International Space Station Space Environments Performance and Anomaly Resolution

Spacecraft Anomalies and Failures Workshop
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Referenced Conference Papers

48th International Conference on Environmental Systems
The International Space Station Radiation Environment: Avionics Systems Performance in Low Earth Orbit SEE Environments

Dr. Steve Koontz-NASA JSC (Retired)

Dr. Robert Suggs-NASA MSFC

Dr. John Alred

Courtney Steagall-NASA JSC

Dr. William Hartman-Boeing Company

Dr. Danny Schmidl-Boeing Company

Ben Gingras-Boeing Company

Paul Boeder-NASA Jet Propulsion Laboratory

14th International Symposium on Materials in the Space Environment
External Contamination Integration of Visiting Vehicles on the International Space Station

Dr. Steven Koontz-NASA JSC (Retired)

Dr. Erica Worthy-NASA JSC

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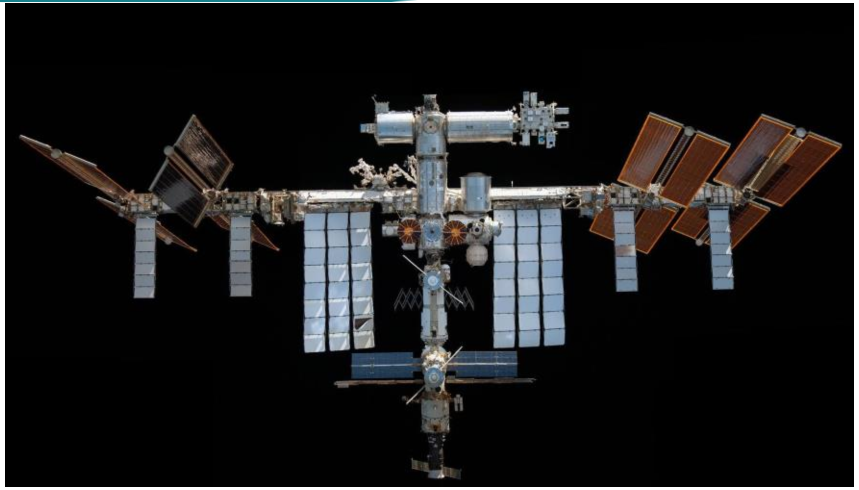
ISS Space Environments

- The International Space Station is the largest and most complex on-orbit platform for space science utilization in low Earth orbit.
- The Space Environments Team addresses natural and induced environments for the ISS Program including external contamination, ionizing radiation, neutral atmosphere and solar ultraviolet radiation, plasma effects, and acoustics.
- For the ISS to fulfill its mission as a long-duration science platform, space environments effects are assessed, monitored, and controlled through design or operational mitigation
- Interactions of ISS hardware with the natural and induced space environments, and the assessment and mitigation of those effects play a critical role in ISS mission operations
- The Space Environments Team has complete system integration responsibility in these area for U.S./International Partner/Russian hardware, visiting vehicles, ISS payloads and operation
- Lessons learned and processes developed for ISS are applicable to the design, assembly, and operations of long-duration space systems



Public Image courtesy of NASA

ISS Space Environment Team

- The Space Environments team is responsible for integration, verification, and on-orbit operations with mission planning support for visiting vehicles and utilization for International Space Station (ISS) as well as on-orbit anomaly resolution for the following technical disciplines:
  - Acoustics
  - External Contamination
  - Ionizing Radiation
  - Plasma
- The Space Environments team also participate in Mission Evaluation Room (MER) activities as needed for these four disciplines.
- Because of its unique qualifications, the ISS Space Environments team identifies on-orbit issues of concern to the ISS Program and lead/assist investigations to quantify induced environments issues and develop operational strategies to mitigate impacts from them.

ISS Space Environments

- Multiple sites for external payloads, with exposure to the associated natural and induced environments, are available to support a variety of space science utilization objectives.
- Contamination is one of the induced environments that can impact performance, mission success and science utilization on the vehicle.
- The ISS has been designed, built and integrated with strict contamination requirements to provide low levels of induced contamination on external payload assets.

Space Radiation

ISS Space Radiation

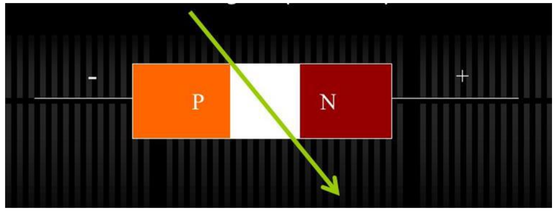
- What are Single Event Environments/Effects (SEE) and why do we care about them?
  - SEE environments consist of the energetic charged particle components of space radiation environments
  - SEE effects are observed when a single charged particle passes through a susceptible microelectronic device causing device anomalies/failures that propagate to system level anomalies/failures
  - SEE effects are an important safety, reliability and mission success issue for spacecraft avionics systems.
- International Space Station (ISS) Natural/Induced SEE Environments
  - 51.6 degrees orbital inclination and ~ 400 km flight altitude determine natural SEE environments
  - Latitude dependent geomagnetic shielding of galactic cosmic rays (GCR) and solar particle events (SPE)
  - Geomagnetic trapping of charged particles create the south Atlantic anomaly (SAA)
  - Avionics systems SEE environment depends on ISS shielding mass processing of the natural SEE environment

ISS Command and Data Handling System (C&DH) Multiplexer de-Multiplexer (MDM) Flight Performance

- System design and pre-flight test/verification approach
- Latitude, geographic region, and shielding mass dependence of total single event upset (SEU) counts in ISS
- MDM dynamic random-access memory (DRAM) between 2010 to 2017.
- Monthly average MDM SEU count timeline from 2005 to 2018
  - Solar cycle, Solar Particle Event, altitude, and shielding mass effects
- ISS MDM SEE functional interrupt (SEFI)
  - Geographic dependence
  - Timeline

