Electromagnetic Compatibility Design, Implementation and Test of the SMAP Spacecraft to Meet Stringent L-Band Radiated Emissions Requirements

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***Abstract*—This paper describes the electromagnetic compatibility (EMC) requirements on the NASA SMAP mission, the implementation of EMC best practices at various levels of development in system level cabling harnesses and subsystems packaging, and the testing and results of flight hardware at the subsystem and spacecraft system levels.**

I. Introduction

NASA's Soil Moisture Active Passive (SMAP) is an Earth observing spacecraft that launched on January 31, 2015 [1]. SMAP provides global measurements of soil moisture and its freeze/thaw state over a 3-year period, to enhance understanding of processes that link the water, energy and carbon cycles.

A. SMAP Instrument Overview

The SMAP instrument consists of the Synthetic Aperture Radar (SAR), built by the Jet Propulsion Laboratory (JPL), and the Radiometer (RAD), delivered by Goddard Space Flight Center (GSFC). The SAR is integrated on a panel of the spacecraft despun (non-spinning) bus, operating at the nominal L-band frequency of 1.26 GHz (but has frequency agility across a wider frequency span). The RAD is mounted on the Spun Platform Assembly (SPA), operating at the L-band frequency of 1.41 GHz. The SAR and RAD share a feed-horn and a 6-meter diameter, deployable, Astromesh Reflector Boom Antenna (RBA) delivered by Astrotech, both of which are mounted on the spinning instrument platform. SMAP integrates calibrated brightness temperatures from the RAD (which has high soil moisture accuracy but coarse spatial resolution of 40 km), with the calibrated backscatter from the SAR (which has high spatial resolution of 1 km to 3 km but lower soil moisture accuracy), to produce a 10-km soil moisture data product that can meet science objectives[2].

B. Motivation

The SMAP instrument is very sensitive to radiated emissions in the L-band science pass band range of 1.20 GHz to 1.41 GHz. Since the SMAP mission only carries one prime instrument, addressing EMC early is critical for mission success.

SMAP's predecessor, the Aquarius instrument, consisted of a similar radar and radiometer suite. Aquarius encountered challenges in meeting radiated emissions requirements during ATLO (Assembly, Test and Launch Operations). This resulted in cost increase and schedule delays, requiring additional rework and implementation of EMC mitigation techniques to reduce the radiated emissions risk.

Given the similarities with the instrument technology between the Aquarius and SMAP instruments, and the lessons learned in electromagnetic compatibility (EMC) testing on Aquarius, the EMC challenges for the SMAP mission were prioritized to reduce costly rework and fixes later in the project lifecycle.

C. Methodology

Methods for addressing the radiated emissions concern for the SMAP project included accurately defining the EMC radiated emissions requirements as early as possible, in order to help establish requirements for hardware design. Also important for the project was to work out the detailed electrical interfacing and grounding requirements.

The SMAP spacecraft leveraged multiple heritage designed subsystems. With this as a focus, the EMC design approach for heritage was to concentrate on cable harness shielding and subsystem packaging to reduce radiated emissions risk.

To improve EMC compliance at the system level, the cable harness strategy was worked in detail with EMC as a priority. Cable shield attenuation experiments were performed on several candidate harness shielding techniques to determine the best approach that would meet the EMC requirements. Shield transfer impedance measurements were also performed up to the gigahertz range, in order to help confirm the best shielding approach, specifically in the Instrument L-Band frequencies. The mechanical constraints of the spacecraft were important factors for the harness strategy due to multiple tight cable routing clearances. Experiments were performed on subsystem

packaging approaches to better address radiated emissions leakage that would occur, specifically at the card slice slots and connector interfaces. A packaging design approach to help reduce radiated emissions from D-connectors was introduced for several SMAP heritage subsystems.

EMC requirements were verified at the subsystem level, the integrated instrument level, and at the SMAP spacecraft system level.

II. Requirements

A. Radiated Emissions Driving Requirement

The EMC campaign focused on meeting the radiated emissions requirements for the SAR and the RAD. The SAR requirement was from 1215 MHz to 1300 MHz @ 1 dBµV/m, and the RAD requirement was from 1372 MHz to 1454 MHz @ –3.2 dBµV/m. Comparing these values to the Mil-Std 461F RE102 levels of roughly 46 dBuV/m in the 1.2 – 1.4 GHz range, SMAP requirements were at least 45 dB more stringent[3]. The SMAP requirements were established based on early interactions with the instrument team and consideration of their performance margins. The -3.2 dBuV/m and 1 dBuV/m requirement carried the standard JPL mission environments margin of 6 dB. However any non-compliances to the above limit would be carefully assessed by the SAR and RAD team to determine the impact to science.

