



EMC Test Challenges for NASA's James Webb Space Telescope



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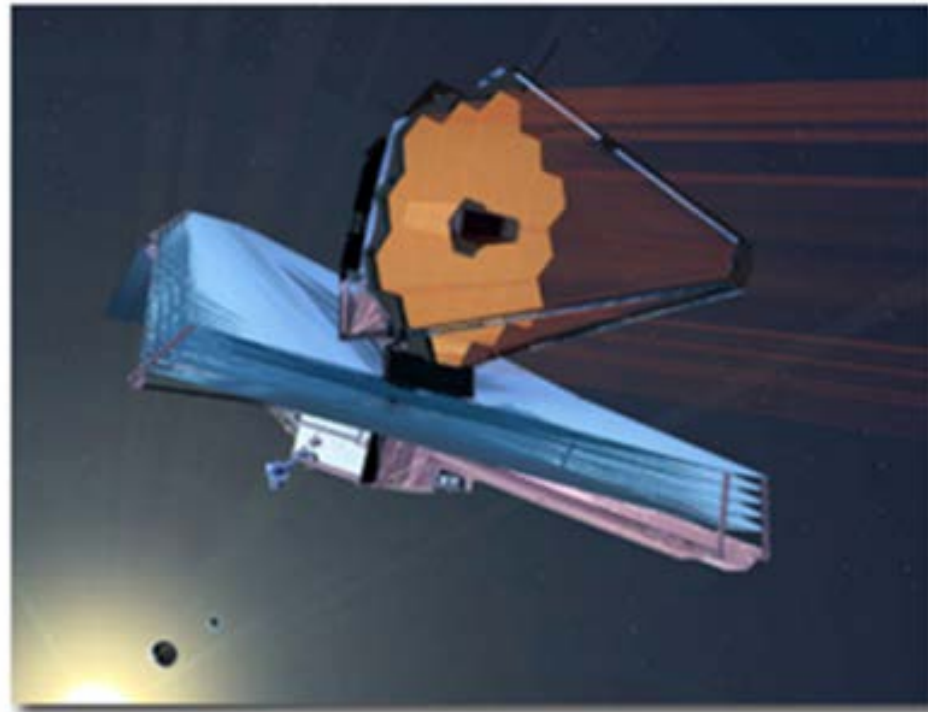
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ACRONYMS

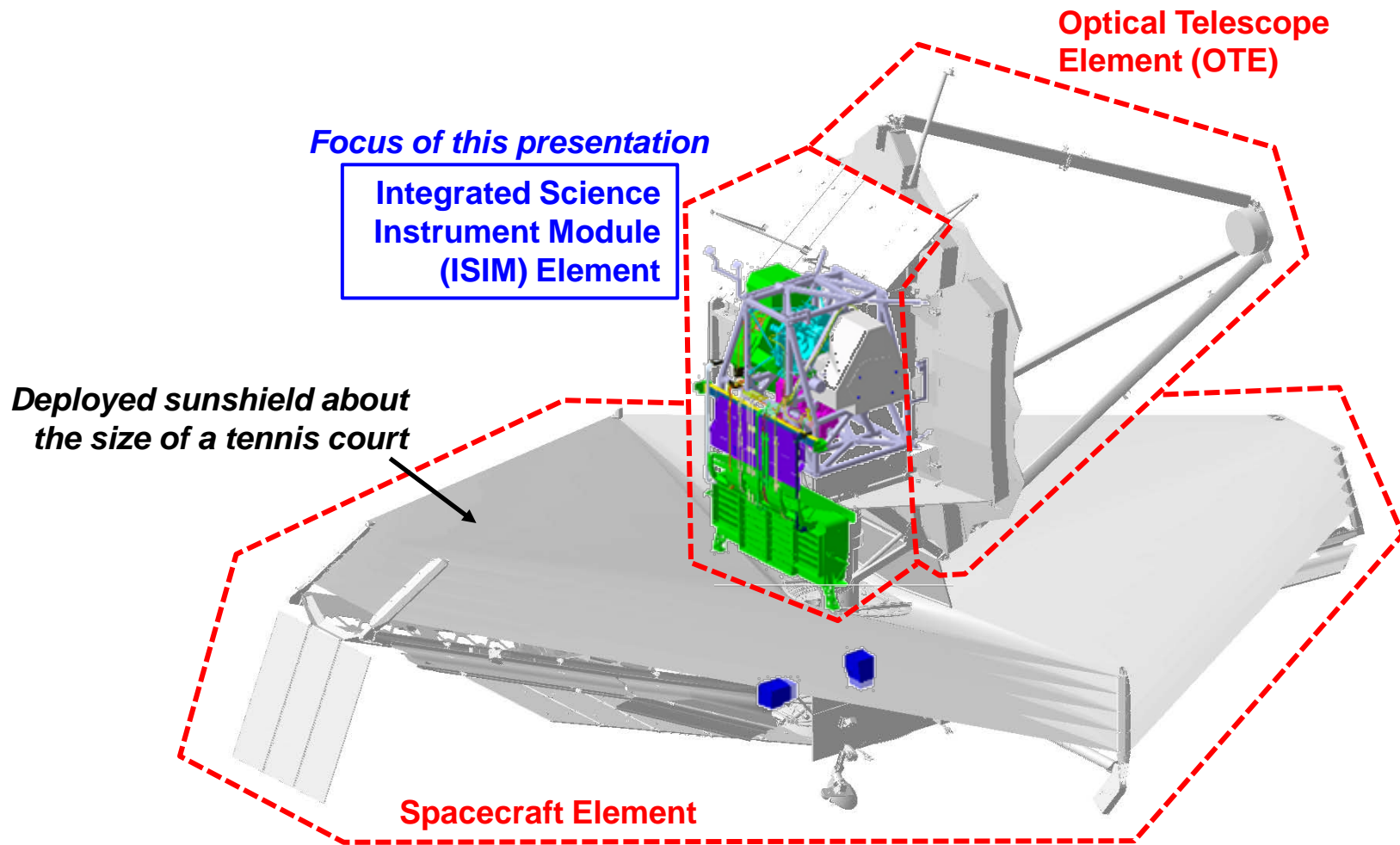
CE	Conducted Emissions
CMCE	Common Mode Conducted Emissions
CS	Conducted Susceptibility
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMV	Electromagnetic Vulnerability
FFT	Fast Fourier Transform
FGS	Fine Guidance Sensor
GSFC	Goddard Space Flight Center
IEC	ISIM Electronics Compartment
IHR	ISIM Harness Radiator
ISIM	Integrated Science Instrument Module
JWST	James Webb Space Telescope
LISN	Line Impedance Simulation Network
NASA	National Aeronautics and Space Administration
MIRI	Mid Infrared Instrument
NIRCam	Near Infrared Camera
NIRSpec	Near Infrared Spectrometer
RE	Radiated Emissions
RMS	Root Mean Square
RS	Radiated Susceptibility

Introduction

- NOTE: This presentation is based on a paper I will be presenting at this year's IEEE EMC Symposium in Ottawa; part of Aerospace EMC special session chaired by Bob Scully
- 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