Single Event Effects Overview

- Single Event Effects (SEE) are those errors, anomalies or failures in microelectronic devices caused by the passage of a single energetic charged particle through the device.
- The charged particle produces ionization/excitation on passage through microelectronic device materials
  - Ionization in the device “sensitive volume” (SV) can cause SEE
  - Every PN junction (and associated depletion region) in solid state microelectronic devices is a potential SV
- Charged particle Linear Energy Transfer, LET, is a measure of how much ionization the charged particle can produce by “direct ionization”
  - LET = dE/dL = a function of charged particle atomic number, z and velocity, v, [(z/v)2] as well as target material electron number density which depends on density, atomic charge number, and atomic mass number
  - LET units used for microelectronics work = (MeV cm2)/mg (Si)
  - High LET => more ionization => greater microelectronics SEE threat
- Charged particles with LET too low to cause SEE by direct ionization can produce high LET nuclear reaction products on collision with device materials nuclei in or near the SV
  - Energetic protons and neutrons cause SEE primarily via in-device nuclear reactions
  - Heavier GCR ions (Z > 1) cause SEE primarily by direct ionization
  - With very few device specific exceptions, natural environment energetic electrons and photons do not cause SEE



A reverse biased PN junction diode. The energetic charged particle produces charge carriers along its track (green arrow) through the depletion region

ISS Radiation SEE Induced Environments

- **Galactic Cosmic Rays (GCR)**
  - Latitude dependent geomagnetic shielding
  - Little or no effect on higher energy GCR (> 20 GeV/n)
- Primary cause of ISS avionics systems SEE
- **The Van Allen Belts (SAA)**
  - Mostly lower kinetic energy protons (than GCR or SEP)
  - Secondary cause of ISS avionics SEE
- **Solar Particle Events (SPE)**
  - Latitude dependent geomagnetic shielding
  - Predominantly lower kinetic energy protons (than GCR), but higher kinetic energy than SAA protons
  - No observable effects on ISS avionics systems to report to date
- **Shielding Mass Effects (Induced Environments)**
  - Space radiation charged particles collide with ISS materials
  - Observable increase in SEE rates with increasing shielding mass in some cases

SEE Concerns

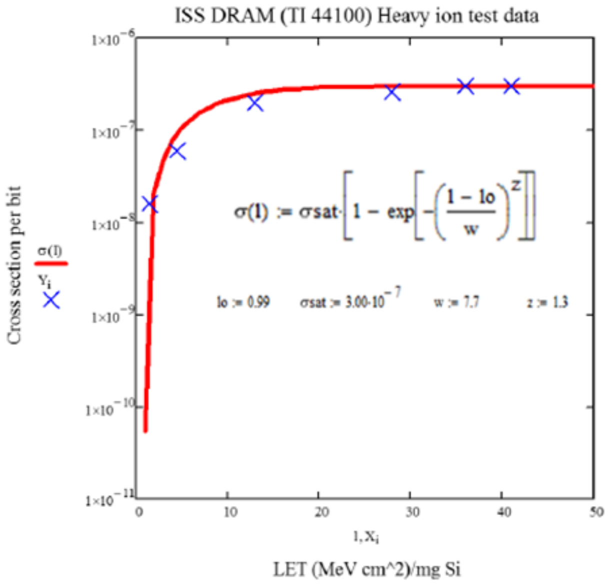
- **Meeting Program Reliability and Mission Success Requirements**
  - Performance based specification (primary ISS requirement)
    - The probability of losing any mission success or safety critical system or subsystem functionality must meet program requirements, during the specified time interval, and in a specified operational environment.
    - Verified by test and analysis at the part, subassembly, subsystem, and system levels prior to flight
  - Prescriptive specification (secondary ISS requirements – avionics systems assembly and manufacturing)
    - Mandates specific parts, manufacturing and assembly procedures believed to maximize safety and reliability
    - Verified by inspection for compliance with the mandate
- **SEE in avionics systems are a potential system failure cause, i.e. a possible cause of not meeting program requirements**
  - The most common hazard effects of the SEE space radiation hazard cause are:
    - Avionics system anomalies
      - Single event effects leading to loss of safety related “must-work must-not-work” functions
    - Electrical power system anomalies
      - Destructive failures of MOS power transistors
- **ISS uses a performance based SEE specification** and part of this presentation is to demonstrate how well that worked.

Design and Preflight Test & Verification Approach

- Nearly 50 standard Multiplexer De-Multiplexers (MDMs) on ISS, were configured as a distributed computing network
- The ISS MDM system is configured as a three-tiered parallel redundant system
  - Tier 1 MDMs (system wide control functions) are two fault tolerant,
  - Tier 2 MDMs (subsystem control functions) are single fault tolerant
  - Tier 3 MDMs are 0 (really 0.5) fault tolerant (numerous sensors and effectors)
- C&DH Fault Detection Isolation and Recovery (FDIR) functions
  - Bus failures
  - MDM failures
- Each Standard MDM consists of a power supply and an Input/Output Control Unit (IOCU) Card
  - Each IOCU card contains an 80386SX processor, a 1553 Bus Interface adaptor and a total of 33,554,432 bits of DRAM memory configured from 8 Texas Instruments TMS 1Mx4 DRAM memory devices
  - A Hamming code single-error-correction-double-error-detection algorithm is imbedded in the DRAM refresh cycle – SEU bad bit residence time < 10 microseconds
  - DRAM SEU events (along with time of occurrence and ISS location) are reported to the ground via ISS telemetry