The SMAP structure did not carry a Faraday cage requirement. This meant that hardware inside the structure needed to test to the same stringent radiated emissions requirements levied at the system level, and were not allowed to rely on additional radiated emissions relief provided by spacecraft structure.

Due to the leverage of heritage hardware for SMAP and based on past project experience, some heritage clock frequencies used 8 MHz. Reviewing past project radiated emissions results, there was a high probability that 8 MHz higher order harmonics would violate SMAP radiated emissions requirements in the L-Band. This necessitated changes in the subsystem design to reduce EMC risk.

B. Electrical Interfacing and Grounding Requirements

In order to minimize ground loops and excess radiated emissions, the electrical interfacing and grounding (EIG) requirements goal for SMAP was to:

- Provide a uniform distribution of electrical charges on the conductive structure (an equipotential structure),
- Provide a system reference (ground) plane for electronic chassis and circuits (zero reference plane),
- Prevent DC currents from flowing through structure.
- Provide for magnetic field cancellation within each harness bundle,
- Attenuate radiated electromagnetic interference (EMI) entering or leaving electrically shielded compartments (Faraday chamber construction), and
- Reduce conducted and radiated emissions by minimizing common-mode current.

To achieve these goals, a set of EIG requirements were levied early on, and the subsequent implementation and verifications were closely monitored to help mitigate potential EMC issues downstream.

The SMAP spacecraft used the Single Point Grounding (SPG) method (a circuit referenced at one point to chassis) to interface between electronic subsystems/hardware.

Following the JPL end-circuit isolation criteria for resistance and capacitance between systems having different ground trees, proper interface isolation was implemented. This was done to prevent current loops and lower radiated emissions.

III. Implementation

Implementing EMC mitigation strategies throughout the lifecycle of the project helped reduce the project risk for EMC, prior to the system level test. One of these methods included holding EMC workshops focused at each subsystem to maximize EMC risk mitigation at their level. On-site EMC training classes were also provided for project engineers and designers.

Example EMC implementation approaches at the system cabling level and the box level are mentioned below.

A. EMC Implementation in System Cabling Level

The bulk of the radiated emissions risk reduction approach relied on the system cabling level to maintain the Faraday cage between subsystems. The strategies implemented on the SMAP spacecraft by JPL are described below.

1) Wire Shielding

A baseline approach was chosen prior to the SMAP Preliminary Design Review (PDR). Based on past experience from Aquarius, all intra-instrument harnesses (regardless of function, including power, telemetry, science data, heater power, and temperature sensors) within the SAR and the RAD subsystem would use shielded wires with high and return wires twisted together. On the spacecraft, all non-power harnesses were baselined with twisted, shielded pairs (TPSJ), while power cables used twisted, unshielded pairs (TP). Power cables on the spacecraft were not shielded due to project mass constraints. Twinax cables were baselined for sensitive clock signals in the 10 MHz range.

2) Cable Harness Overshield

Several shielding effectiveness tests were performed early in the project to determine the amount of shielding required on cables to meet the radiated emissions requirement. It was determined that when using twisted unshielded pairs, the worst case radiated emissions profile was >40 dB above spec in the RAD frequency range (Fig. 1, top). With TPSJ, the emissions were still >28 dB above spec at worst case (Fig. 1, middle). In order to achieve sufficient margin, the cable harness would need a shield overwrap in addition to using only TPSJ (Fig. 1, bottom).

