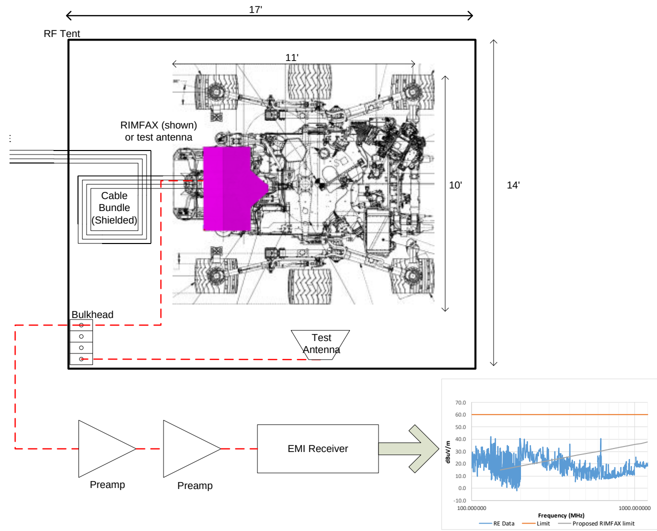


Fig. 4 RIMFAX receiving setup with rover inside RF tent

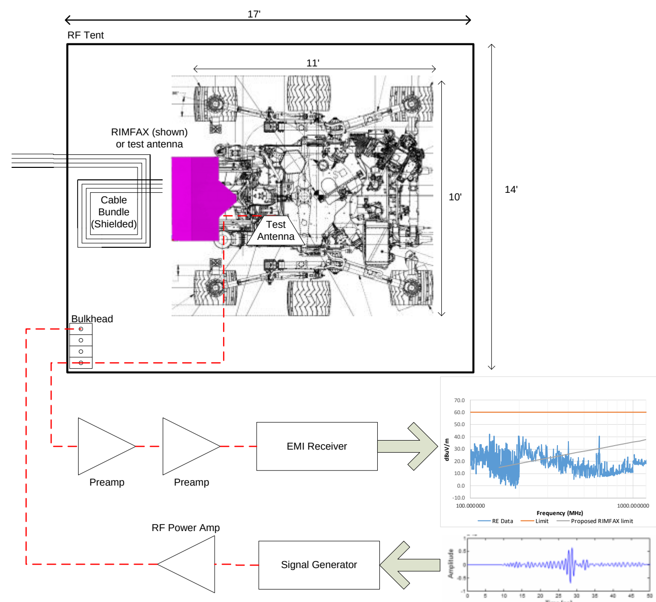


Fig. 5 RIMFAX transmitting setup with rover inside RF tent

III. TEST RESULTS

A. RIMFAX receiving

As an initial check to determine the effect of the test setup on measurements, radiated emissions (RE) data from the VSTB and MSL flight rover were compared in order to help understand the differences in EMI environment (Fig. 6). Equivalent flight systems were enabled so that the differences could be traced to the unique configuration of the test bed, in particular the use of ground support equipment (GSE) umbilical ("plugs-in") and non-flight electronics/chassis RF sealing. A plugs-in condition is considered worst-case in terms of radiated noise due to the presence of numerous noise generators in the

GSE racks. Additionally, due to the use of many off-the-shelf components in the GSE over which limited control may be afforded to grounding, uncontrolled common mode noise currents may couple onto harness shields and radiate inside the tent. MSL plugs-in vs. plugs-out RE data in the UHF band is consistent with the difference observed in Fig. 7 and corroborates this theory: a difference in spurious emissions between plugs-out and plugs-in of 25-30 dB. Difference in the noise floor between VSTB and MSL can be traced to differences in measurement technique.