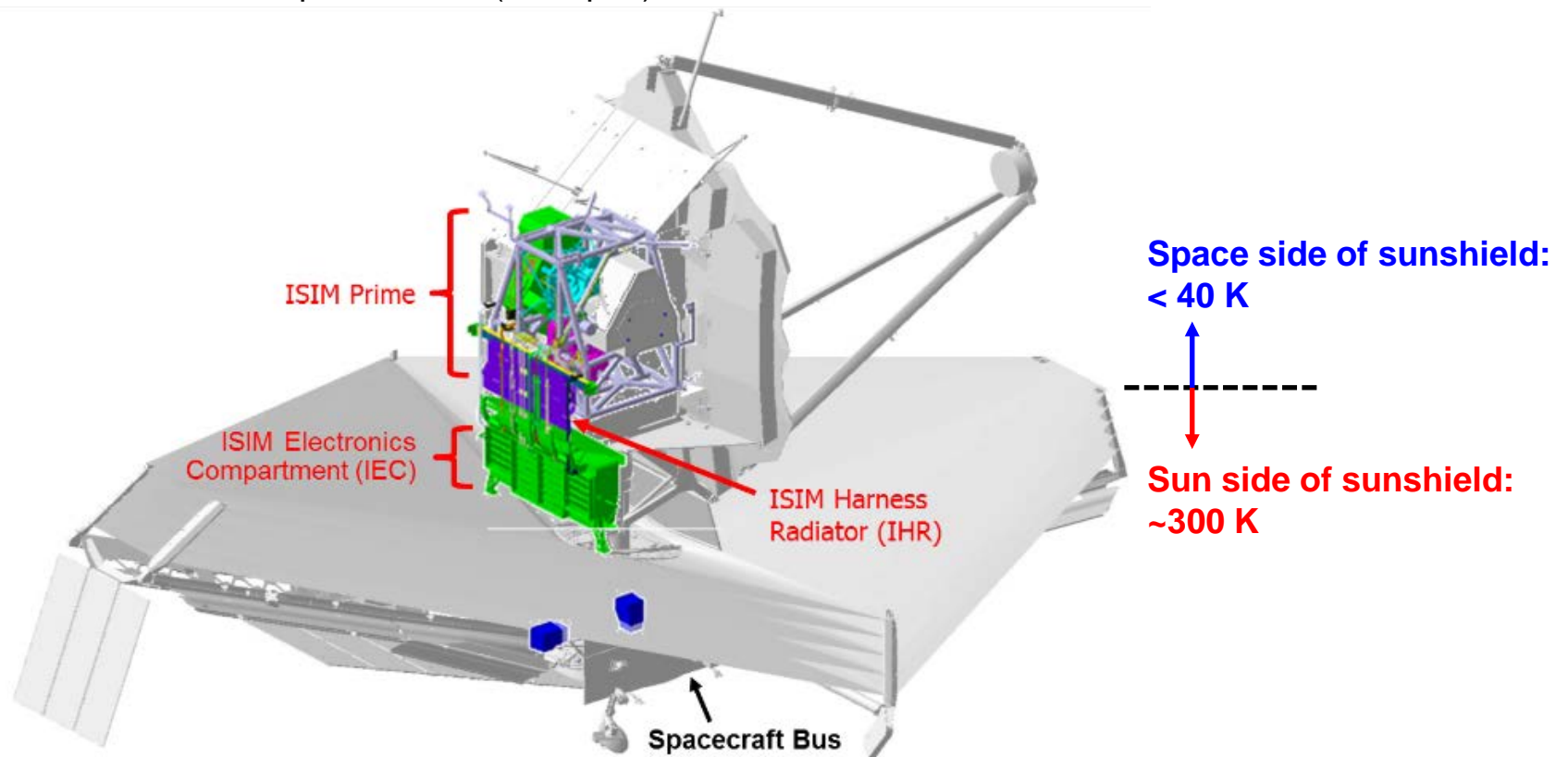


“Elements” of JWST



JWST's science payload is ISIM (Integrated Science Instrument Module), which consists of four instruments:

- Fine Guidance Sensor (FGS)
- Mid-Infrared Instrument (MIRI)
- Near Infrared Camera (NIRCam)
- Near Infrared Spectrometer (NIRSpec)



EMC Challenges for JWST

- Full end-to-end EMC verification not feasible at Observatory level
 - Size (availability of chamber of sufficient size at spacecraft vendor facility)
 - Schedule (time and logistics to transport observatory to another facility)
 - Operating temperature
 - All instruments implement infrared detectors operated at cryogenic temperatures
 - Similar constraints preclude thermal vacuum testing at integrated Observatory level
 - Verification at Observatory level limited to RF self-compatibility
- EMC verification had to be addressed at lower levels
 - Element level, i.e. ISIM, OTE, and spacecraft
 - Instrument level
 - Subsystem/unit level

EMC Challenges for ISIM

- Integrated payload test
 - Not a box, not an integrated observatory (for which criteria are defined)
 - Needed to re-evaluate test criteria (next slides)
- All instruments implement infra-red detectors
 - Operated at cryogenic temperatures in on-orbit configuration
 - Electronics boxes inside IEC operate near 300 K
 - Cables must accommodate this thermal gradient
 - Implement wires and shields made with higher resistance conductors
 - Compromised performance and shielding effectiveness
- This test presented final opportunity to perform radiated testing on ISIM
 - Test was performed at ambient temperature (~300 K)
 - Not expected to affect the power quality or RE
 - Expected to affect the RS; detector response known to be temperature dependent
 - Intra-ISIM compatibility (i.e. instrument-to-instrument crosstalk) was evaluated during ISIM thermal vacuum testing with detectors operating at on-orbit temperatures
- Detector data volume and processing time
 - 18 detector channels
 - 30-45 minutes processing time to evaluate for susceptibility

EMC Challenges for ISIM (cont.)

- ISIM placed on metallic test fixture
 - Non-metallic structure would have been preferable for EMI/EMC, but not practical choice for supporting entire ISIM environmental test campaign
 - Included thermal vacuum, acoustics, vibration
- Contamination concerns
 - Test performed in class 10,000 clean room
 - ISIM was bagged (next slide)

ISIM in GSFC Large EMC Chamber (Class 10,000 clean room)

JWST-PV-082594



EMC Challenges for JWST and ISIM (cont.)

- EMI tests performed at instrument, subsystem, and/or unit level, based on MIL-STD-461C and MIL-STD-462:
 - Conducted Emissions
 - CE01/CE03
 - Common Mode Conducted Emissions (CMCE)
 - Inrush current
 - Conducted susceptibility
 - CS01/CS02
 - CS06
 - Common Mode Conducted Susceptibility (CMCS, CS114 test method)
 - Radiated emissions
 - RE01
 - RE02
 - Radiated susceptibility
 - RS01
 - RS03

**NO NEED TO REPEAT THESE
TESTS AT ISIM LEVEL**

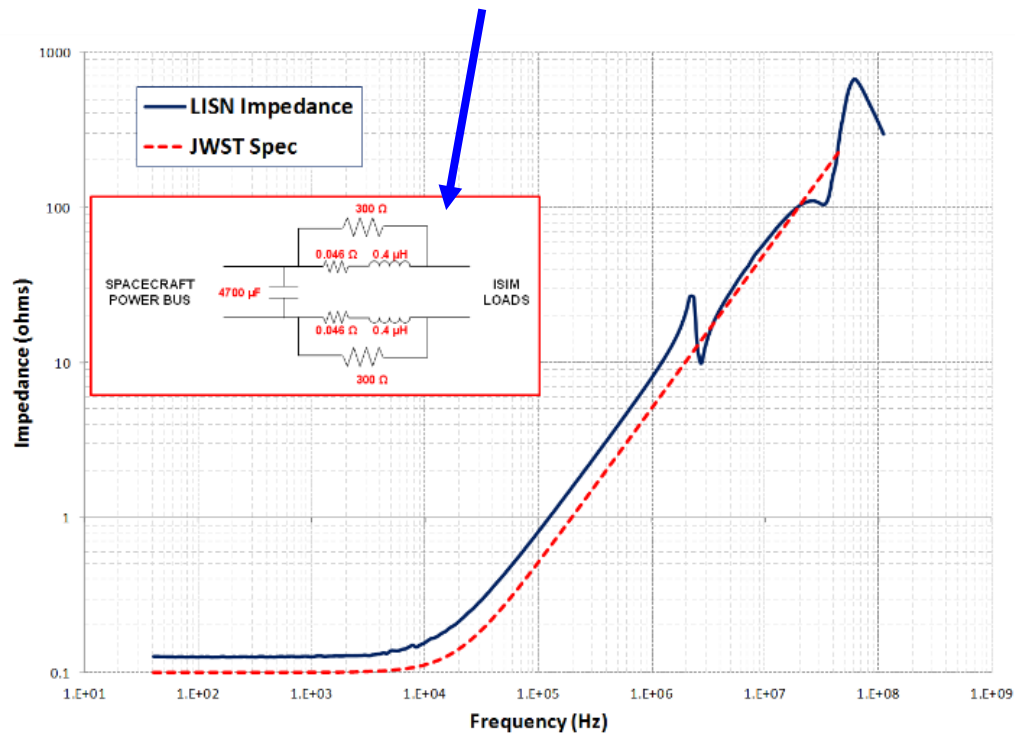
EMC Challenges for JWST and ISIM (cont.)

- Re-Evaluated ISIM level test criteria:
 - Power Quality
 - Aggregate bus ripple
 - Time domain
 - Frequency domain
 - Transients
 - Turn-on
 - Turn-off
 - Operational (mechanism movements, heaters, etc.)
 - Aggregate Radiated Emissions (RE)
 - On-orbit configuration
 - Launch configuration
 - Aggregate Radiated Susceptibility (RS), a.k.a. Electromagnetic Vulnerability (EMV)
 - On-orbit configuration
 - Launch configuration