ISS MDM Preflight Test and Verification

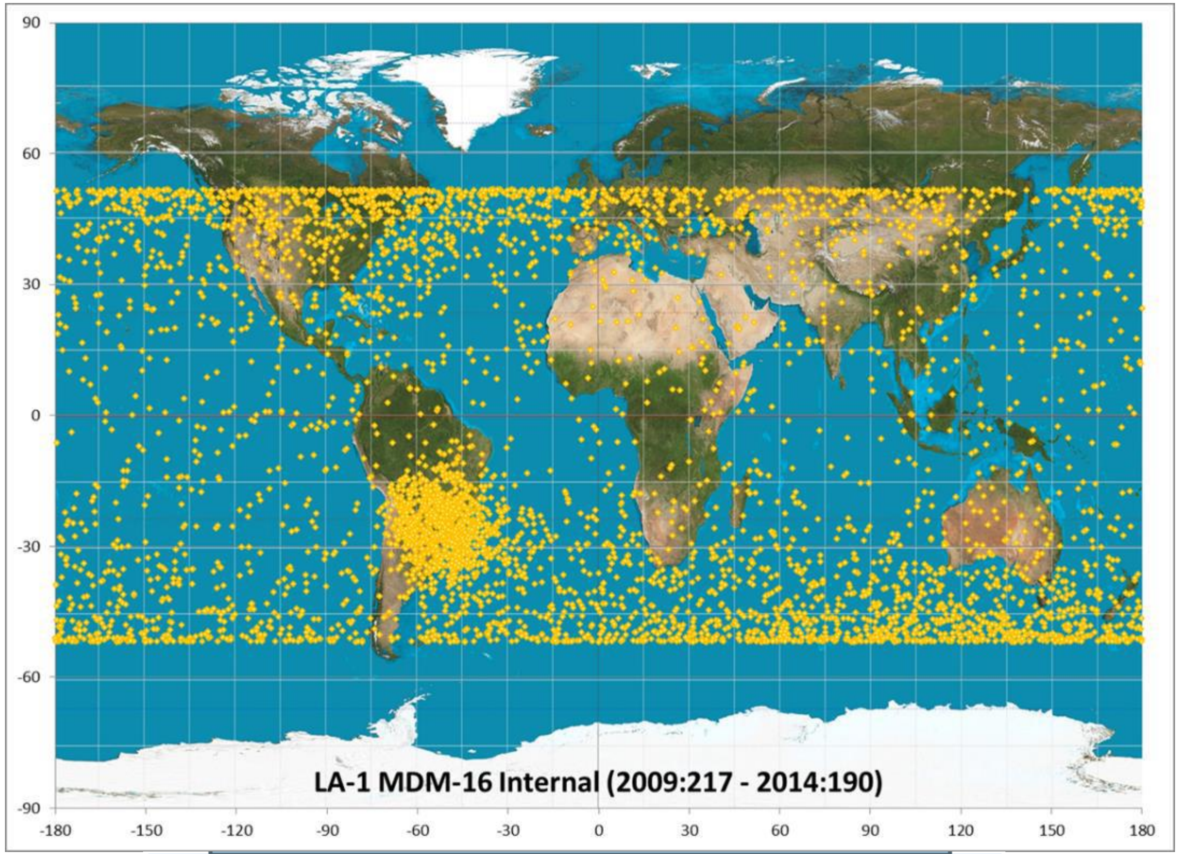
- MDM parts lists are screened for potentially SEE susceptible devices (SSDs)
- SSDs are subjected to heavy ion testing to determine device SEE cross section (σ) as a function of ion LET
    - Soft errors (SEU)
    - Single Event Functional Interrupt (recoverable)
    - Destructive SEE
- Proton (GCR, trapped, and SPE) σ calculated from heavy ion σ
    - https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4033188
- Expected on-orbit device SEE rates calculated using σ values determined by test combined with CREME-86/96 SEE environment models
- Box and System level SEE rated calculated from device see rates combined with box/system functional block diagrams (and conventional reliability engineering methods) to estimate on orbit system SEE failure rates



NOTE: It was assumed that the IP test data for the TI-44100 part would be applicable to the TMS-44400 one. That was not a good assumption

ISS MDM DAM SEUs

- SEUs in MDM DRAM are identified and corrected by an EDAC algorithm implemented as part of the normal memory refresh cycle
- Each memory location is refreshed every few microseconds and SEUs are reported in the telemetry stream along with an ISS time mark
  - SEU bad-bit residence time is less than a few microseconds
  - About 20 % of SEUs happen in the South Atlantic Anomaly and about 70% at high latitudes
  - Very few outside the AA at low latitude



Device	Median Shielding Mass g/cm²	In-Flight SEU/bit day	FLUKA Predicted SEU/bit day (FLUKA)	CREME-96 Predicted SEU/bit day (CREME)	FOM Predicted SEU/bit day (FOM)
TMS44400	10	8.5×10^{-8}	8.8×10^{-8}	1.1×10^{-7}	2.5×10^{-7}
TMS44400	40	7.0×10^{-8}	7.2×10^{-8}	3.1×10^{-8}	6.8×10^{-8}

MDM DRAM SEU Counts between 2010-2018

MDM GCR counts versus Geographic Latitude: 02/2010 through 2017																					
Latitude (deg)	% Time	Internal (shielding mass ~ 40g per square cm)								External (shielding mass ~ 10g per square cm)											
		AL-1	LA-1	LA-2	LA-3	N2-1	N2-2	N3-1	N3-2	P1-1	P1-2	P3-1	P3-2	PTR1	S0-1	S0-2	S1-1	S1-2	S3-1	S3-2	STR1
40 to 52	19.5%	1883	1858	2032	2077	1753	1725	1823	1826	1766	1650	1698	1624	1834	1878	1672	1692	1735	1641	1649	1797
20 to 40	16.1%	697	669	692	738	573	612	656	664	426	446	391	439	432	485	481	483	434	438	438	497
-20 to 20	28.6%	719	732	762	768	588	678	720	658	468	467	446	459	447	567	513	497	468	448	486	517
-40 to -20	16.2%	790	814	867	849	656	702	799	737	631	584	588	602	635	670	583	597	645	648	607	668
-52 to -40	19.7%	2037	2067	2056	2084	2024	1892	2022	1946	2162	2031	2129	2066	2236	2025	2017	1948	2155	2053	2150	2171

Total MDM SEU counts for both internal (high shielding mass) and external (low shielding mass) MDMs excluding counts in the SAA region: 02/2010 through 2017. The counts are reported for 5 different geographic latitude zones with the annual percentage of total flight time in each latitude zone. SEUs in this region are caused predominantly by GCRs.