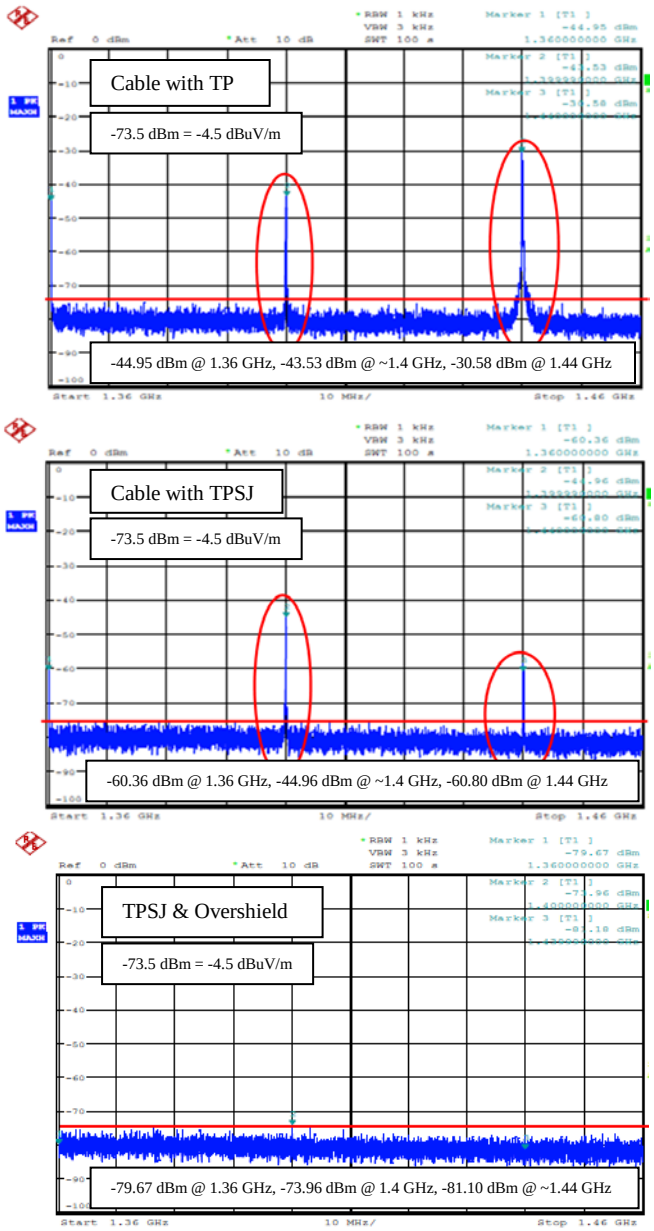

Fig. 1. Wire shielding and overshield shielding effectiveness test results.

Shield transfer impedance measurements on several JPL cable shield and overshield configurations were performed to compare the relative shielding performance. This test showed that TPSJ wrapped with commercially available nickel-copper fabric tape (with conductive adhesive) provided better shielding effectiveness at the L-band frequency, while the copper overbraid approach performed better at lower frequencies. While having better performance in the L-Band Instrument frequency range, the nickel-copper conductive tape also had the mechanical advantage of being lighter than the copper overbraid while maintaining flexibility. The disadvantage is that the tape tends to shed metallic particles, especially when the cables go through articulated joints and, hence, require wrapping with Kapton tape.

When testing TPSJ with this nickel-copper conductive tape wrap, the radiated emissions met the requirement when the connector ends were well sealed. Hence this conductive tape was baselined for all cable harness overshields under JPL oversight.

3) Connectors

Circular connectors were used as much as possible for all the SMAP harness field joint brackets since they provide a stronger electrical bond and shell continuity between a mated receptacle and plug, compared with D-sub and Micro-D rectangular connectors.

Pin assignments were chosen such that for sensitive signals, high and return were on adjacent pins, allowing the wires to be twisted as close to the connector as possible, reducing current loop area. Placing these signals closer to the outer periphery of the shell also decreased the impedance. Guard pins were used when power and signal were in the same connector.

4) Signal Separation

EIG requirements specified that the signals be separated into harnesses by category as shown below (not all categories listed):

- Power
- Digital signals
- Analog signals
- Pyrotechnic signals,
- Non-pyro burn wire and hot-wire release signals
- Radio Frequency signals
- MIL-STD-1553B signals
- Direct access test signals

5) Mechanical Configuration

On SMAP, the harness team was involved early in the project lifecycle as part of the integrated mechanical team, allowing the team to provide input into location and orientation of boxes, connectors and harness routing paths. This led to an optimal design early on, in terms of mechanical constraints and EMC performance. On the instrument, power cables were routed at least one inch away from sensitive RAD electronics and on separate support tie-downs than the RF cables. Another implementation was to mount the instrument box such that connectors would be pointed away from the feed-horn—a potential source of radiated emissions.

On the spacecraft, the CDH subsystem was placed above mid-deck and the power assemblies were placed below mid-deck. This arrangement provided better separation between power and CDH cables, with data cables being routed through the upper hinge, on the top side of the mid-deck; power cables were routed on the lower hinge, near the bottom of the panel (Fig. 2).

