EMC Testing on the Integrated Science Instrument Module (ISIM)

A Summary of the EMC Test Campaign for the Science Payload of the James Webb Space Telescope (JWST)

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***Abstract*— This paper describes the electromagnetic compatibility (EMC) tests performed on the Integrated Science Instrument Module (ISIM), the science payload of the James Webb Space Telescope (JWST), at NASA's Goddard Space Flight Center (GSFC) in August 2015. By its very nature of being an integrated payload, it could be treated as neither a unit level test nor an integrated spacecraft/observatory test. Non-standard test criteria are described along with non-standard test methods that had to be developed in order to evaluate them. Results are presented to demonstrate that all test criteria were met in less than the time allocated.**

I. Introduction/Description of EUT

The James Webb Space Telescope (JWST) will be the premier observatory of the next decade, serving thousands of astronomers worldwide. It will study every phase in the history of our Universe, ranging from the first luminous glows after the Big Bang, to the formation of solar systems capable of supporting life on planets like Earth, to the evolution of our own Solar System. A conceptual diagram of JWST is shown in Figure 1.

The science payload of JWST is the Integrated Science Instrument Module (ISIM), which consists of four instruments: the Fine Guidance Sensor (FGS), the Mid-Infrared Instrument (MIRI), the Near Infrared Camera (NIRCam), and the Near Infrared Spectrometer (NIRSpec).

Figure 2 shows a conceptual diagram of ISIM as it will be installed on JWST. Each instrument includes an optical assembly that mounts on a composite structure; this assembly is called ISIM Prime. Electronics boxes mount inside the ISIM Electronics Compartment (IEC); these boxes provide support functions for each instrument as well as for the integrated ISIM. The harnesses that connect the IEC to ISIM Prime are routed along the ISIM Harness Radiator (IHR). ISIM Prime, the IEC, and the IHR will all be integrated to the back of the telescope assembly as shown in the figure. The telescope assembly with the ISIM equipment will rest at the top of a deployable tower and separated from the spacecraft bus by a sunshield. For a sense of scale, the deployed sunshield will be approximately the size of a tennis court.

All of the science instruments implement infra-red detectors, which must be operated at cryogenic temperatures in their on-orbit configuration. For this reason, ISIM Prime will be cooled to temperatures below 40 K, while the electronics boxes inside the IEC will be maintained at a temperature near 300 K. Because the harnesses on the ISIM Harness Radiator must accommodate this thermal gradient, they use wires and shields made with such higher resistance conductors as phosphor bronze and stainless steel. As such, the performance and shielding effectiveness of these cables will be compromised when compared with equivalent cables made with copper wires and shields that do not have to operate in a cryogenic environment.

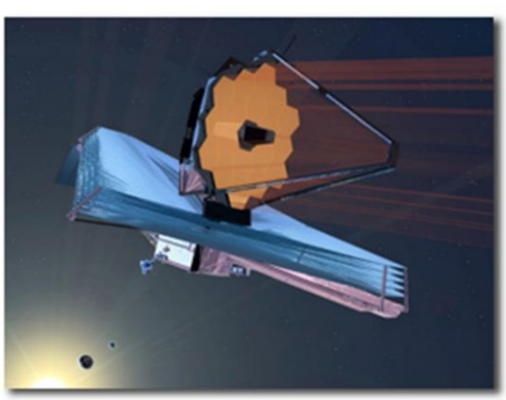

Figure 1. JWST Conceptual Diagram

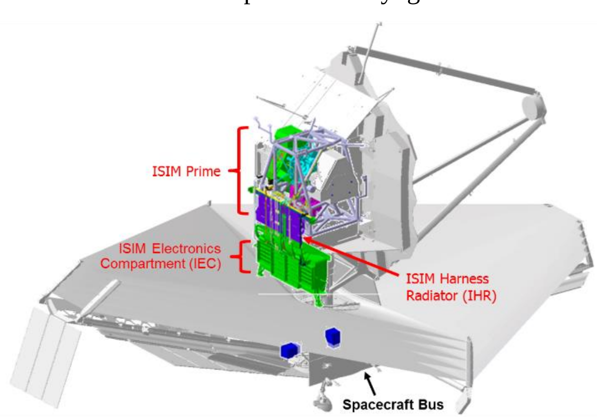

Figure 2. ISIM on JWST

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Due to the large size and complex architecture of JWST, a full EMC test at integrated observatory level is not practical. The only EMC-related test planned for observatory level is an RF self-compatibility test in which it is verified that the S-band receiver can maintain lock on a low-level uplink signal when all observatory equipment is operating. For this reason, it was necessary to address EMC verification at lower levels of integration, including the ISIM science payload, and separately, the spacecraft.