MDM SAA counts: 02/2010 through 2017																			
Internal (shielding mass ~ 40g per square cm)								External (shielding mass ~ 10g per square cm)											
AL-1	LA-1	LA-2	LA-3	N2-1	N2-2	N3-1	N3-2	P1-1	P1-2	P3-1	P3-2	PTR1	S0-1	S0-2	S1-1	S1-2	S3-1	S3-2	STR1
1346	1619	1441	1299	1755	1410	1153	1275	3872	3658	4172	4264	3601	2373	2733	3235	3628	3723	3680	3182

Total MDM SEU counts for both internal (high shielding mass) and external (low shielding mass) MDMs counts in the SAA region only: 02/2010 through 2017. SEUs in this region are caused predominantly by Van Allen belt trapped protons.

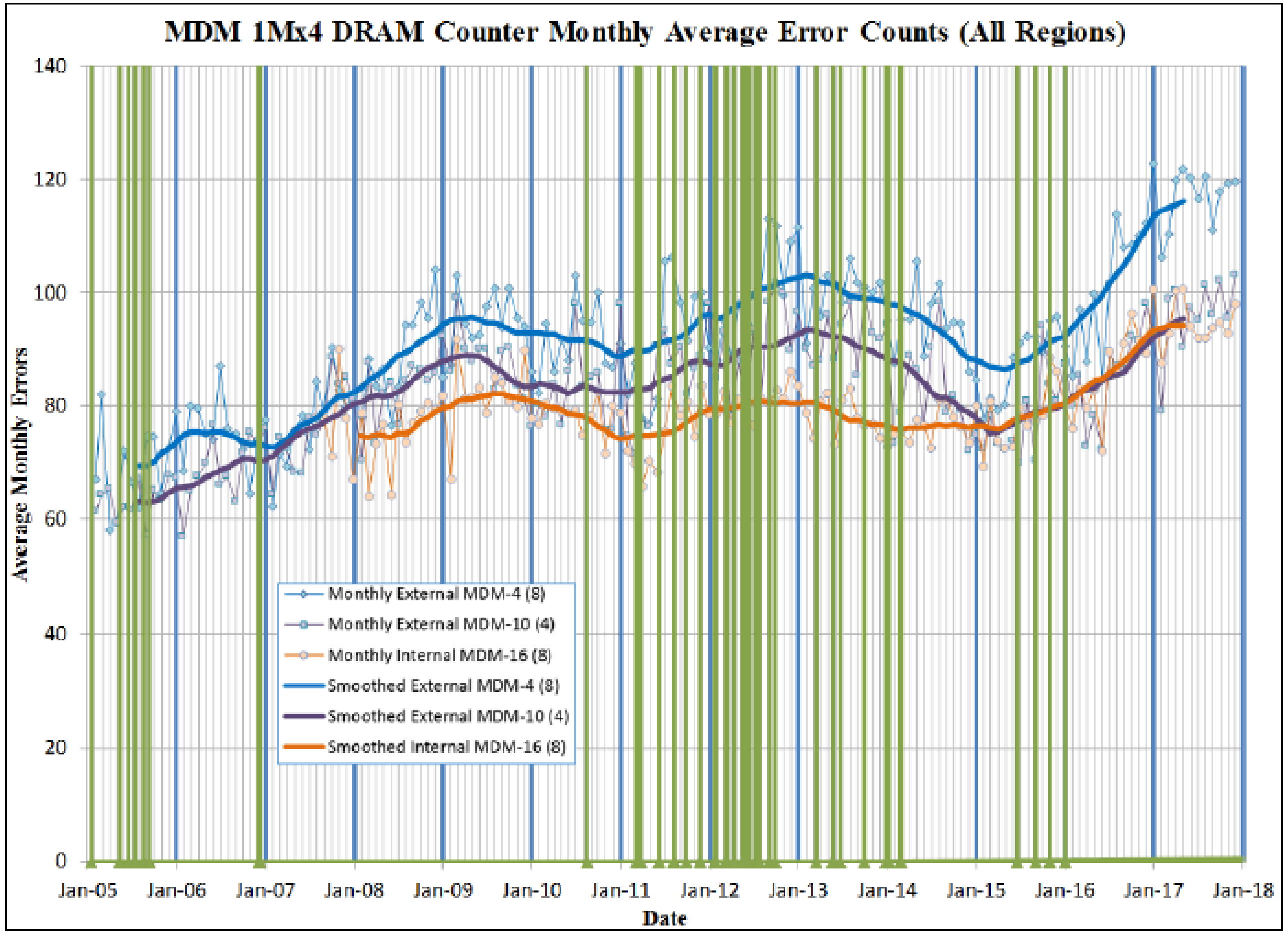
MDM DRAM SEU Count Factors

Statistical Averages for ISS MDMs	All 20 ISS MDMs	8 Internal MDMs	12 External MDMs
Mean SEU count inside SAA (SAA Region) with standard deviation	2671 ± 1112	1412 ± 182	3510 ± 527
Mean SEUs count outside SAA (GCR Region) with standard deviation	5632 ± 403	6030 ± 318	5367 ± 168
% of total counts in SAA Region	31.2 % ± 11%	13% ± 9%	39% ± 4%
% of total counts in GCR Region	68.8%	87%	61%
% of GCR region total in highest latitude regions (poleward of 40 degrees latitude)	68% ± 4%	64% ± 1%	71% ± 2%