One unique aspect of the SMAP cabling is that many spacecraft harnesses had to be routed over a mechanical hinge line. To reduce stiffness of the cables in this service loop, the EMI conductive tape and Kapton overwraps on individual

cables were replaced with a common overwrap over multiple harnesses, using conductive fabric that still maintained the faraday cage of the harnesses.

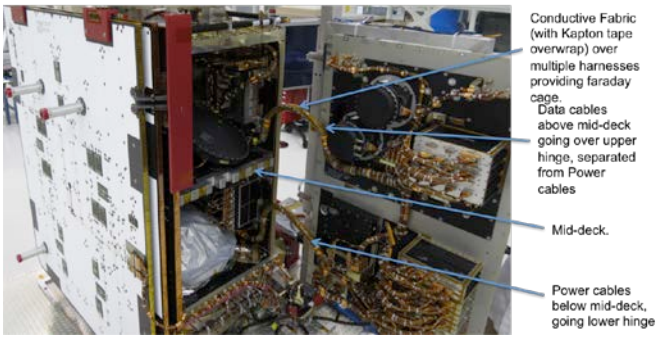

Fig. 2. Example harness routing for SMAP.

6) Heaters and PRTs:

All wires to platinum resistance thermostats (PRTs) and heaters were TPSJ. The PRTs and selected heaters situated near sensitive circuits were also enclosed under conductive tape to maintain a faraday cage from the wires to the PRT (Fig. 3).

Fig. 3. Conductive tape over PRT.

On SMAP, systems engineering identified and documented the temperature sensors and heaters that needed to be shielded with conductive tape, taking into account factors such as: (1) whether the PRT/heater was on during science operations, (2) proximity of these thermal hardware to sensitive boxes, (3) whether the box reading the telemetry had any filtering on the circuits, and (4) whether or not they were inside the spacecraft structure.

B. EMC Implementation in Heritage Subsystems

Due to the design limitations of heritage hardware, a packaging solution needed to be proposed to address stringent radiated emissions requirements while not changing heritage board designs. Radiated emissions tests were performed on mock chassis structures, and major radiated emissions leakage areas were discovered to originate from slots between card slices and from D- subminiature and micro-D connectors.

Using a standard micro-D 100 pin connector example, the longest dimension would be approximately 1.5 inches. At 1215 MHz with a wavelength of 24.69 cm, using the below slot antenna equation[4], the calculated shielding effectiveness of this slot aperture would be 10.21 dB. This was insufficient for our applications as demonstrated by test results in the previous paragraph.

$$S = 20\log\left(\frac{\lambda}{2l}\right) \qquad \text{Equation 1}$$

In order to resolve the radiated emissions leakage between card slices, one approach used for the SMAP Command Data and Handling (CDH) subsystem was to employ a cover plate with gaskets around connector openings (Fig. 4). The cover plate would effectively seal any open slots between card slices. In subsystems where the cover plate was not possible, such as the Power Controller Assembly/Power Distribution Assembly (PDA/PCA), nickel-copper conductive tape was used to seal the slots (Fig. 5).

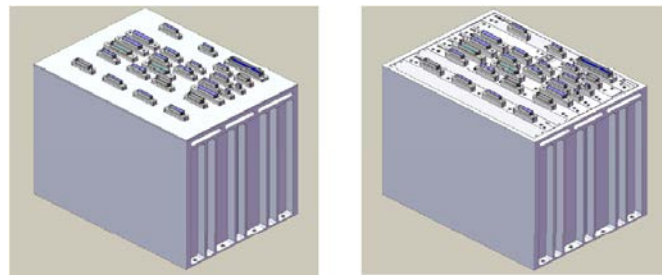

Fig. 4. CDH model with and without cover plate.