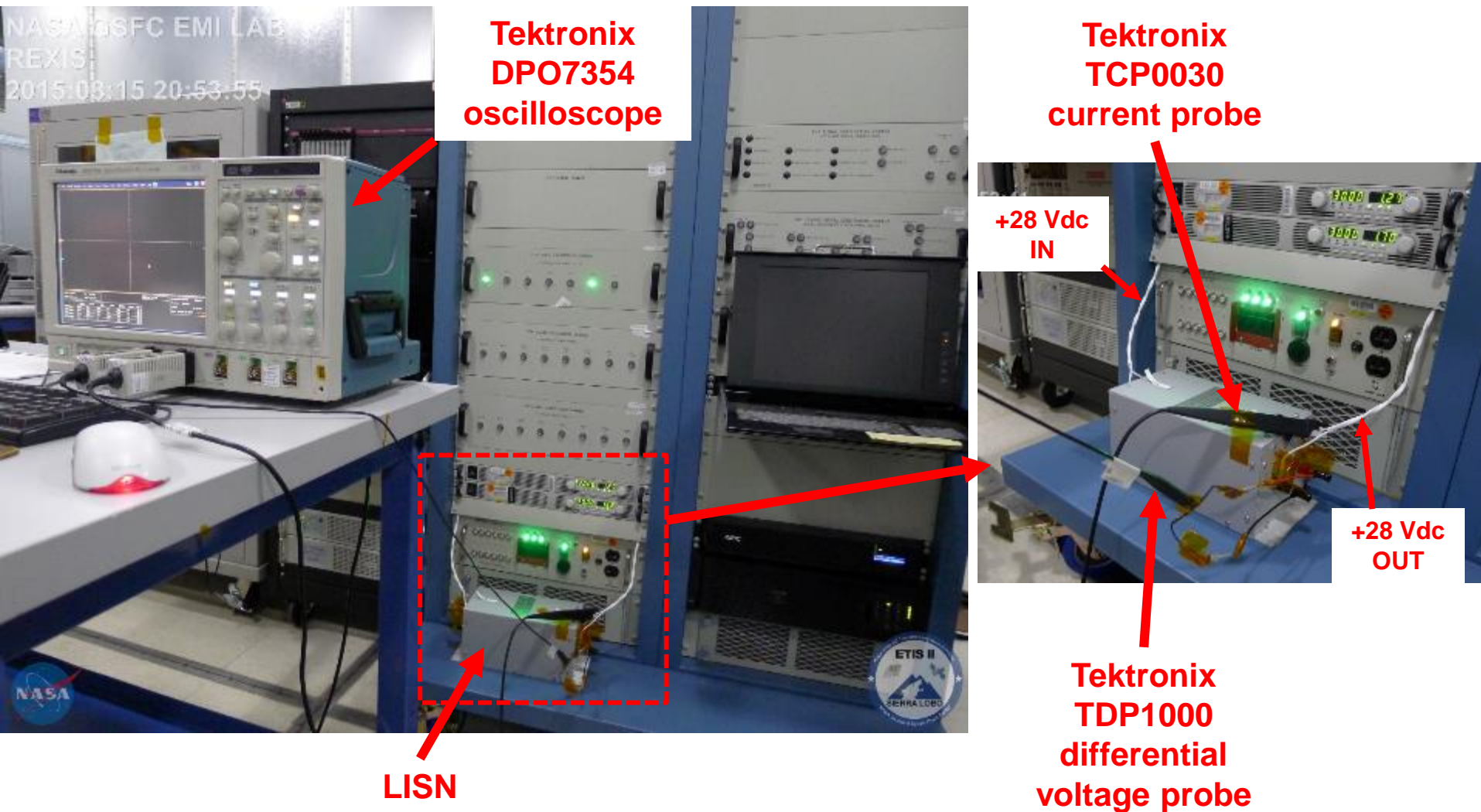
Power Quality Measurements with JWST Custom LISN



Modeled from spacecraft
source impedance



Power Quality Measurements with JWST Custom LISN (cont.)



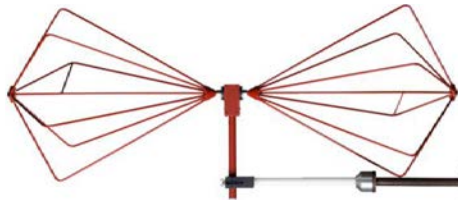
Power Quality Measurements Summary

(Details in backup slides)

- Aggregate bus ripple
 - Time domain
 - Largest measured ripple: 168 mV p-p
 - Requirement: 1 V p-p
 - Frequency-domain
 - Largest measured signal: 615 μ Vrms at ~64 MHz
 - JWST CS01/CS02 requirement: 1 Vrms from 30 Hz to 400 MHz
- Transients
 - Most transients were within CS06 pulse amplitude and duration
 - In all cases, bus potential was maintained well within the range of 22 to 35 VDC to which each electronics box was tested at unit level

**POWER QUALITY IS NOT EXPECTED
TO BE A PROBLEM ON THE
INTEGRATED OBSERVATORY**

Radiated Testing – Antenna Selection



BICONICAL (ETS Lindgren 3110C)

Frequency range: 30 MHz – 200 MHz

Linearly polarized

Need horizontal and vertical polarizations at each position



CONICAL LOG SPIRAL (ETS Lindgren 3101)

Frequency range: 200 MHz – 1 GHz

Used outside of S-band notch

Circularly polarized

Measures both polarizations simultaneously

3 dB beamwidth of ~ 60 degrees



CONICAL LOG SPIRAL (ETS Lindgren 3102)

Frequency range: 1 GHz – 10 GHz

Used outside of S-band notch

Circularly polarized

Measures both polarizations simultaneously

3 dB beamwidth of ~ 60 degrees



DOUBLE-RIDGED GUIDE (ETS Lindgren 3117)

Frequency range: 1 – 18 GHz

Used for S-band notch measurements

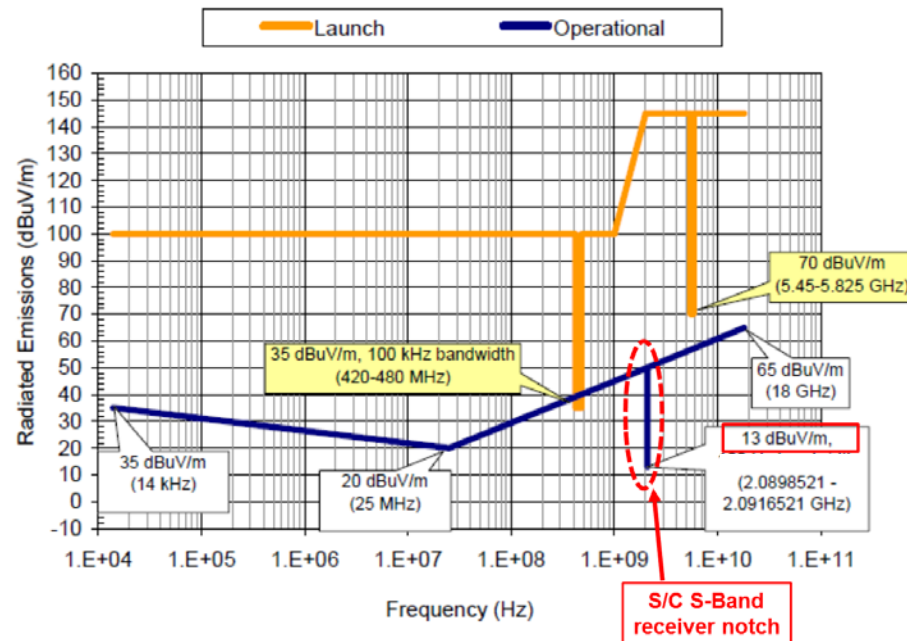
Linearly polarized

Need horizontal and vertical polarizations at each position

Images courtesy of ETS-Lindgren

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
- Criteria:
 - ISIM must not generate any emissions that could interfere with S-band receiver, which operates in frequency range of 2.0898521 - 2.0916521 GHz, limit of 13 dB μ V/m
 - Outside of S-band, radiated emissions test provides a very sensitive check that cable quality and electrical bonding of the ISIM is of a similar quality to that evaluated during box-level EMI qualification



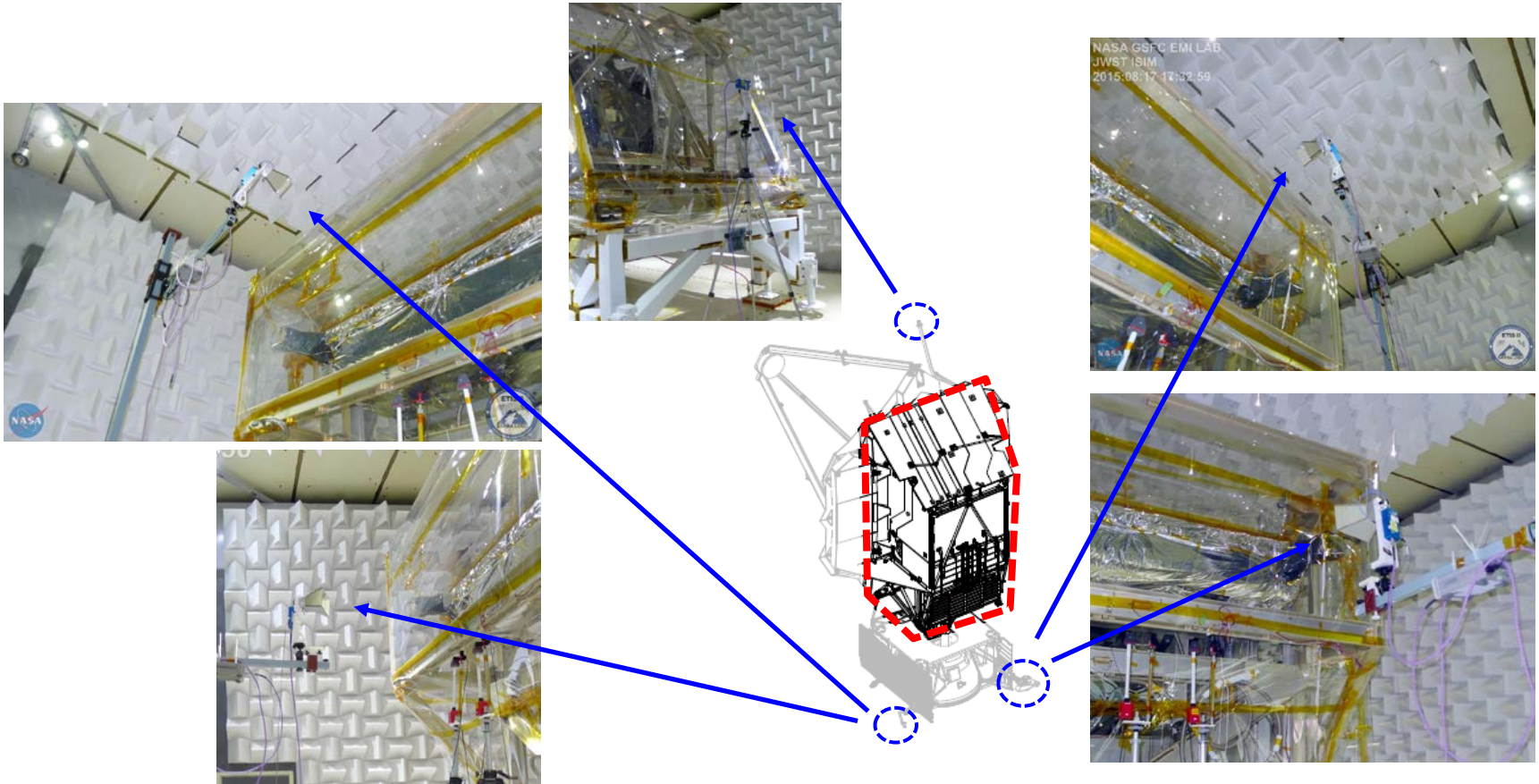
Aggregate Radiated Emissions (cont.)