Statistical Analysis of ISS MDM DRAM SEU count data, 02/2010 through 12/2017

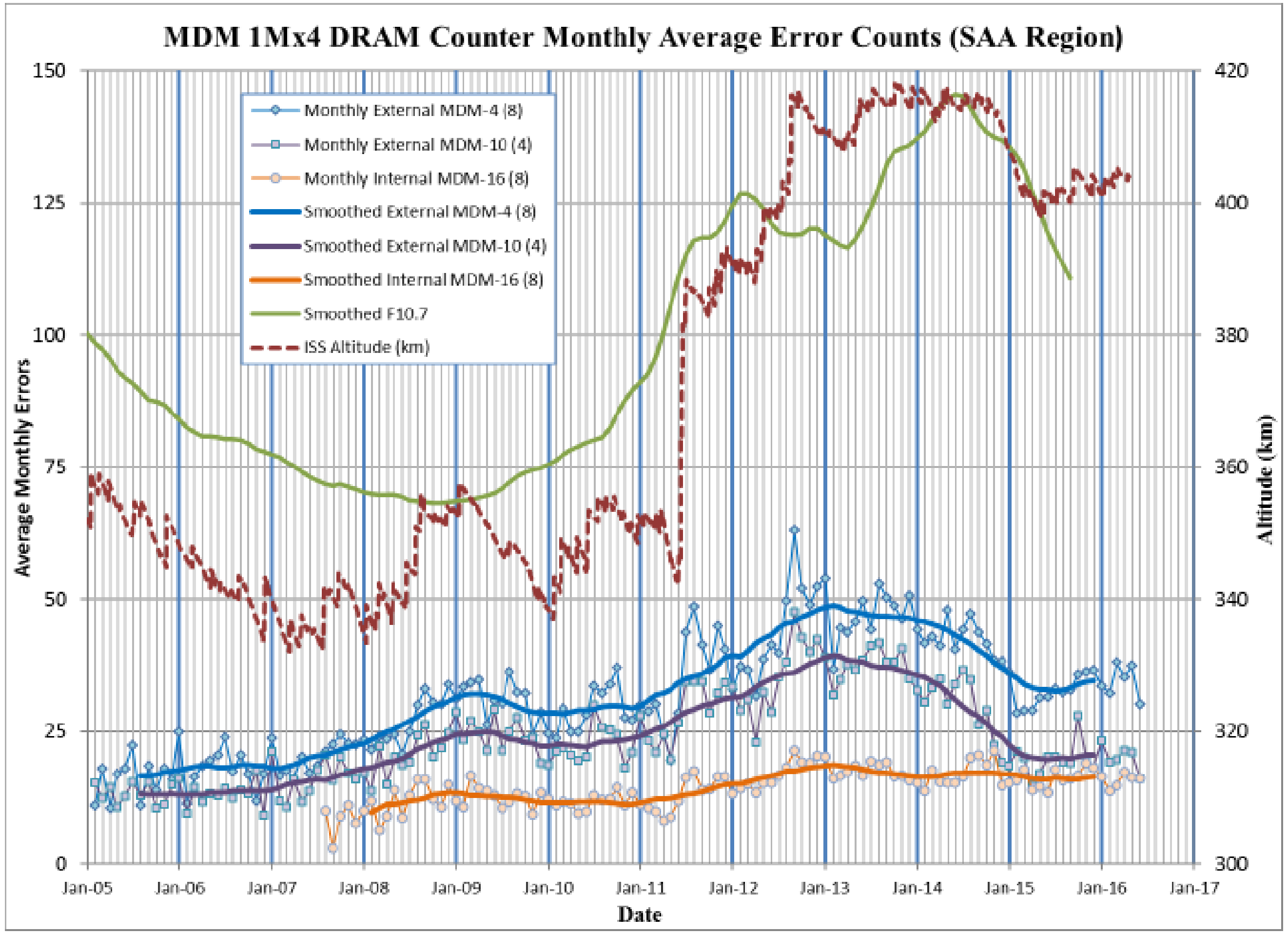
The reported differences between the internal and external MDM group DRAM SEU counts are statistically significant. Applying the "t test" for the significance of the observed differences between the internal and external MDM mean counts results in a t statistic of 6.107, for 18 degrees of freedom, and $p < 0.0001$ for the GCR region and a t statistic of 10.756 for 18 degrees of freedom and $p < 0.0001$ for the SAA region. The p value is the probability that the null hypothesis (i.e. the internal mean count is really the same as the external mean count but only appears different in this case on account of Poisson process random fluctuations) is true.

Solar Cycle, SPE, Altitude and Shielding Mass Effects



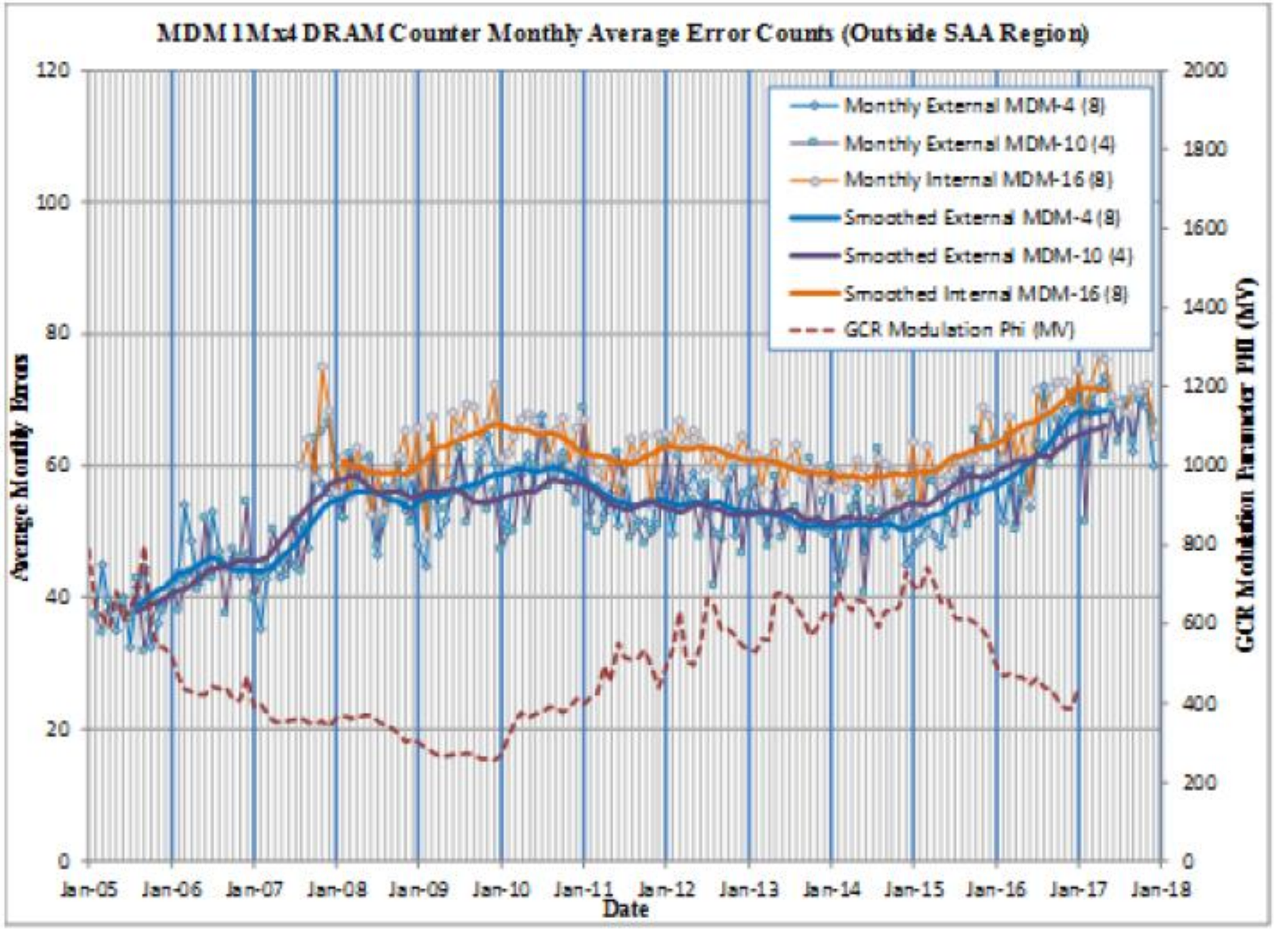
Monthly average MDM DRAM SEU rates for the 2005 to 2017 time frame, and for all geographic regions. Monthly average SEU count data for eight external MDM-4s, four external MDM-10s, and eight internal MDM-16s are plotted against calendar year. Green vertical lines mark major solar particle events (NOAA 10/10 criteria, >10 pfu >10 MeV).