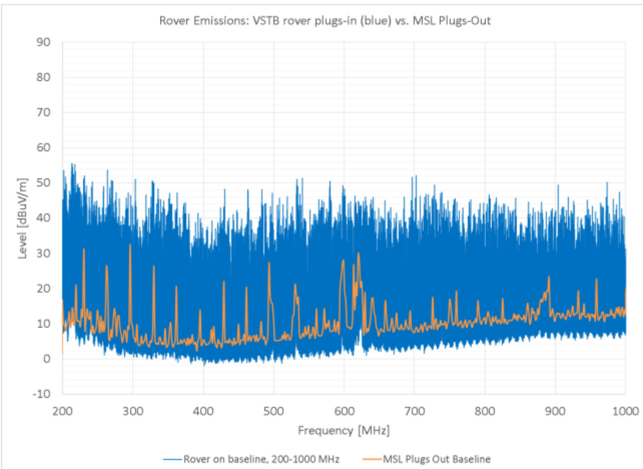
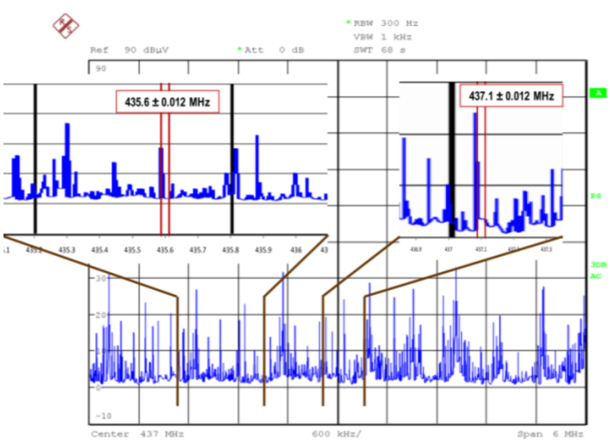
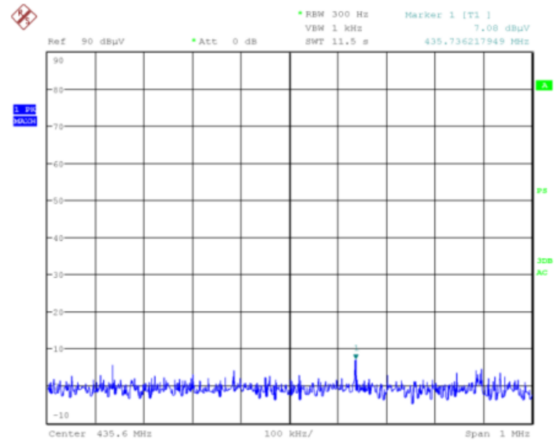


Fig. 6 VSTB emissions (plugs-in) vs. MSL Plugs-Out



(a)



(b)

Fig. 7 (a) MSL Plugs-In vs. (b) MSL Plugs Out

There is an observable but very small difference in the rover driving vs. stationary emissions when viewed from an antenna external to the rover at approximately 1 m distance (Fig. 8). This result is consistent with previous data on MSL wheel actuators that show radiated emissions exceeding the measurement noise above 200 MHz are relatively small, even at operating currents many times that on the actual rover (Fig. 9). This result is consistent throughout the test with different antennas and measurement parameters, leading to the conclusion that the act of rover driving results in a negligible difference vs. rover stationary in the frequency range of the RIMFAX instrument.

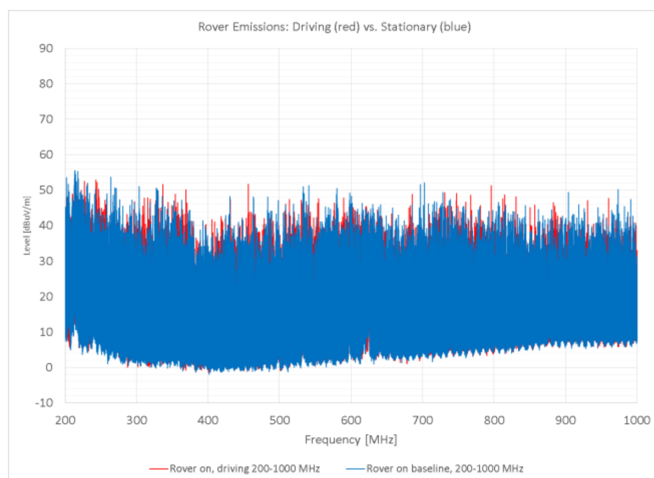


Fig. 8 Rover Radiated Emissions: Driving (red) vs. Stationary (blue)