Each of the instruments had been subjected to the full suite of EMI tests (conducted emissions, conducted susceptibility, radiated emissions, radiated susceptibility) required by the JWST project at the instrument, subsystem, and/or unit level, and which are based on the requirements and test methods of MIL-STD-461C and MIL-STD-462.

The MIL-STD-461C and MIL-STD-462 based tests are inherently unit level tests, and there was no reason to repeat any of them at the integrated ISIM level. ISIM is an integrated payload that remains to be integrated into a larger assembly, namely, the JWST Observatory. As such, this test was clearly not a fully integrated observatory level test, for which there are generally defined test criteria.

The nature of this test placed it between a unit level test and an observatory level test, which made it a non-standard test without well-defined test criteria. The very nature of this test required a significant re-evaluation of test criteria.

The re-evaluated test criteria were divided into the following categories:

- Power Quality
- Aggregate Radiated Emissions (RE)
- Aggregate Radiated Susceptibility (RS)

This test presented the final opportunity to perform radiated testing on ISIM. An additional challenge was posed by the fact that all of the science instruments implement infra-red detectors, which will be operated at temperatures below 40 K in their on-orbit configuration. Because an EMC test at ISIM level at on-orbit cryogenic temperatures was not practical, the test was performed at ambient temperature (~300 K). Although the difference in temperature was not expected to significantly affect the power quality or RE portions of the test, it was certainly expected to affect the RS portion, because the response of the detectors is known to be dependent on temperature.

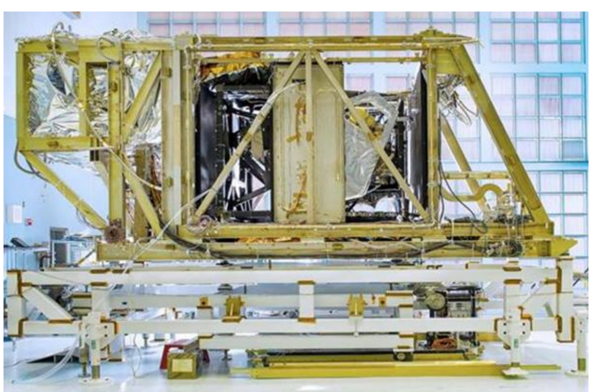

Figure 3. ISIM Installed in Mounting Frame

An assessment of intra-ISIM EMC was not feasible at ambient temperature. That assessment was performed during ISIM thermal vacuum testing with all detectors operating at their on-orbit temperatures. No major issues were observed.

For the ISIM environmental test campaign, which included thermal vacuum, acoustics, vibration, as well as EMC, all of the equipment shown in Figure 2 was mounted in a metal frame as shown in Figure 3. Although a non-metallic frame would have been preferred for EMC, it was not a practical choice for supporting the complete set of environmental tests.

II. POWER QUALITY

As previously mentioned, each instrument had been subjected to the full suite of CE and CS tests prior to integration into ISIM. These are inherently unit level tests that were not necessary to repeat at ISIM level. At the integrated ISIM level, the driving concerns from a conducted standpoint consisted of power quality measurements of two types:

- Aggregate voltage ripple
- Turn-on/turn-off transients

All of the power quality tests required the use of a custom Line Impedance Simulation Network (LISN) to represent the power bus common source impedance of the JWST spacecraft.

A. JWST Custom LISN

As is common for most GSFC platforms, the JWST power bus common source impedance is dominated by the wiring between the battery terminals and the common distribution point. On JWST, this wiring is approximately 0.8 m long, and the (+) and (-) bundles are separated by approximately 30 cm.

The bus impedance follows the general harness impedance model shown in Figure 4. At low frequencies, the wire resistance of approximately 0.1 Ω dominates. As frequency increases, the inductance of 0.8 µH between the (+) and (-) wire bundles dominates. As frequency continues to increase, the characteristic impedance of the transmission line formed by the (+) and (-) bundles dominates. For the large separation of the bundles, the characteristic impedance is several hundred ohms.