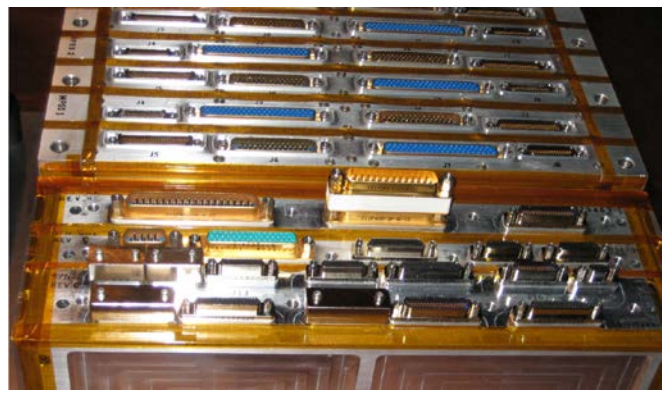

Fig. 5. Conductive tape with Kapton layer to seal slots for PDA/PCA

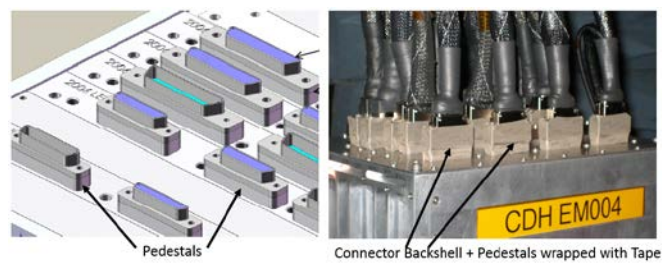

Fig. 6. Connector pedestal approach with tape.

Addressing the radiated emissions leakage from D-subminiature connectors and Micro-D connectors, the packaging design solution required a combination of a machined raised pedestal and conductive tape overwrap to fully seal the leakage (Fig. 6). The pedestals and chassis are one piece of metal. Conductive tape was used to wrap from the backshell of the connector to the pedestal on the chassis. This packaging approach was effective and used to reduce the radiated emissions risk for heritage hardware on SMAP using D type connectors[5].

IV. TESTING

All SMAP subsystems were required to undergo EMC testing. This section highlights a subsystem level test, the Integrated Instrument Test, and the SMAP Spacecraft System Level EMC Test.

A. SAR Subsystem-Level EMC Testing

The SAR subsystem was a new design and hence was able to take advantage of some additional EMC design practices related to the circuit board. EMC mitigation also focused on the packaging strategies, including restricting use of D-subminiature connectors, using circular type connectors, using gaskets for tight packaging, and routing of wires inside subsystems to minimize noise coupling. Due to the tight schedule, the SAR subsystem would go through EMC testing for the flight model only.

The other challenge with preparing for the SAR subsystem EMC test was having several modes of operations available to the SAR. The SAR is a frequency agile radar with capability to fluctuate the pulse repetition intervals (PRI) and the transmit/receive frequencies. With these two degrees of freedom, this amounted to hundreds of operating modes that the SAR could be configured to. It would be impractical to test for all the operating modes. Given this situation, the SAR instrument engineers were able to envelope all these modes into the four operating modes that were used during the EMC test.

A comprehensive suite of EMC tests was performed on the SAR subsystem. The early design work was effective, limiting the SAR radiated emissions non-compliances to a few frequencies in the L-band, with amplitudes that were within waiver territory. After careful analysis by both the SAR and RAD instrument teams, it was decided that these non-compliances were acceptable to use as-is. The result was initiating and approving a waiver ensuring low risk of impacting the instrument mission objectives.

B. Integrated Instrument-Level EMC Testing

The integrated instrument consists of the SAR, the RAD, and the hardware used to both spin and control the spinning of the instrument. At the integrated instrument level, an EMC test was performed; this was the only opportunity to test the instrument while spinning (Fig. 7). Additionally, there was concern about the SAR and the RAD being compatible, since earlier subsystem level tests showed that radiated emissions requirements were being violated, both by the SAR and the RAD. The approach for EMC would be to measure the background radiated emissions as the test progressed, including measuring radiated emissions in the L-Band frequency range, and to ensure the S-Band telemetry channels (as the only other potential victim receiver on SMAP) were devoid of interference. The main pass/fail criteria was the Instrument data. If radiated emissions were detected, but the science data did not see the interference, then the test was considered a success—the instrument demonstrated self-compatibility.

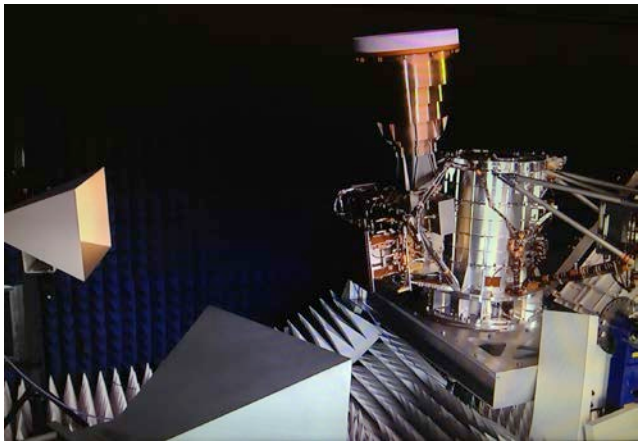

Fig. 7. SMAP integrated instrument EMC test.