- Mechanism Movements

- Each instrument included a set of mechanisms (e.g. filter wheels, focus mechanisms, etc.)
 - Operated at the on-orbit temperatures below 40 K
 - Most mechanisms had limited allocations for operation at ambient temperature
- Most sensitive victim that is being protected by RE test is S-band receiver
 - 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 (recommended in the recently released MIL-STD-461G)

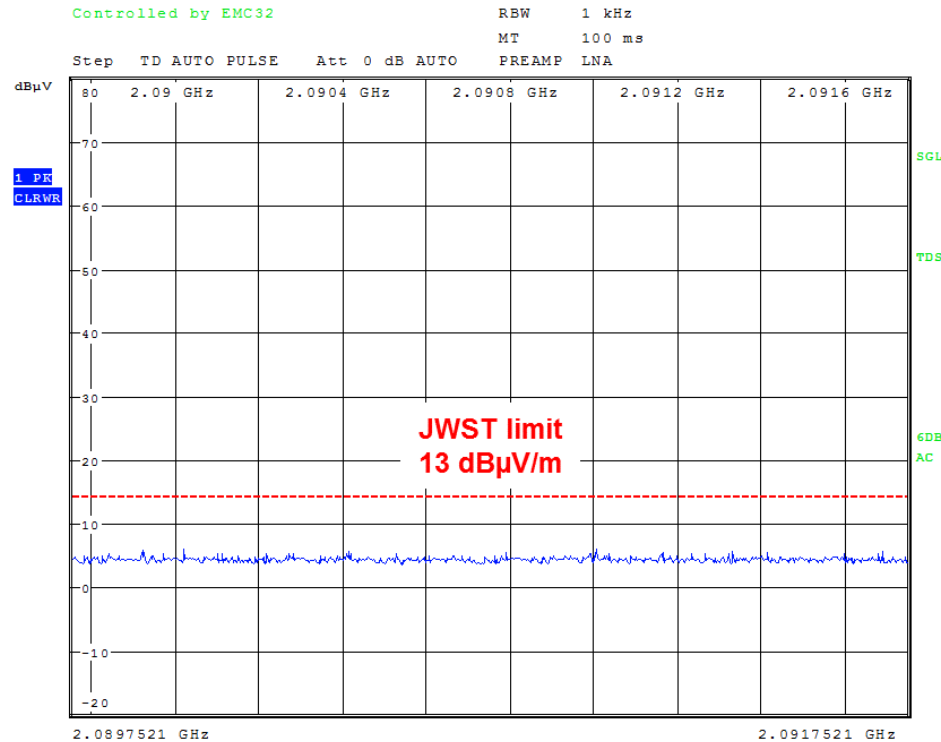
Aggregate Radiated Emissions (cont.)

- Considerations for antenna locations
 - Representative of relative locations of the S-band antennas on spacecraft
 - Multiple locations to address possible reflections from metallic structure
 - S-band notch level of 13 dB μ V/m requires DRG (conical log-spiral does not have required sensitivity)



Aggregate Radiated Emissions (cont.)

- All RE scans compliant
- Inside and outside S-band notch



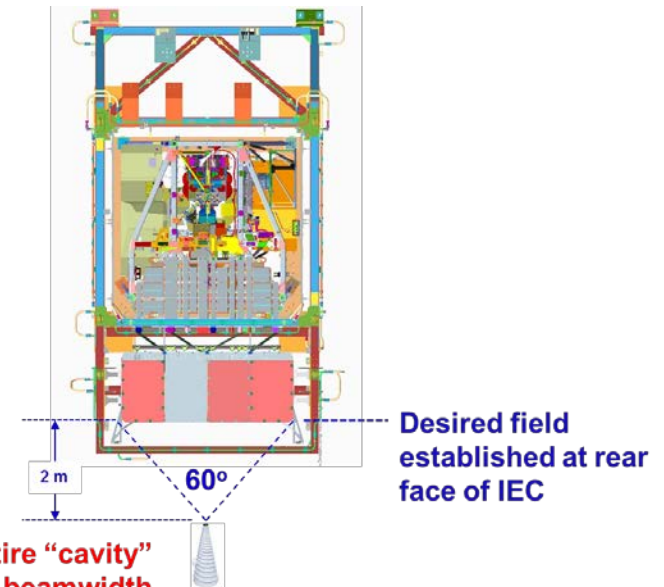
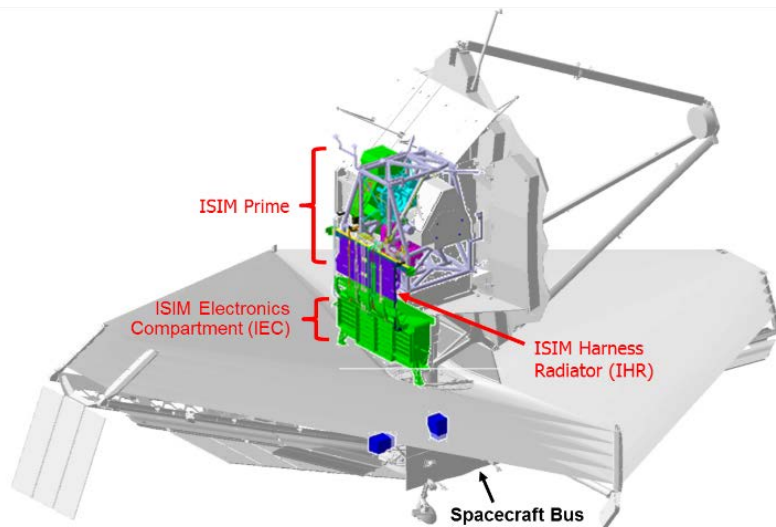
ALL SCANS SIMILAR

Test No.087

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Aggregate Radiated Susceptibility

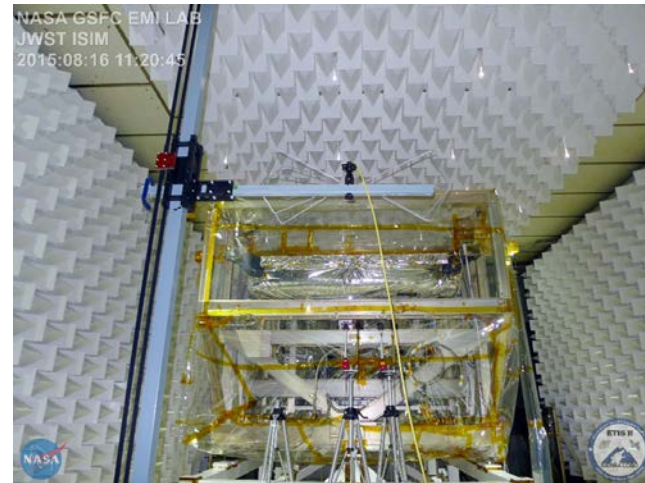
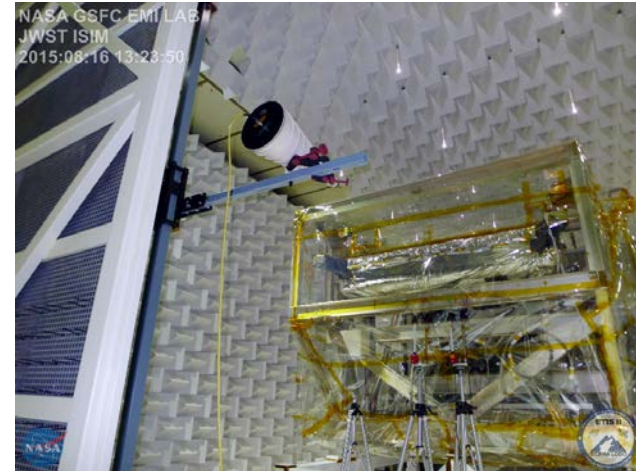
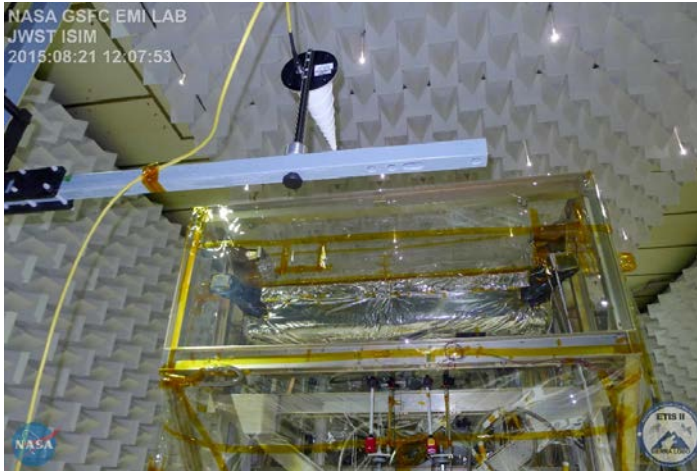
- Test antennas placed to simulate radiated energy from direction of spacecraft
- By moving antenna back to distance of 2 m, entire IEC “cavity” could be illuminated with a single position (HUGE time savings)