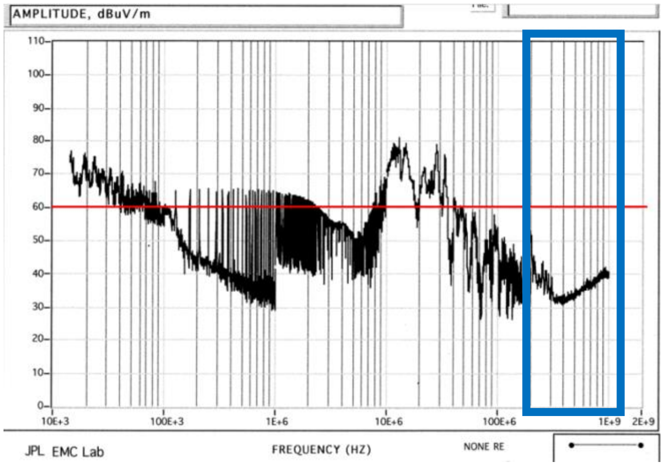


Fig. 9 MSL wheel actuator radiated emissions at 10 times nominal current, RIMFAX range in blue box

The limiting factor for the weakest signal the RIMFAX receiver can detect is the thermal noise given by the first amplifier in the receiver chain. The measured noise generated by the rover is shown in Fig. 10 (a). The bottom of the blue trace at -110 dBm and gently rising to the right is the thermal noise of the preamplifier used in the test. The line spectrum above the thermal noise of the test preamp is the noise generated by the rover. The measured spectrum is amplitude only. Assigning a random phase to the each sample in the spectrum and transforming the spectrum to the time domain gives an RMS average value of -99 dBm, as observed in Fig. 10 (b). The theoretical thermal noise in the RIMFAX receiver is -109 dBm. The rover increases the RIMFAX receiver noise level by 9 dB in the Shallow Sounding operating mode and has an impact on radar performance.

The increase in the overall thermal noise level will decrease the System Dynamic Range (SDR) of the RIMFAX radar system, the figure of merit for its radar performance. The SDR of a radar system is given by [1]:

$$SDR = \frac{P_T N_F G^2}{2 k_B T_0 F B_{IF} (SNR)}$$

where P_T is the transmitted power in watts, N_F is the number of integration points, G is the dimensionless gain of the radar antenna, k_B is Boltzmann's constant (1.38E-23 $m^2kgs^{-2}K^{-1}$), T_0 is the effective noise temperature of the system in Kelvin, B_{IF} is the receiver IF bandwidth in Hz, and SNR is the dimensionless required radar receiver signal-to-noise ratio. The increase in rover noise manifests as an increase in the effective noise temperature of the system T_0. While the effective noise temperature is inclusive of ambient temperature, it is also a function of component non-idealities, losses, and broadband noise radiators like the rover system.

The data shows that the rover has an impact to received power in excess of thermal noise in all modes. This translates to a nearly one-for-one loss in SDR (9 to 13 dB, depending on mode) but there is still > 40 dB of margin to the requirement. Much of this margin results from the processing gain of taking many thousands of frequency data points. Therefore FFI feels that Rover-RIMFAX self-compatibility will be low risk. FFI also concurs with JPL that this test is worst-case due to the reflective conditions inside the RF tent and the plugs-in condition. FFI conclusions align with those from JPL in that no appreciable difference can be observed between rover stationary and rover driving conditions in the RIMFAX frequency ranges.

Time domain data for long-duration scans showed no appreciable emissions on the time scales collected. Some periodic noise was evident the line but it appears to not contain significant frequency content within the range of the RIMFAX radar and is likely a product of the plugs-in condition.