These physical impedances in the wiring are represented by the bulk circuit elements shown in Figure 4. The figure also shows that the measured LISN impedance is in good agreement with the JWST specified source impedance.

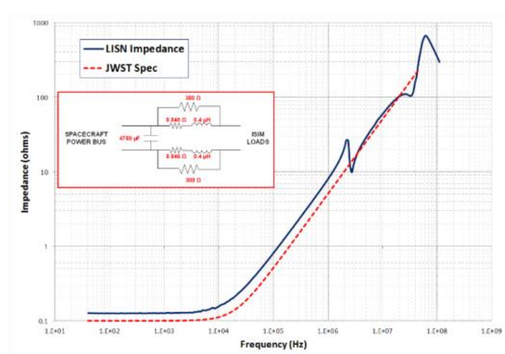

Figure 4. JWST LISN and Impedance Curve

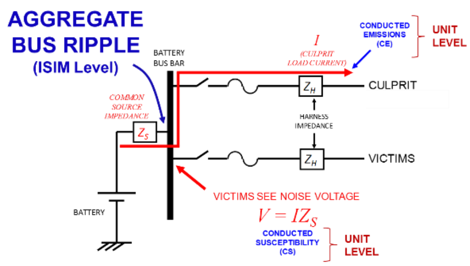

Figure 5. Aggregate Bus Ripple Measurement

Clearly, this LISN impedance is significantly lower than that of the default 50 µH LISN specified by MIL-STD-461F. Had the 50 µH been used for these tests, the results would almost certainly have been different (not likely for the better).

B. Aggregate Voltage Ripple

The primary conducted requirement at the integrated ISIM level was that when measured in the time domain, the load induced ripple on the bus could not exceed 1 V peak-to-peak (+/- 500 mV peak-to-peak) across a LISN representative of the spacecraft power bus source impedance, as shown conceptually in Figure 5.

Although not specifically required, it was also desired to measure the aggregate voltage ripple in the frequency domain. The results could then be compared directly against the JWST limits for CS01/CS02, 1 Vrms from 30 Hz to 400 MHz, to which each instrument had been tested prior to integration into ISIM. The CS01/CS02 limit is clearly more stringent than the time domain limit. This means that if the time domain voltage ripple limit is met, there is ample margin to ensure compatibility at the system level.

An important consideration for the frequency domain measurement was that the LISN output must not be connected directly to the 50 Ω input of a spectrum analyzer. At best, the analyzer input could load down the LISN output and affect the measurement. At worst, the analyzer input could be damaged.

This test approach was facilitated by using an oscilloscope that provided a capability for performing a Fast Fourier Transform (FFT) on the measured signal. This approach also allowed the use of the same high-impedance differential voltage probe used for the time domain measurement, thus avoiding any issues with a 50 Ω spectrum analyzer input. The time domain and frequency domain measurements could be very efficiently performed with the same device, and the frequency domain measurement took essentially no additional time to perform.

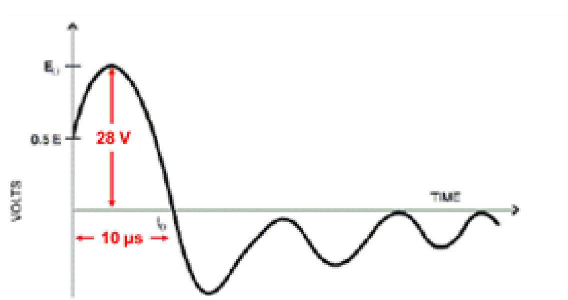

Figure 6. JWST CS06 Transient

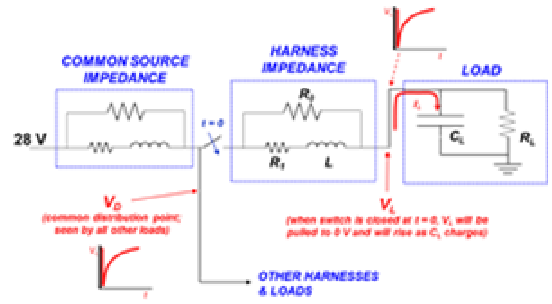

Figure 7. Typical Turn-On Transient

The largest frequency-domain signal measured was 615 µVrms at approximately 64 MHz. This is well below the JWST CS01/CS02 limit of 1 V rms.

The largest voltage ripple measured in the time-domain was 168 mV peak-to-peak. This is well under the JWST limit of 1 V peak-to-peak requirement.