At $r = 2$ m, the entire “cavity”
is within the 3 dB beamwidth
of the antenna

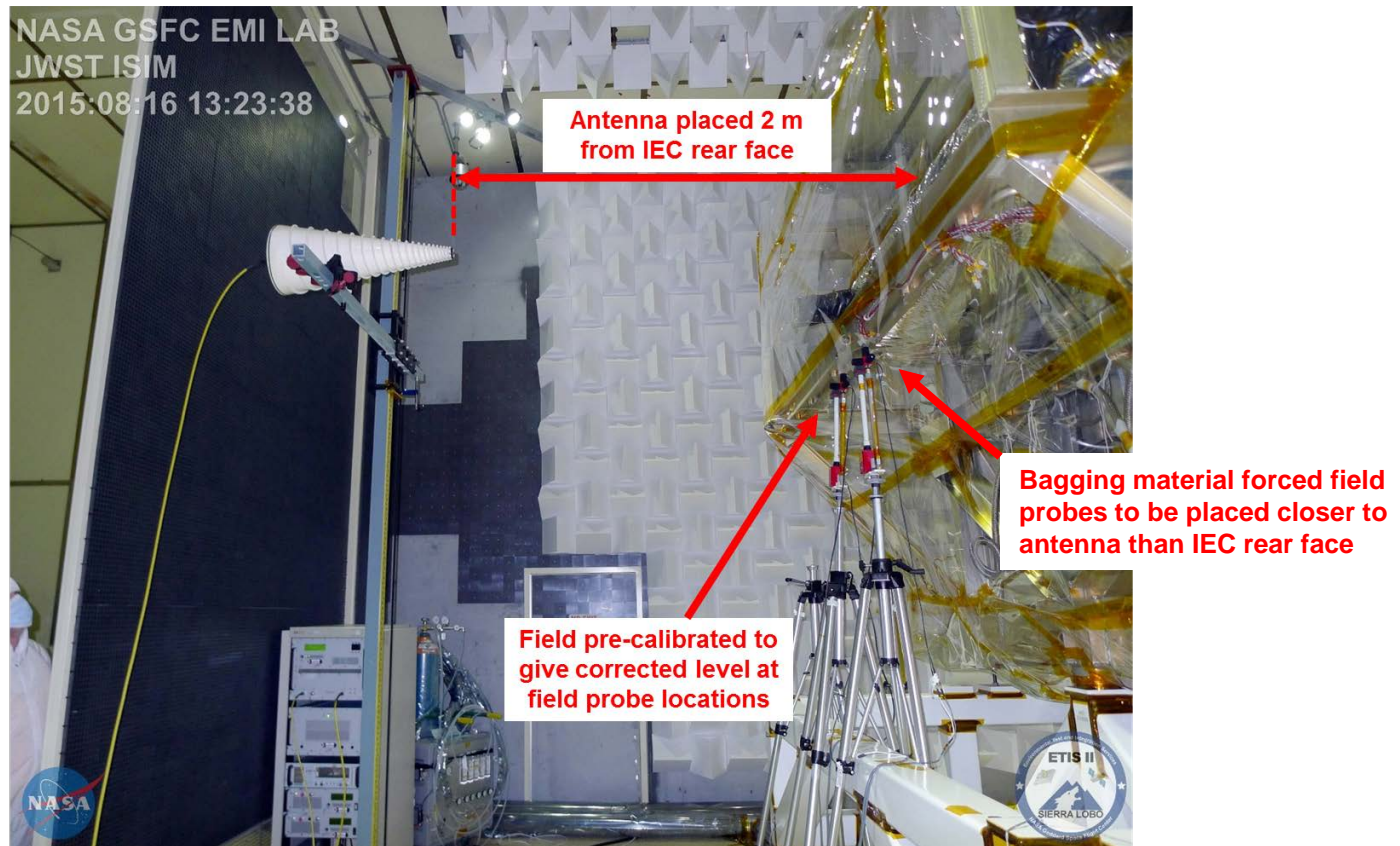
Aggregate Radiated Susceptibility (cont.)

- Single antenna position to cover IEC cavity



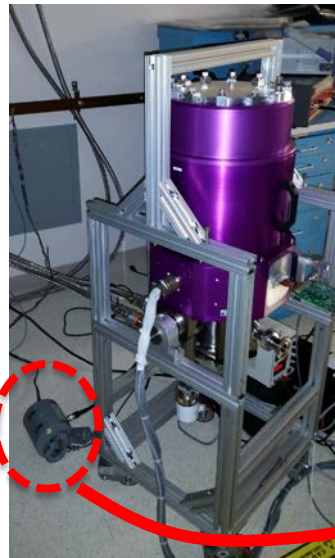
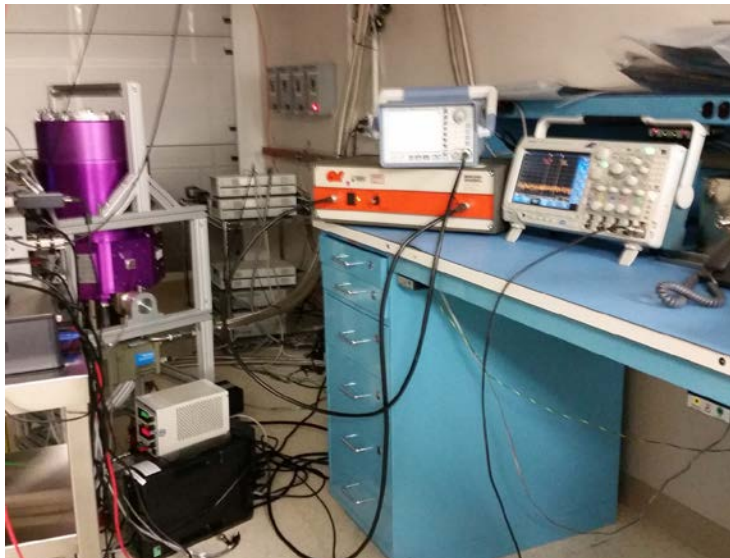
Aggregate Radiated Susceptibility (cont.)

- Field pre-calibrated and corrected for probe locations
 - Distance from antenna (1.78 m to probes vs. 2 m to antenna)
 - Probes near edge of 3 dB beamwidth



Aggregate Radiated Susceptibility (cont.)

- Adjustment of Field Levels for Ambient Operations
 - JWST on-orbit RS limit is 2 V/m, 14 kHz – 18 GHz
 - Applies at on-orbit operating temperatures of < 40 K
 - ISIM level test was to be performed at room ambient temperature (~ 300 K).
 - Prior to ISIM tests, detector susceptibility at ambient vs. cryo temperatures was characterized using CS114 test method of MIL-STD-461F
 - For given culprit signal, signal-to-noise ratio at room temperature was $\sim 10\times$ lower than at cryo temperature
 - At either temperature, amplitude of coupled signal was approximately proportional to square of the voltage/current of applied signal

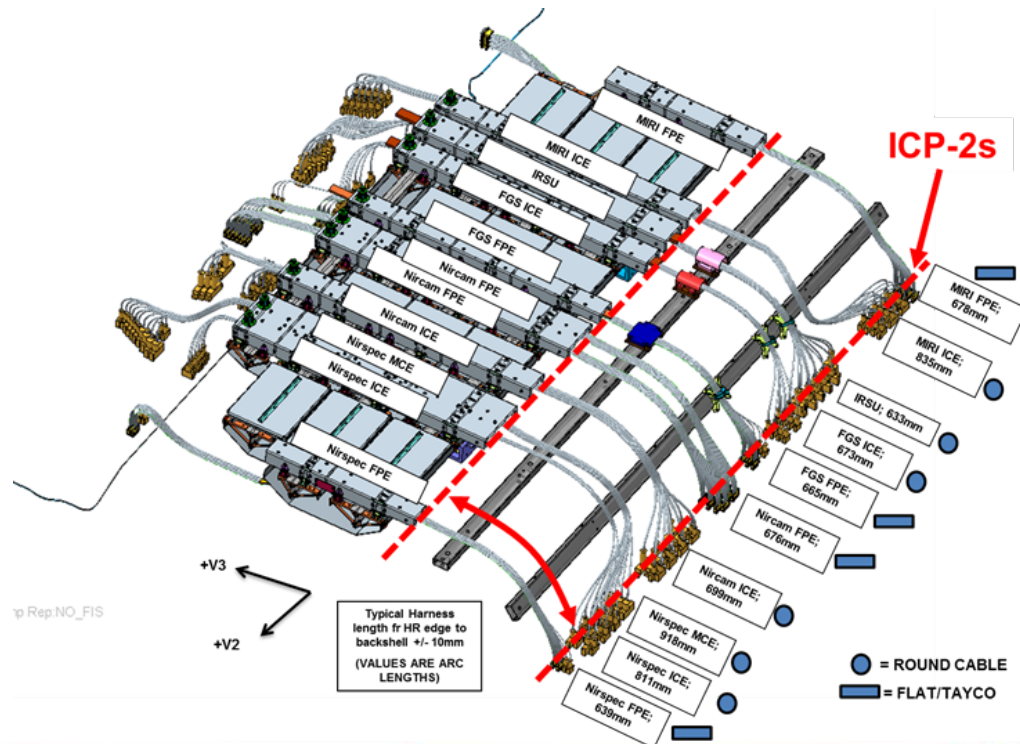


Aggregate Radiated Susceptibility (cont.)