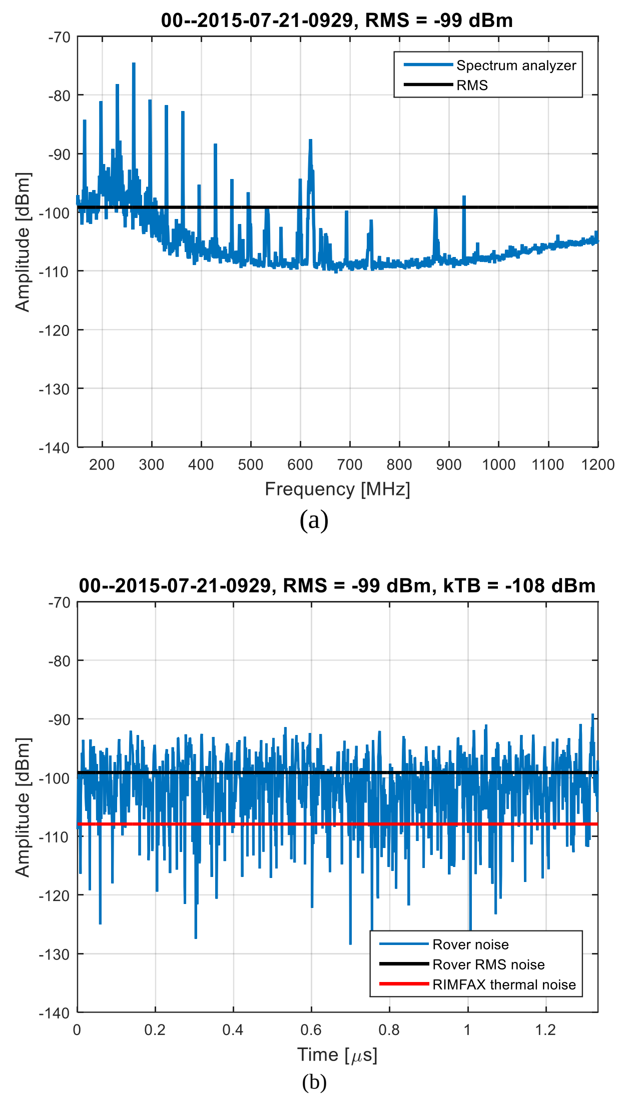


Fig. 10 Rover impact to thermal noise in Shallow Sounding Mode: (a) frequency domain (b) time domain

B. RIMFAX Transmitting

Risk to the rover system resulting from the RIMFAX RF environment was evaluated via quantitative and qualitative analysis of several available data points. Analysis of the spectrum received by the breadboard UHF antenna while the RIMFAX prototype antenna transmitted showed that the maximum expected receive power by the UHF radio is -12 dBm (Fig. 11). This yields an S_{21} value of approximately -31 dB at UHF frequencies, which provides sufficient margin to the 0 dBm damage threshold of the UHF radio.

Rover 8 Hz power bus telemetry provided a qualitative metric for evaluating the overall health of the rover during RIMFAX transmissions. Power bus voltages and currents were evaluated throughout all transmit activities and showed no anomalous behavior. Additionally, high data rate telemetry for the rover's motor control subsystem showed no anomalous readings despite having several actuators and harnesses immediately adjacent to the RIMFAX prototype.

The rover's rear HazCam captured test images of a light source with and without the RIMFAX prototype antenna transmitting. Analysis of the captured images showed no degradation in the image quality as a result of RIMFAX transmissions.

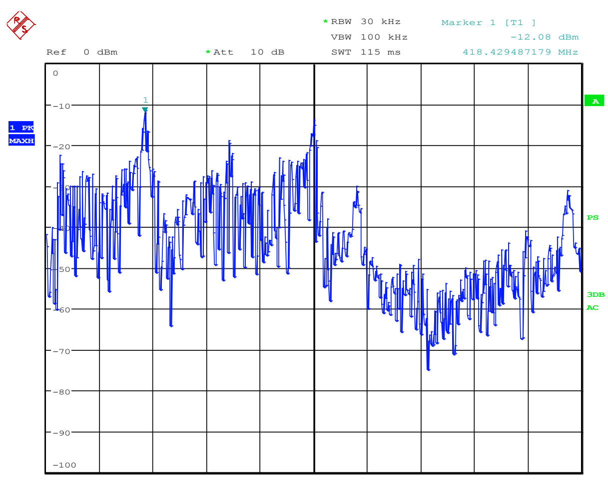


Fig. 11 UHF antenna received power (Max Hold, continuous sweep) from emulated RIMFAX Deep Sounding Ex 2 transmit mode at 19 dBm, various discrete frequencies 400-500 MHz,

TABLE 3. RIMFAX TRANSMIT IMPACT ON ROVER, RESULT SUMMARY

Metric	Result
UHF antenna received power	Max -12 dBm. No issue.
Power bus telemetry, 8 Hz	No anomalies.
RMCA telemetry, 512 Hz	No anomalies.
Rear HazCam images	No anomalies.