Given these results, aggregate voltage ripple from ISIM is not expected to pose a problem at integrated observatory level.

These tests only account for ISIM's contribution to the total bus ripple. The additional contributions from remaining spacecraft equipment is not expected to contribute significantly to bus ripple, because each remaining spacecraft component will be tested at unit level to the same CE01/CE03 limits as all of the ISIM equipment.

C. Turn-On/Turn-Off Transients

All equipment will generate transients on the bus when turned on or turned off. Although not specifically required, it was desired to characterize these transients at the integrated ISIM level. The measured transients would then be compared to the CS06 pulses, positive and negative, to which each instrument had been tested. The CS06 pulse waveform, along with the JWST specified amplitude of +/- 28 V and width of 10 µsec, is shown in Figure 6.

A typical turn-on transient is shown conceptually in Figure 7. When a load is switched onto the bus, its front-end filter capacitors will look like a dead short immediately after the switch is closed, and they will draw a large current spike until they begin to charge up to the bus voltage. This large current spike drawn from the bus will tend to pull the bus potential down, possibly to as low as 0 V. The negative CS06 pulse is intended to simulate this type of transient.

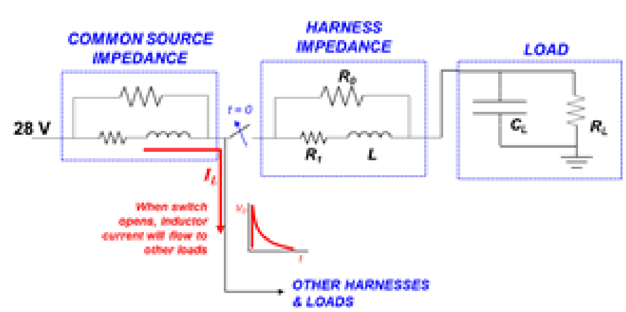

Figure 8. Typical Turn-Off Transient

A typical turn-off transient is shown conceptually in Figure 8. When a load is switched off of the bus, the sudden change in current through the inductive portion of the common source impedance may cause a surge in bus potential. The positive CS06 pulse is intended to be a very worst-case envelope of this type of transient.

During the ISIM level test, most of the measured transients had amplitudes and durations that were well within the envelope of the JWST CS06 pulse shown in Figure 6. Although some transients had durations of as long as 25 msec, those transients had amplitudes of 1 V or less. Even with these worst-case transients, the primary bus voltage was maintained well within the range of 22 to 35 VDC to which each electronics box was tested at unit level.

Given these results, none of these transients is expected to pose any significant compatibility problems on the bus.

III. AGGREGATE RADIATED EMISSIONS

Prior to delivery to ISIM, all instruments were tested for RE02 as part of their respective EMI test programs. At ISIM level, the goal was to demonstrate that the aggregate radiated emissions were still within acceptable limits.

The primary criterion is that ISIM must not generate any emissions that could interfere with the JWST S-band receiver, which operates in the frequency range of 2.0898521 - 2.0916521 GHz. The emissions limit in this frequency range is 13 dBμV/m. Outside of S-band, the radiated emissions test provides a qualitative check of ISIM construction, e.g. that cables were built and terminated properly, boxes were bonded properly to structure, etc.

In the 30 – 200 MHz range, it was decided to use the traditional linearly polarized biconical antenna. This antenna also has a 3 dB beamwidth of at least 60 degrees (+/- 30 degrees from boresight) over its frequency range in the E-plane; it is essentially isotropic in the H-plane.

In the 200 MHz to 1 GHz and the 1 – 10 GHz ranges, it was decided to use the ETS-Lindgren 3101 and 3102 conical log spiral antennas, respectively. Each has a 3 dB beamwidth of at least 60 degrees (+/- 30 degrees from boresight) over its frequency range of interest. In addition, the conical log spiral antennas are circularly polarized, which means they measure horizontal and vertical polarizations simultaneously; there is no need to perform separate scans for horizontal and vertical polarization. This reduces the test time at each antenna position by a factor of 2 when compared to linearly polarized antennas.

In addition to simply having large beamwidths, the selected antennas also have a nearly constant beamwidth over their respective frequencies of interest. These antennas maximize coverage of ISIM at each position, thus minimizing the number of positions, making most efficient use of test time, and facilitating the aggregate nature of the RE test at ISIM level.