Solar Cycle, SPE, Altitude and Shielding Mass Effects



Monthly average MDM DRAM SEU rates inside the SAA (excluding the GCR region). Monthly average SEU count data for eight external MDM-4s, four external MDM-10s, and eight internal MDM-16s are plotted against calendar year. DRAM SEU monthly rates compared to solar F-10.7 index and ISS altitude

Solar Cycle, SPE, Altitude and Shielding Mass Effects



GCR region MDM DRAM SEU monthly rates compared to the GCR modulation parameter, ϕ. Note the small variations in external MDM DRAM SEU rate accompanying the small variations in ϕ during 2011.

Environment Factors on Monthly Average MDM SEU Counts

- MDM DRAM SEU rates show very different dependences on shielding mass, altitude, and the 11-year solar cycle inside and outside the SAA.
- Outside the SAA high energy GCRs determine SEU rates which increase with increasing shielding mass (secondary particle shower effects), and show little dependence on altitude, and an expected weak dependence on the solar cycle (GCR modulation factor Phi)
- Inside the SAA, lower energy trapped protons determine SEU rates which increase with decreasing shielding mass and show a strong dependence on altitude and solar cycle (F10.7)

Predictions vs. In-Flight Observations

- Specific Program Requirement
  - Mean Time To Recover (MTTR) << MTBF
    - **Recovery requires ground intervention and takes ~ 24 hours**
- On-orbit MTBF calculated from:
  - Heavy ion test data on all SEE susceptible components
  - ISS SEE design environment (SSP-30512)
  - A reliability engineering functional block diagram of the MDM
- For the total compliment of ~50 MDMs:
  - Predicted lock-up rate = 10/year
  - Observed lock-up rate = 1 per year
- The number of observed lock-ups is between about and 10 times smaller than the number of lock-ups predicted
- Flight MDMs are meeting requirements with considerable margin

MDM DRAM Anomaly Summary

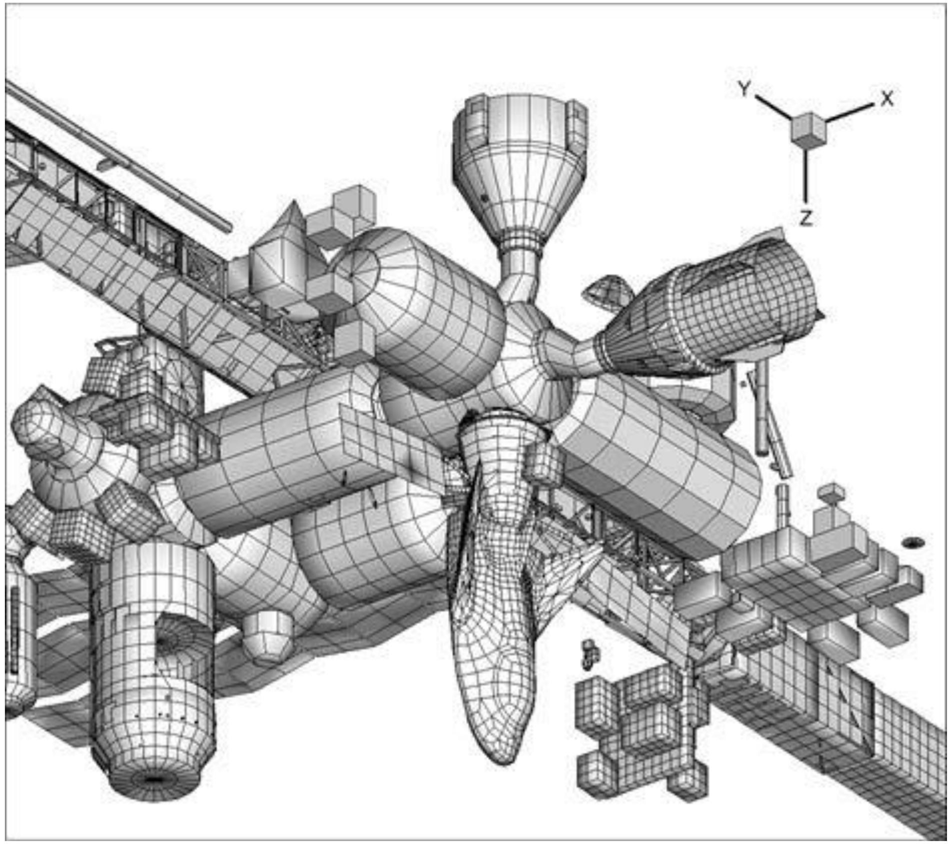
- ISS MDM DRAM SEU counts displayed a strong dependence on both shielding mass and geographic location
  - Internal (high shielding mass) and external (low shielding mass) MDM DRAM SEU count rates differ in the SAA vs. the GCR regions
    - For the 12 external MDMs, 39% of the total SEU counts were inside the SAA region and 61% in the region
    - GCR For the 8 internal MDMs, 13% of the total SEU counts were inside the SAA region and 87% in the GCR region
  - The observed effects are attributed to:
    - Differences in shielding mass between the two MDM populations,
    - The relatively low kinetic energy of SAA trapped charged particles compared to GCR charged particles and,
    - Secondary particle showers caused by nuclear reactions between ISS shielding mass materials and high energy GCR particles
  - In the GCR region SEU count increases with increasing shielding mass and in the SAA region SEU count decreases with increasing shielding mass
- In the GCR region, the highest MDM DRAM SEU count rates were observed in the high latitude region, poleward of 40°, for both MDM shielding mass environments
  - For the 12 external MDMs, 71% of the total GCR region SEU counts were poleward of 40 degrees latitude
  - For the 8 internal MDMs, 64% of total GCR region SEU counts were poleward of 40 degrees latitude
- We have observed no correlations between SPEs and MDM monthly average DRAM SEU rates or MDM SEFI events for either MDM shielding mass environment