At the conclusion of the integrated instrument-level test, the SAR and RAD did indeed demonstrate self-compatibility, with the Instrument operating in multiple science modes, and spinning at multiple rotations per minute. Note that radiated emissions non-compliances previously seen at the subsystem level test were still visible at the integrated instrument level.

C. SMAP System-Level EMC Testing

The final verification was at the SMAP system-level EMC test (Fig. 8). In this configuration, the SMAP instrument was integrated into the flight system. The whole spacecraft was to be tested for EMC compliance with launch range-radiated emissions and radiated susceptibility requirements, as well as satisfying self-compatibility and plugs out objectives. In order to accommodate the SMAP spacecraft, an investment was made for a new anechoic chamber at JPL big enough to fit the spacecraft.

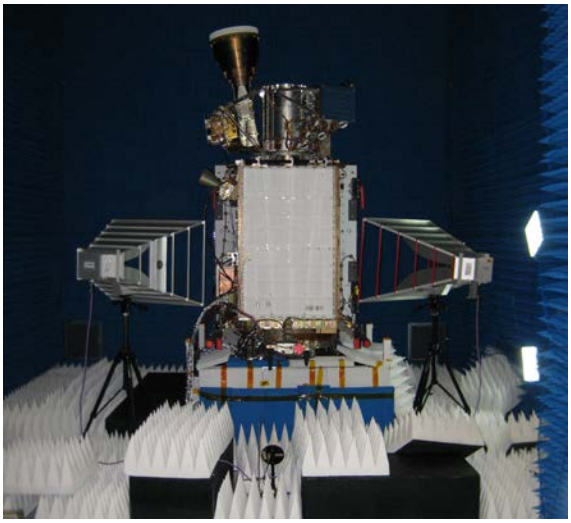

Fig. 8. SMAP spacecraft system-level EMC test.

The first two test objectives centered on the SMAP spacecraft meeting launch site and launch vehicle radiated emissions and radiated susceptibility requirements. During this test, the SMAP spacecraft was in the launch configuration. The results showed no emissions seen above the specifications, and

the SMAP spacecraft did not see any anomalies or susceptibilities during radiated susceptibility testing.

The next verification was the self-compatibility test, where the spacecraft underwent three major test campaigns, each emphasizing a specific function of the instrument. Throughout each campaign, no major issues were noted, as various guidance, navigation, and control subsystems were operated. The self-compatibility test was successfully completed.

The final test was the plugs out test for the SMAP spacecraft. This test was important to ensure that commands could be received and sent through air-link, using the spacecraft S-Band and X-Band antennas. Another unique aspect about the plugs out test was being able to use it as a dry run for the flight launch scenario up to ascent. This was the first time a launch scenario was exercised during plugs out verification at JPL. At the end of this test, the SMAP operators were able to dry run a launch scenario up to ascent with the spacecraft, while demonstrating and achieving all the plugs out test objectives.

V. CONCLUSION

The SMAP EMC system-level test results showed that a conscious effort to establish requirements early in the program, and then implement EMC mitigation in the design, led to a successful EMC test campaign. This included meeting radiated emissions and radiated susceptibility, self-compatibility and plugs out requirements. Testing demonstrated that the instrument and the spacecraft were compatible, and one of the most challenging radiated emissions requirements for a JPL spacecraft was met.

Lessons learned included

- Perform EMC testing as early as possible to reduce EMC risk, even if heritage data demonstrated compliance. A subsystem heritage radiated emissions test results demonstrated EMC compliance and they implemented the same EMC best practices for SMAP. However, when they tested the SMAP flight model hardware in the EMC lab (engineering model hardware testing was omitted due to confidence in heritage test results), they failed radiated emissions requirements dramatically. Many weeks were spent in the EMC lab to attempt to fix the problem to no avail. A waiver was granted after careful evaluation from the science team.
- EMC collaboration with SMAP design engineers early in the program led to impactful EMC design features for system level cable harnessing and packaging design features for heritage hardware. This was pivotal in meeting the stringent L-Band radiated emissions requirements.
- Wise selection of subsystem clocks/operating frequency was crucial. Violating frequency harmonics ended up falling outside the actual science passband frequencies.

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BIOGRAPHIES

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