The ETS-Lindgren 3102 conical log spiral antenna factor is not low enough to facilitate measuring 6 dB below the specified S-band limit of 13 dBμV/m. For this reason, it was desired to use the traditional linearly polarized double-ridged guide (DRG) antenna for the S-band notch measurements. The measurements were taken with the DRG antenna placed in locations that were representative of the relative locations of the S-band antennas on the JWST spacecraft.

Each instrument included a set of mechanisms (e.g. filter wheels, focus mechanisms, etc.). These mechanisms are intended to be operated at the on-orbit temperatures of below 40 K; most mechanisms had limited allocations for operation at ambient temperature. As such, many mechanisms were given an allocation of only one operation for this entire test.

As stated above, the most sensitive victim that is being protected by the RE test is the S-band receiver. For this reason, it was decided to perform all of the mechanism movements during the scans in the S-band notch in order to determine if any of the mechanism operations might pose a risk of interference with the S-band receiver.

Because mechanism movements are inherently non-continuous operations of finite time duration, the standard radiated emissions measurement technique was not considered sufficient for capturing emissions in the S-band notch due to mechanism operations.

It was decided to use the FFT-based time domain scan capability of the EMI receiver in order to maximize the likelihood of capturing these emissions. This capability is recommended in the recently released MIL-STD-461G.

Radiated FFT based time-domain scans revealed that the worst-case measured emissions from the DUT were at least 5 dB below the 13 dBμV/m level in the S-band notch. Moreover, the measured values were in the noise floor of the measurement equipment, indicating that the margin is likely greater than 5 dB.

Given the above, mechanism movements are not expected to pose any risk of interference to the S-band receiver at integrated observatory level. All RE scans outside the S-band notch were also fully compliant to the limit.

IV. AGGREGATE RADIATED SUSCEPTIBILITY

A. Antenna Selection and Position

The antennas selected for the RS test were the same as those used for the main portion of the RE test, i.e. the biconical in the 30 – 200 MHz range, the ETS-Lindgren 3101 conical log spiral in the 200 MHz – 1 GHz range, and the ETS-Lindgren 3102 conical log spiral above 1 GHz.

In the EMI lab at GSFC, the drive amplifiers used for RS testing above 1 GHz work in frequency ranges that are divided approximately into octaves: 1 – 2 GHz, 2 – 4 GHz, 4 – 8 GHz, and 8 – 18 GHz. Because JWST does not use any RF transmitters above 8 GHz, it was decided that it would not be a good use of test time to change out amplifiers in order to perform a scan from 8 – 10 GHz. Therefore, the upper frequency limit for RS testing at the ISIM level was set to 8 GHz.

In addition, JWST uses no RF transmitters below 1 GHz. Ordinarily, this would suggest that there is no need to perform RS testing at the payload level below this frequency. However, the compromised shields on the cryogenic cables connecting the

IEC to ISIM Prime presented sufficient concerns as potential victims that it was desired to use the RS test as a way of characterizing their sensitivity. For this reason, RS testing at the ISIM level was performed down to 30 MHz.

As shown in Figure 9, the desired on-orbit levels were to be applied to the rear face of the IEC. When ISIM is mounted to the spacecraft, this is the face that will be pointed directly toward the spacecraft bus. For this reason, the test antennas were placed on this side of ISIM.

At a distance of 2 m from the rear face of the IEC, each antenna could provide full illumination of the entire IEC “cavity” with one antenna position as shown in Figure 10.

B. Adjustment of On-Orbit Field Level for Ambient Operations

The required level for radiated susceptibility in the On-Orbit configuration was 2 V/m. This requirement applies at on-orbit operating temperatures of < 40 K. This test was to be performed at room ambient temperature (~300 K).

Prior to performing this test at the integrated ISIM level, a set of tests were performed on a prototype detector subsystem in order to characterize the relationship between the susceptibility at room temperature vs. cryo temperature. For these characterization tests, it was decided to use the CS114 test method of MIL-STD-461F for bulk current injection.

The results of these measurements showed that for a given culprit signal, the signal-to-noise ratio at room temperature was approximately a factor of 10 less than that measured at cryo temperature. Moreover, it was also determined that at either operating temperature, the amplitude of the coupled signal was proportional to the square of the voltage/current amplitude of the applied culprit signal, i.e. it was proportional to the power of the applied culprit signal.