MDM DRAM Summary Cont'd

- Between January 2005 and January 2018, the external MDM SEU rates responded primarily to:
  - The expected increases in trapped proton flux with ISS altitude, offsetting any reduction in trapped proton population through the last solar maximum
- In the SAA region the internal MDM SEU rate shown very little variation between 2005 and 2017
  - As solar cycle 24 winds down, both GCR and trapped proton fluxes are expected to increase and both the internal and external MDM SEU rates observed to be increasing after January 2015
- In the GCR region, the internal MDM DRAM SEU rates are following changes in the heliospheric GCR modulation factor, ϕ, between 2005 and 2017
  - As solar cycle 24 winds down, ϕ is decreasing so that more GCR particles of lower kinetic energy are able to enter the inner solar system and all MDM SEU rates are increasing outside the SAA following January 2015

Contamination

Visiting Vehicles Docked at ISS



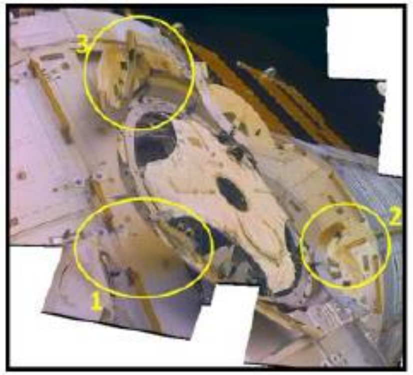
- ISS is currently visited by commercial vehicles and international partner spacecraft.
- Many commercial crew and cargo vehicles are in development.
- ISS Program’s emphasis has shifted from assembly to science utilization
- Critical to maintain ISS contamination control requirements

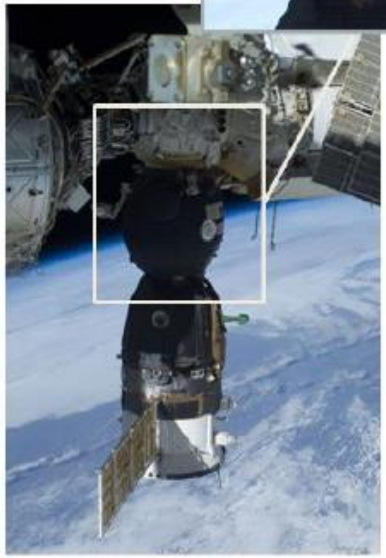
Visiting Vehicle Contamination Concerns

- The International Space Station (ISS) external contamination environment includes contributions from ISS elements, visiting vehicles, and external payloads.
- External contamination can impact performance, mission success, and science utilization.
- Visiting vehicles induce multiple types of molecular contamination on ISS
    - *Materials outgassing*
    - *Thruster plume induced contamination*
    - *Thruster plume induced erosion/pitting*
    - *Vacuum venting/leakage*
    - *Particulates*
    - *Induced contamination to unpressurized cargo*
    - *Visiting-vehicle contamination sensitive surfaces*
- The Space Environments Team of the ISS Program Office has developed visiting vehicle requirements and methodologies to address the increasingly complex challenge of integrating multiple visiting vehicles while maintaining overall ISS contamination control requirements.