- Adjustment of Field Levels for Ambient Operations (cont.)
 - Equivalent applied field level at room temperature is $\sqrt{10}$ x higher than desired level at cryo temperature
 - 2 V/m at cryo temperature converts to 6.3 V/m at room temperature
 - In order to characterize the radiated susceptibility at on-orbit operating temperature, it was decided to apply pre-calibrated electric field intensities of the following levels:
 - 6.3 V/m (full level)
 - 3.1 V/m (6 dB down from full level)
 - 2.0 V/m (10 dB down from full level)
 - Playing back pre-calibrated levels proved very efficient
 - Facilitated successive scans at the different levels
 - No delays from waiting for the 30-45 minute processing time
 - Pre-calibrations took 1 day; RS scans completed in 1 day
 - Real time levelling would likely have taken at least twice as long and posed higher risk of overtest

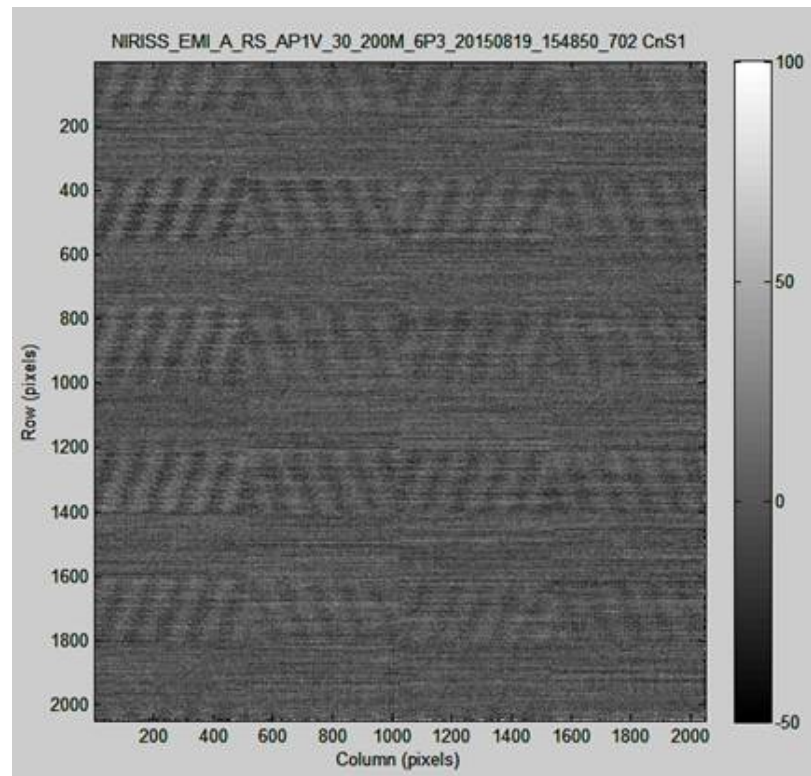
Aggregate Radiated Susceptibility (cont.)

- Detector subsystems showed susceptibilities at instrument/subsystem level
 - At frequencies in 10s of MHz range
 - Likely resonant lengths of exposed cables (4-6 m)
- Exposed cable lengths are different in integrated ISIM configuration
 - 0.6 – 0.7 m
 - Susceptibilities expected to shift to 100 – 300 MHz range



Aggregate Radiated Susceptibility (cont.)

- Modulation enhances visibility of susceptibility at any given frequency
 - “Herring bone” pattern in example plot below
 - More obvious in statistical analysis
- Without modulation, susceptibility produces same offset in all pixels
 - Frame plots and statistical analysis do not show susceptibility (DC shift only)
 - Gives “false positive” result



Aggregate Radiated Susceptibility (cont.)

- Results

- No susceptibilities observed at 2.0 V/m (compliant with JWST requirement)
- Some susceptibilities observed at 6.3 V/m level
 - All in frequency range of 100 - 300 MHz (as predicted)
 - No susceptibility at 6.3 V observed above 300 MHz
- Main culprit on spacecraft is S-band transmitter operating at 2.27 GHz
- Levels of 2 V/m and higher are achievable only from intentional transmitters (not from accidental emissions from electronics)

**RISK OF POTENTIAL INTERFERENCE TO ISIM FROM
SPACECRAFT HAS BEEN ADDRESSED AS
THOROUGHLY AS POSSIBLE**

>12 YEARS IN THE MAKING

THE MAGNIFICENT SEVEN + 1

They tested like eight hundred...

JWST-PV-082594



Summary

- The ISIM EMC Test presented a number of unique challenges
- 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

Acknowledgments

- Many thanks to 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:
 - John Lichtig of Lichtig EMC Consultants for his tireless efforts on many levels
 - 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 of my career, and it was a tremendous honor to be part of it



Thanks for attending!

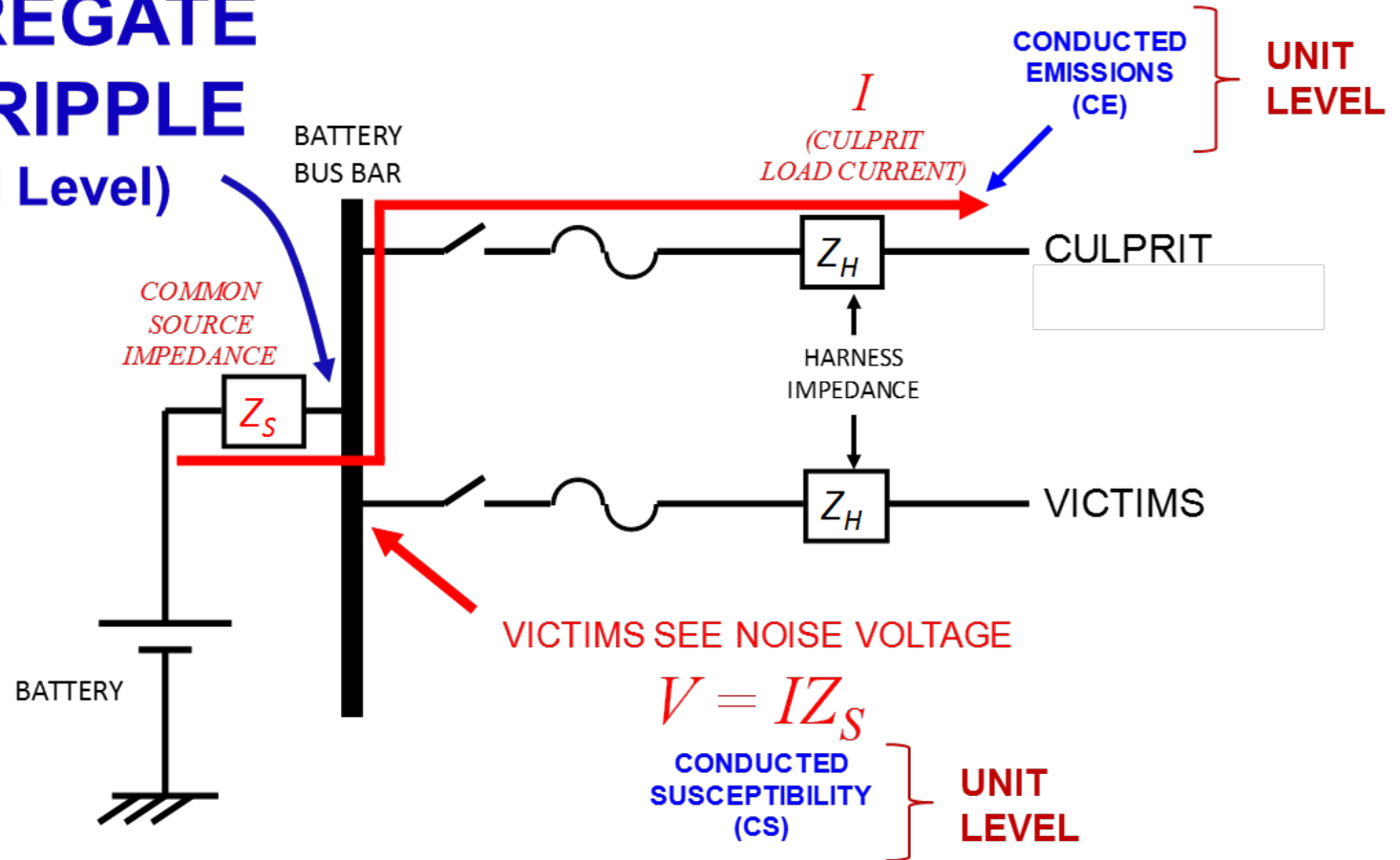
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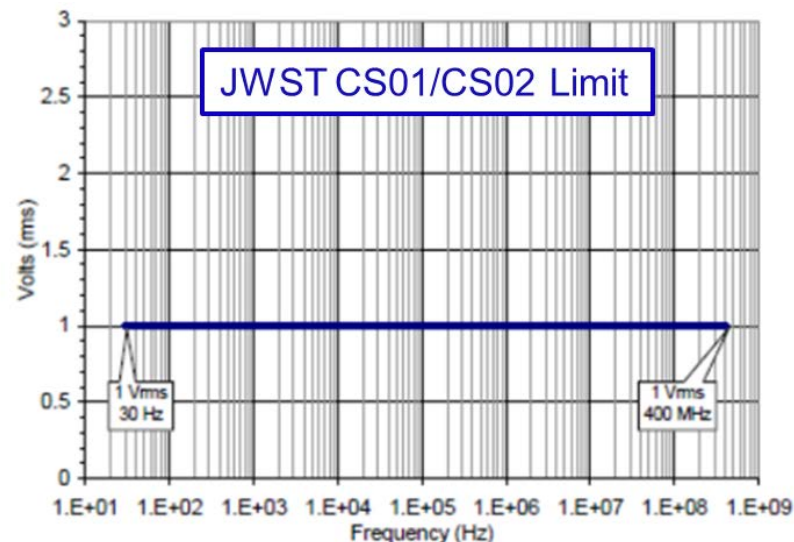
Backup Slides