Given these results, it was determined that the equivalent applied field level at room temperature should be a factor of $\sqrt{10}$ higher than the desired level at cryo temperature. Therefore, the 2 V/m required level at cryo temperature would convert to an equivalent level of 6.3 V/m at room temperature.

In order to characterize the radiated susceptibility at on-orbit operating temperature, it was decided that electric field intensities of 6.3 V/m (full level), 3.1 V/m (6 dB down from full level), and 2.0 V/m (10 dB down from full level) would be applied.

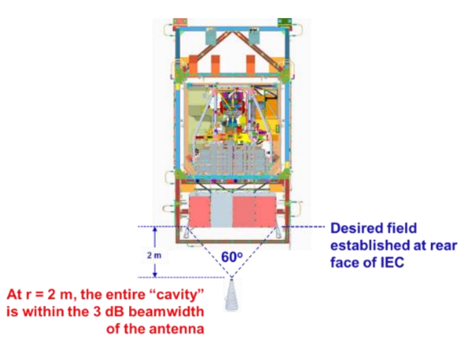

Figure 9. Field Levels at Rear Face of IEC

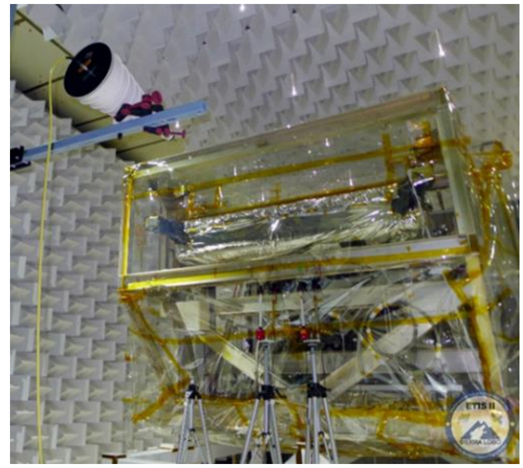

Figure 10. Single Antenna Position for RS

C. Corrected Level for Field Probe Placement

The electric field probes used to monitor the applied field were placed as shown in Figure 11. They were placed under the metal beam of the support structure in order to minimize the effects of possible reflections. This placed them at a distance of 1.78 m from the test antenna and near the edge of the 3 dB (half-power) beamwidth of the antenna. In order to apply the desired levels to the rear face of the IEC, the levels sensed by the probes needed to account for these two correction factors.

For this test, it is assumed that ISIM is sufficiently in the far-field such that the electric field is inversely proportional to the distance from the test antenna. In this case, the ratio of the electric field at the field probes to the electric field at the IEC, due only to the difference in distance, is given by:

$$\left(\frac{E_{PROBE}}{E_{IEC}}\right)_{DIST} = \frac{1/(1.78\ m)}{1/(2\ m)} = 1.12$$

Because the field probes are near the edge of the 3 dB (half-power) beamwidth of the antenna, this means that the electric field intensity at the probes is approximately 3 dB (factor of $\sqrt{2}$) lower than that applied at the IEC along the axis of the antenna.

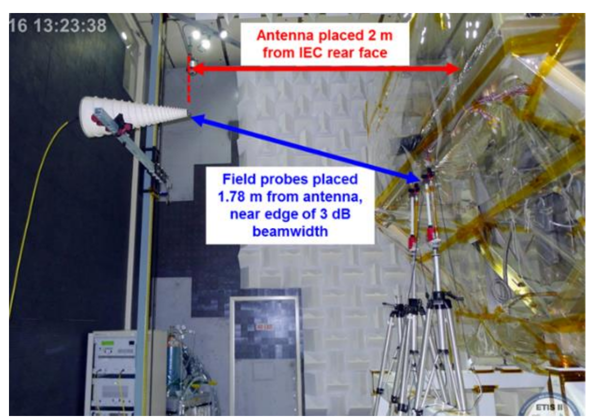

Figure 11. Field Probe Placement

The ratio of the electric field at the field probes to the electric field at the IEC, due only to being near the edge of the 3 dB beamwidth, is given by:

$$\left(\frac{E_{PROBE}}{E_{IEC}}\right)_{3\ dB} = \frac{1}{\sqrt{2}} = 0.707$$

The ratio of the total electric field at the field probes to the electric field at the IEC is given by the product of these two factors:

$$\left(\frac{E_{PROBE}}{E_{IEC}}\right)_{TOT} = 1.12\ \times 0.707 = 0.80$$

Using this correction factor, the adjusted on-orbit levels applied at the field probes for the biconical antenna in the 30 – 200 MHz frequency range were 5.0 V/m (full level), 2.5 V/m (-6 dB), and 1.6 V/m (-10 dB).