IV. CONCLUSION

Compatibility tests between the RIMFAX prototype antenna and the Mars rover test bed VSTB demonstrated overall low risk to the existing RIMFAX and rover designs. In order to ensure integrity of the data from the test, thoughtful test design and data post processing were required. The test required a custom RF tent to provide shielding from the noisy ambient environment of the test venue. While the tent shielding effectiveness could have been augmented with the use of connectors on the GSE umbilical cables instead of a pass-through, shielding effectiveness was sufficient as-is without undergoing the cost of additional custom cables and risk of connector de-mating/mating on critical hardware. However, others wishing to undergo a similar compatibility test program will need to weigh their system requirements against the measurement sensitivity to determine if such accommodations are required.

In a similar vein, understanding the figure of merits for compatibility was critical to ensuring that the test maximized value. The RIMFAX instrument required that the radar System Dynamic Range remain above 100 dB in order to ensure integrity of the scientific data. EMC Radiated Emissions requirements are often based on receiver sensitivity but may ignore other important parameters downstream in the RF system that may impact levels of concern and requirement definition. Knowledge of the SDR requirement and its input parameters helped guide test design and evaluation beyond simple figures of merit like receiver sensitivity.

Future work will involve EMC testing of RIMFAX electronics at various levels of integration. Final self-compatibility testing at the rover system level prior to launch will provide a more accurate assessment of risk until the start of Mars surface operations, expected to begin in 2021.

V. ACKNOWLEDGMENT

Nelson Huang and Pablo Narvaez provided EMC requirements and test equipment assistance.

Dr. Daniel Nunes provided scientific input on ground penetrating radar operation and related noise issues.

Kathryn Rowe (UCLA) processed received radar data and interfaced with the FFI team.

Boyan Kartolov designed the mechanical accommodations on the VSTB for the RIMFAX prototype antenna.

Jim Wang and Ken Diaz supported VSTB logistics and planning.

Robert Hogg provided driving support.

Michelle Haddock, Andrea Martinez, Scott Shermer, and Manuel Martin Soriano provided test setup support.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

VI. References

[1] Hamran, Svein-Erik, Hans Amundsen, Tor Berger, Sverre Brovoll, Lynn Carter, Leif Damsgård, Jo Eide, Rebecca Ghent, Jack Kohler, Michael Mellon, David Paige, Dirk Plettemeier and Mats Jørgen Øyan. RIMFAX a GPR for the Mars 2020 rover mission." *IWAGPR 2015, International Workshop on Advanced GPR*, Firenze, Italy. July 2015.

[2] Hamran, Svein-Erik, "UWB radar system performance." Chapter in *Radar Technologies, In-Tech*, ISBN 978-3-902613-49-3, 2010.

VII. Biography

Edward Gonzales has been an Electromagnetic Compatibility Engineer at NASA's Jet Propulsion Laboratory since 2014. He is co-lead EMC Engineer for the Mars 2020 Rover and provides support for SWOT, Europa, and selected cubesat missions. He received his B.S.E.E. (magna cum laude) and M.S.E.E. degrees with an electrophysics emphasis from the University of Southern California. He is a member of IEEE and HKN.

Elizabeth Cordoba is the Lead Payload Systems Engineer for the seven instruments on the Mars 2020 Rover. Her past experience includes Instrument Systems Engineering and Flight Systems Verification and Validation Lead on the SMAP mission. She received her B.S. in Aerospace Engineering from Georgia Tech and her M.S. in Aeronautics and Astronautics from MIT.

Dr. Svein-Erik Hamran is the Principal Investigator of the RIMFAX instrument from FFI in Norway.