AGGREGATE BUS RIPPLE (ISIM Level)



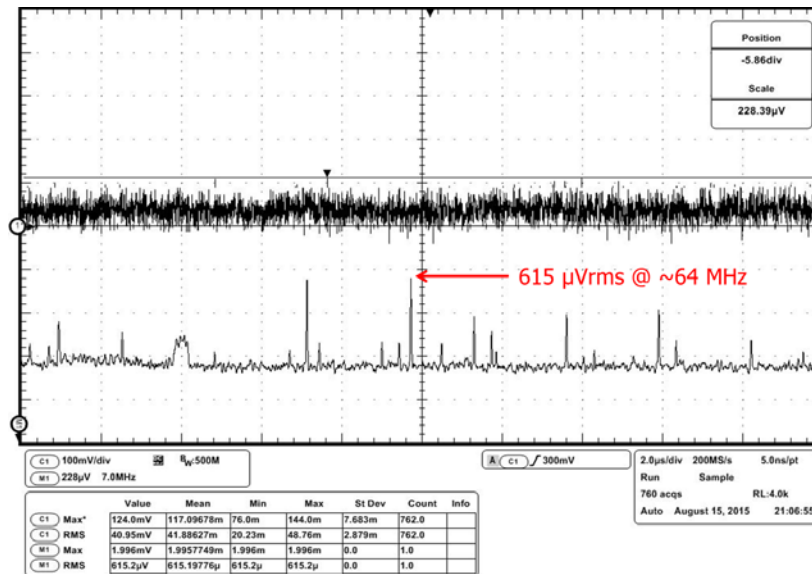
Power Quality Measurements

- Aggregate bus voltage ripple criteria:
 - Time domain
 - JWST requirement at ISIM level
 - Limit: +/- 500 mV peak-to-peak (1 V peak-to-peak)
 - Frequency-domain
 - Not required; engineering data only
 - Easy to perform using oscilloscope with FFT capability
 - Measurements compared to CS01/CS02 limit applied at unit level



Power Quality Measurements (cont.)

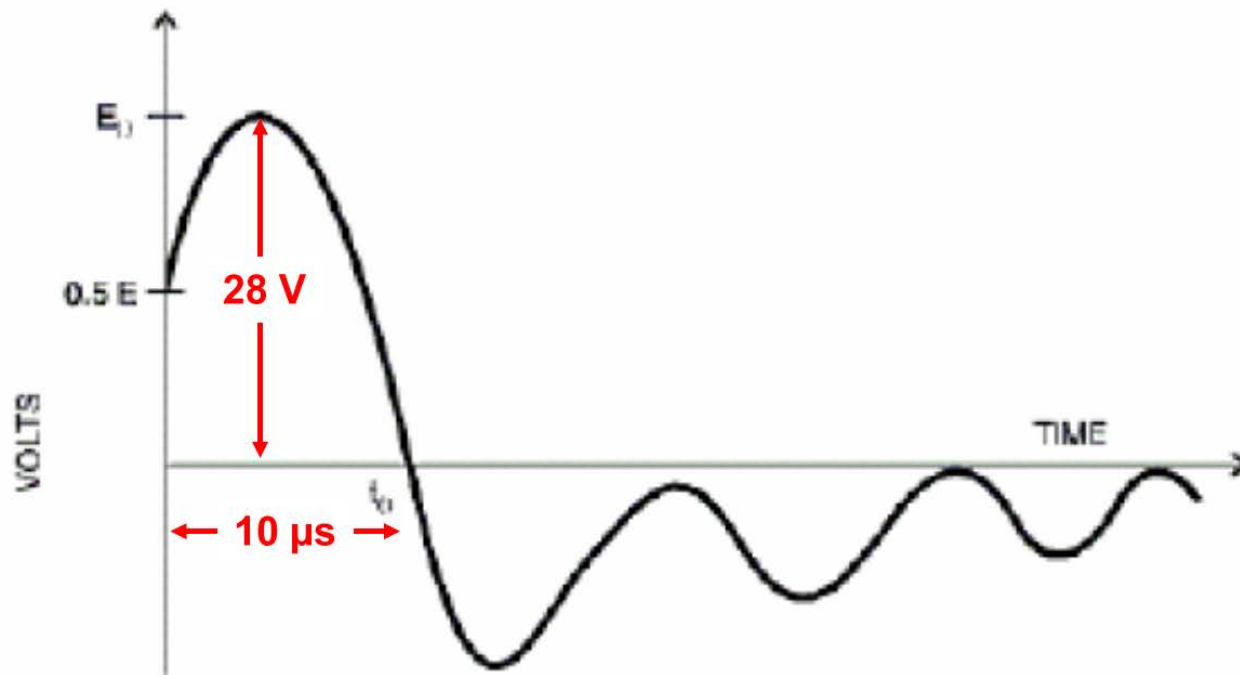
- Aggregate bus voltage ripple results:
 - Time domain
 - Largest measured ripple was 168 mV p-p
 - Well under 1 V p-p requirement
 - Frequency-domain
 - Largest frequency-domain signal measured was 615 μVrms at ~64 MHz
 - Well under 1 Vrms requirement for CS01/CS02



**AGGREGATE VOLTAGE RIPPLE
FROM ISIM IS NOT EXPECTED TO
POSE A PROBLEM AT INTEGRATED
OBSERVATORY LEVEL**

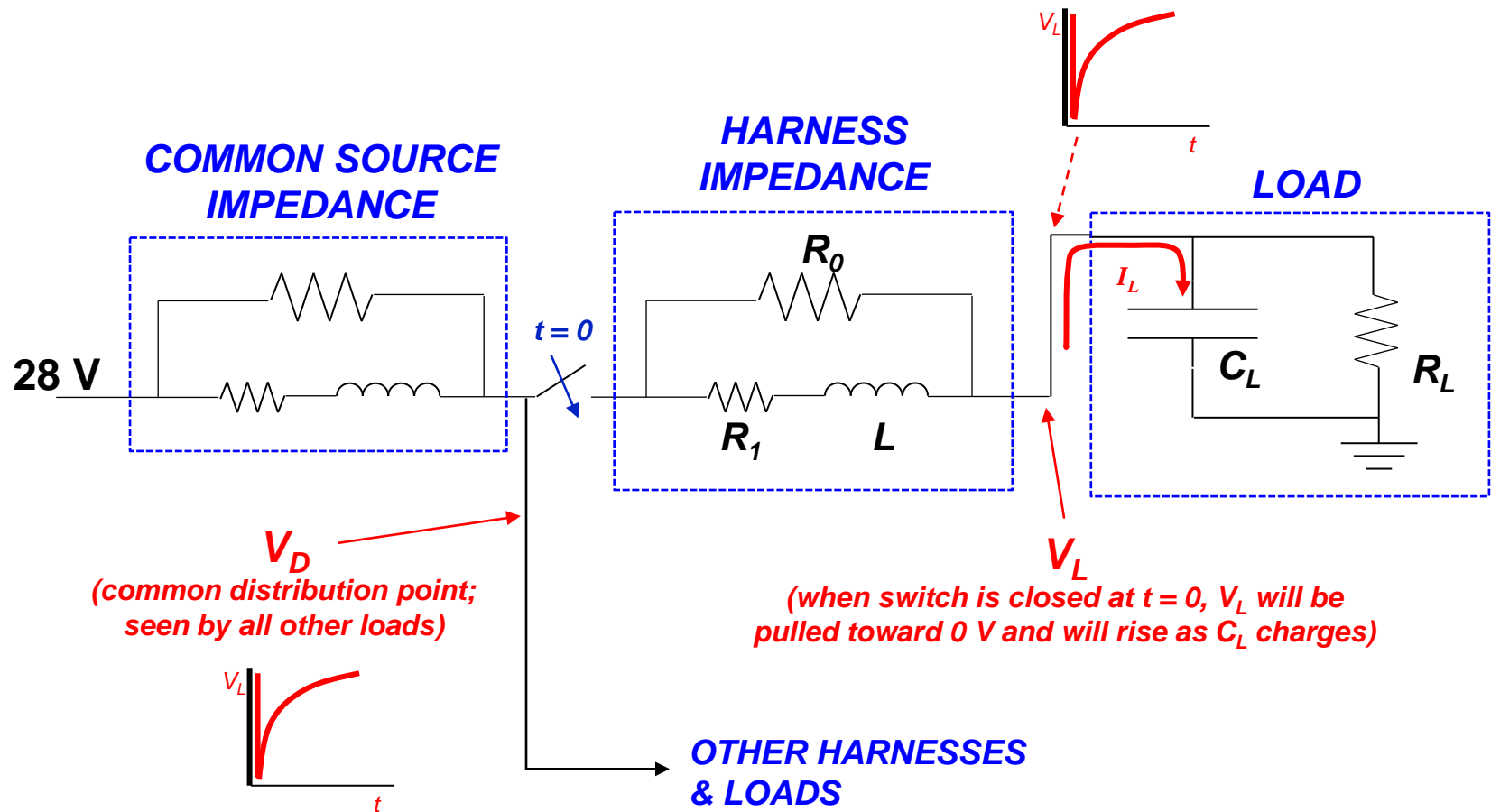
Power Quality Measurements (cont.)