An additional correction factor was needed for the conical log spiral antennas in the 200 MHz – 1 GHz and 1 – 8 GHz ranges. These antennas are circularly polarized, which means that they provide horizontally and vertically polarized components simultaneously. The field probe monitors display the root sum squared (RSS) total of all field components, and the control loop levels on this value. In order to get the desired field intensity in both the horizontal and vertical directions, the control loop must level on a value that is √2 (3 dB) higher than each of the specified values.

Therefore, when using the conical log-spiral antennas in the 200 MHz – 1 GHz and 1 – 8 GHz ranges, the adjusted on-orbit levels applied at the field probes were 7.1 V/m (full level), 3.5 V/m (-6 dB), and 2.2 V/m (-10 dB).

D. Pre-Calibration of Electric Field Level

Radiated susceptibility tests were performed using the "substitution method." Excitation levels were pre-calibrated and prerecorded while ISIM was powered off. The pre-recorded levels were "played back" and applied while ISIM was powered on.

For the on-orbit levels, the field was pre-calibrated to the maximum level of 6.3 V/m (corrected to 5.0 V/m at the field probes for the biconical antenna; corrected to 7.1 V/m at the field probes for the conical log-spiral antennas). During the actual radiated susceptibility test with ISIM powered on, the 6.3 V/m field was applied by playing back the full levels as-calibrated; the 3.1 V/m field was applied by applying 6 dB less than the as-calibrated levels; the 2.0 V/m field was applied by applying 10 dB less than the pre-calibrated levels.

This test approach allowed the RS test to be completed much more efficiently than it would have been using the standard technique of real-time leveling of the field. Due to the nature of the detector subsystems in each of the instruments, and the number of detector channels to read out and process, there was a significant lag between performing the RS scan and evaluating susceptibility. Rather than wait for the results of a given RS scan before proceeding, it was decided to perform all of the scans, using the levels defined above, in immediate succession.

Using this approach, the pre-calibrations were performed in one day, and all of the RS scans were completed in a second day. It is estimated that the traditional real-time leveling approach would have taken approximately 4 days to perform.

E. RS Results

All detector subsystems were fully compliant at the JWST requirement level of 2.0 V/m.

Some susceptibilities were observed at the 6.3 V/m level at various frequencies between 100 MHz and 300 MHz, corresponding to likely resonances for the exposed cables connecting between the IEC and ISIM Prime. Similar susceptibilities had been observed at instrument level at frequencies corresponding to resonant lengths of the exposed cable lengths in those test configurations. The susceptibilities shifted to the expected frequency range for the integrated ISIM configuration.

No susceptibilities were observed at the 6.3 V/m level outside of the 100 – 300 MHz frequency range. No emissions are expected from the spacecraft in this frequency range at anywhere near these levels.

In particular, no susceptibilities were observed at the 6.3 V/m level at the S-band transmit frequency of 2.27 GHz. From this, it may be concluded that there is little to no risk of interference to ISIM from the S-band transmitter, which is the most likely source of potential interference on the observatory.

Given these results, it may be concluded that radiated susceptibility is not expected to be a problem for ISIM once it is integrated onto the JWST Observatory.

V. SUMMARY

The ISIM EMC Test presented a number of unique challenges due to its nature of being an integrated payload. Test criteria had to be re-examined, and in some cases, test methods had to be developed for them. All test objectives were met, and it can be stated without hesitation that ISIM passed the test with flying colors. Moreover, despite a few setbacks, the test was completed in 8.5 days of the 10 days allocated.

VI. ACKNOWLEDGMENTS

The author would like to thank everyone on the NASA/GSFC EMI test team and the JWST/ISIM project team who contributed to the planning and execution of this test and helped to make it the amazing success that it was. Additional thanks are in order to John Lichtig of Lichtig EMC Consultants for his tireless efforts on many levels and to Ken Javor of EMC Compliance for his consistently excellent technical guidance and relentless proofreading. This test embodied and epitomized everything that is meant by the term "team effort." Leading this effort will certainly go down as one of the highlights in the author's career, and it was a tremendous honor to be part of it.