- Turn-on/turn-off transients criteria:
 - Not required; engineering data only
 - “Get it for free” with oscilloscope and LISN already in setup
 - Compare measured transients to CS06 pulse applied at unit level



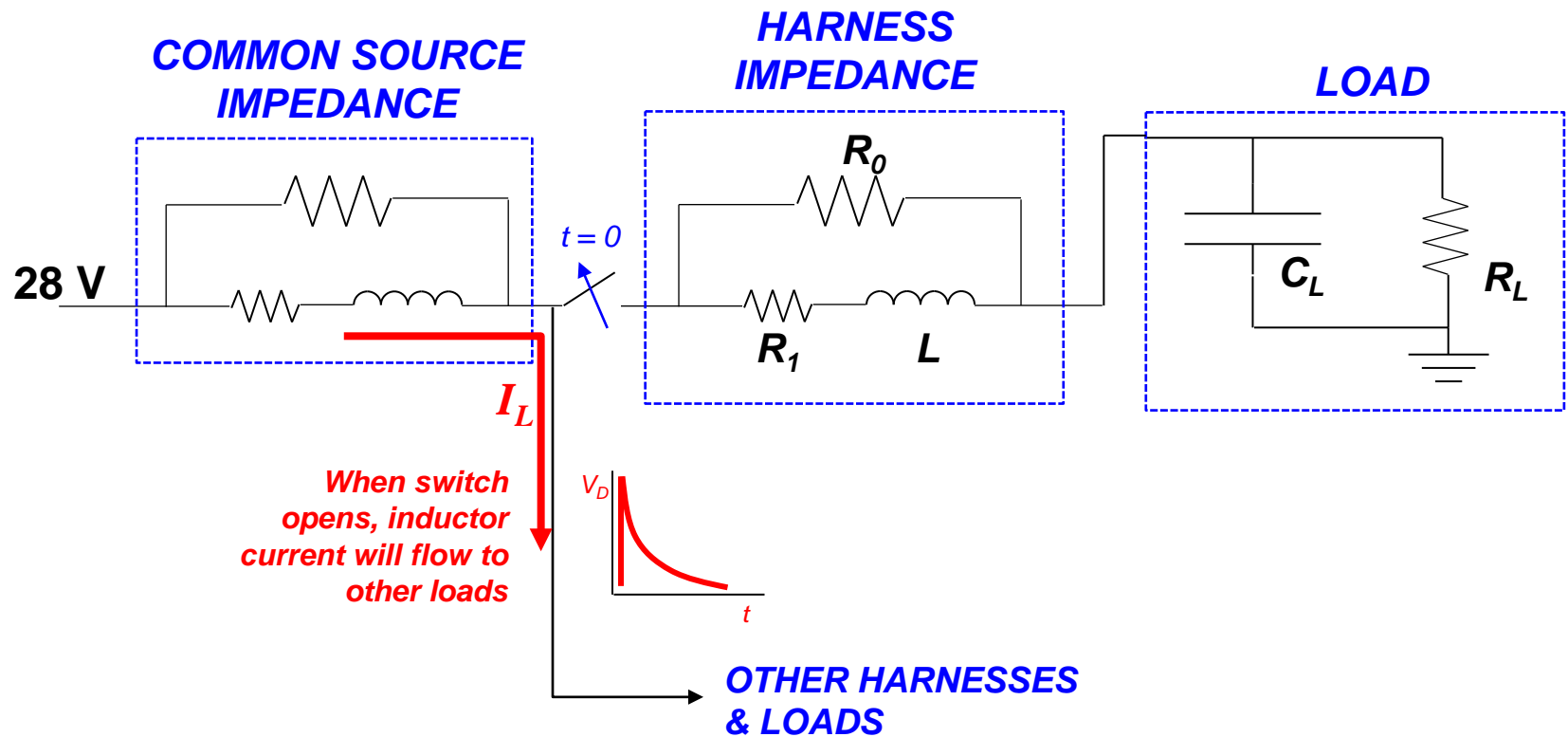
Power Quality Measurements (cont.)

- Turn-on transients



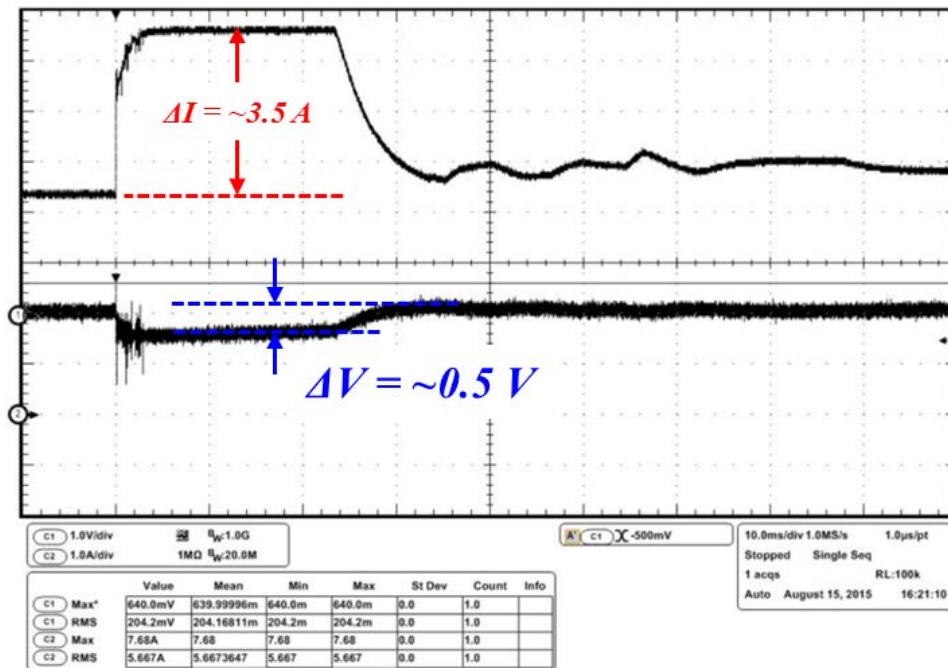
Power Quality Measurements (cont.)

- Turn-off transients



Power Quality Measurements (cont.)

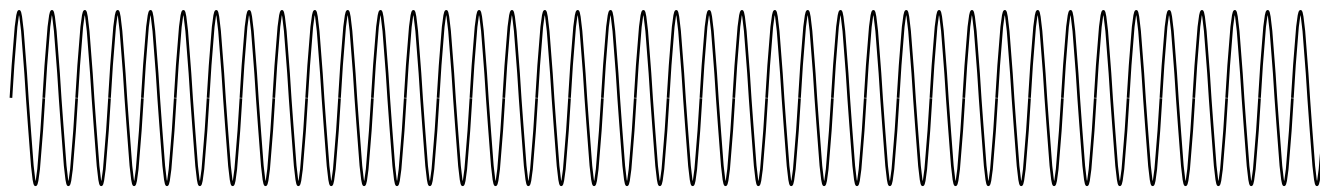
- Turn-on/turn-off transients results:
 - Most transients were within CS06 pulse amplitude and duration
 - Worst case: transient that dropped bus potential by ~ 0.5 V for 25 msec
 - Bus potential was maintained well within the range of 22 to 35 VDC to which each electronics box was tested at unit level



**TURN-ON/TURN OFF TRANSIENTS
FROM ISIM ARE NOT EXPECTED TO
POSE A PROBLEM AT INTEGRATED
OBSERVATORY LEVEL**

Aggregate Radiated Susceptibility (cont.)

- RS criteria for detector subsystems
 - 10 μsec pixel period (100 kHz sampling rate)
 - To first order, noise is determined by taking statistics on pixel data
 - Any frequency above 50 kHz will be under sampled (RS at ISIM level applied >30 MHz)
 - Susceptibility at any given frequency will manifest itself as the total energy integrated over a pixel period
 - At a susceptible frequency, an unmodulated (continuous wave) signal will produce an approximately equally shifted signal in all pixels
 - Performing statistics on such frames may show a shifted mean, but the standard deviation will not look much different from a non-RS frame
 - Observed during instrument/subsystem level tests



**TOTAL ENERGY
INTEGRATED TO GIVE
SAMPLED PIXEL VALUE**



Aggregate Radiated Susceptibility (cont.)

- RS criteria for detector subsystems (cont.)
 - Pulse modulation of RS signals specified by MIL-STD-461F, section 4.3.10.4.2:
 - 1 kHz pulse modulation
 - 50% duty cycle (500 μ sec on, 500 μ sec off)
 - At a susceptible frequency, a pulse modulated signal will produce a frame with groups of 50 “noisy” pixels interspersed with groups of 50 “clean” pixels
 - Susceptibility at any given frequency is much more obvious
 - Also observed during instrument/subsystem level tests