Examples of ISS External Contamination Sources

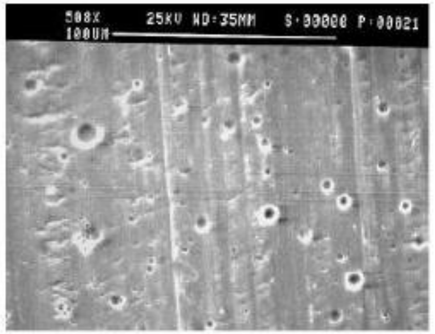
Material Outgassing

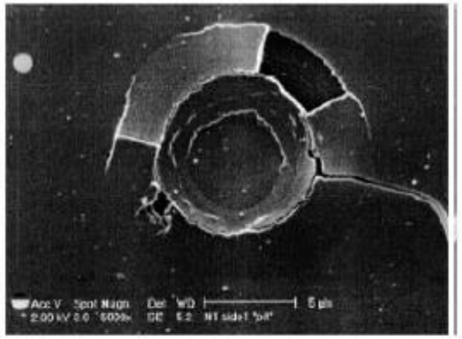




Images Courtesy of NASA

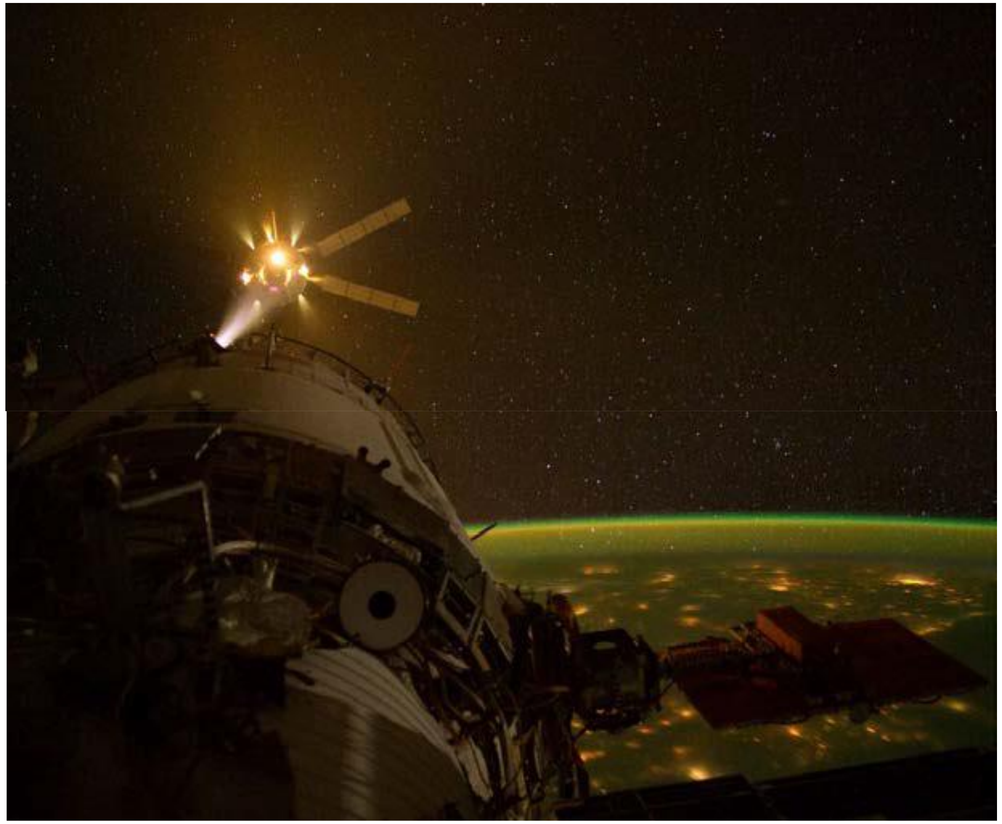
Thruster Plumes





Plume droplet impact features from SPIFEX and PIC Flight Experiments

Examples of ISS External Contamination Sources



Performance Vs. Expectation Returned Flight Hardware

Space Environments has shown good agreement between contaminant deposition measurements made on returned hardware and analysis predictions.

Returned after 4 year mission
Exposed to Space Shuttle and Russian vehicles
Excellent agreement between predicted and measured contamination (within factor of ~1.6).

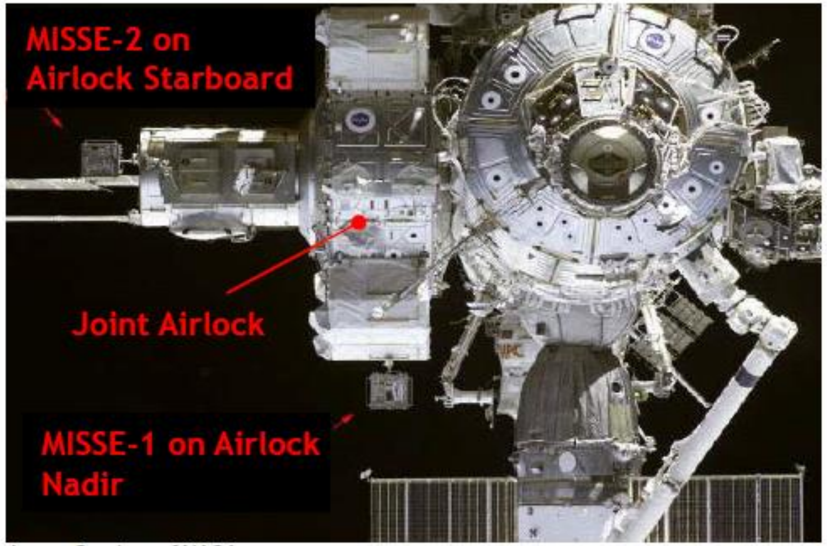


Image Courtesy of NASA

Incremental tray return (1, 2.5, and 4 years)
Exposed to Space Shuttle and Russian vehicles
Very good agreement between predicted and measured contamination (within factor of 2-3).

Image Courtesy of NASA

On-Orbit Imagery

Space Environments has also used on-orbit imagery of contamination to corroborate visiting vehicle contamination analysis predictions

Discoloration of the Node 2 nadir common berthing mechanism
(Composite Image)

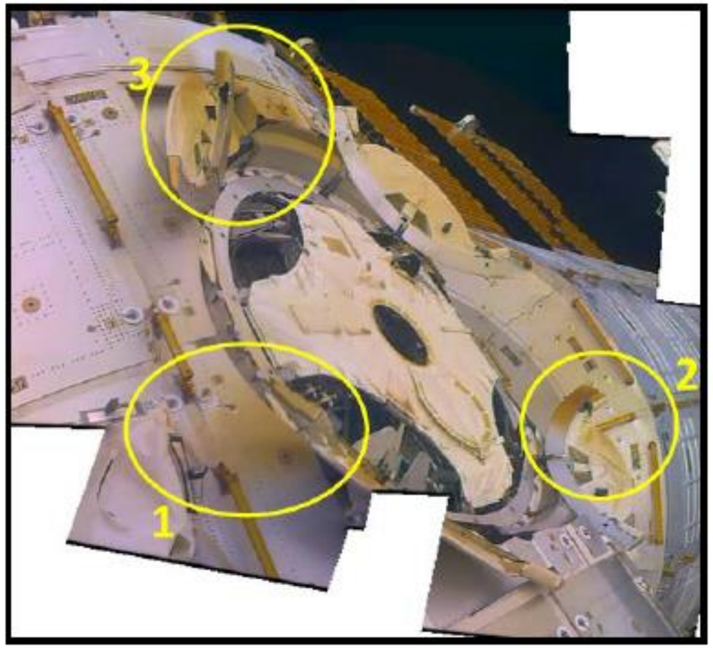
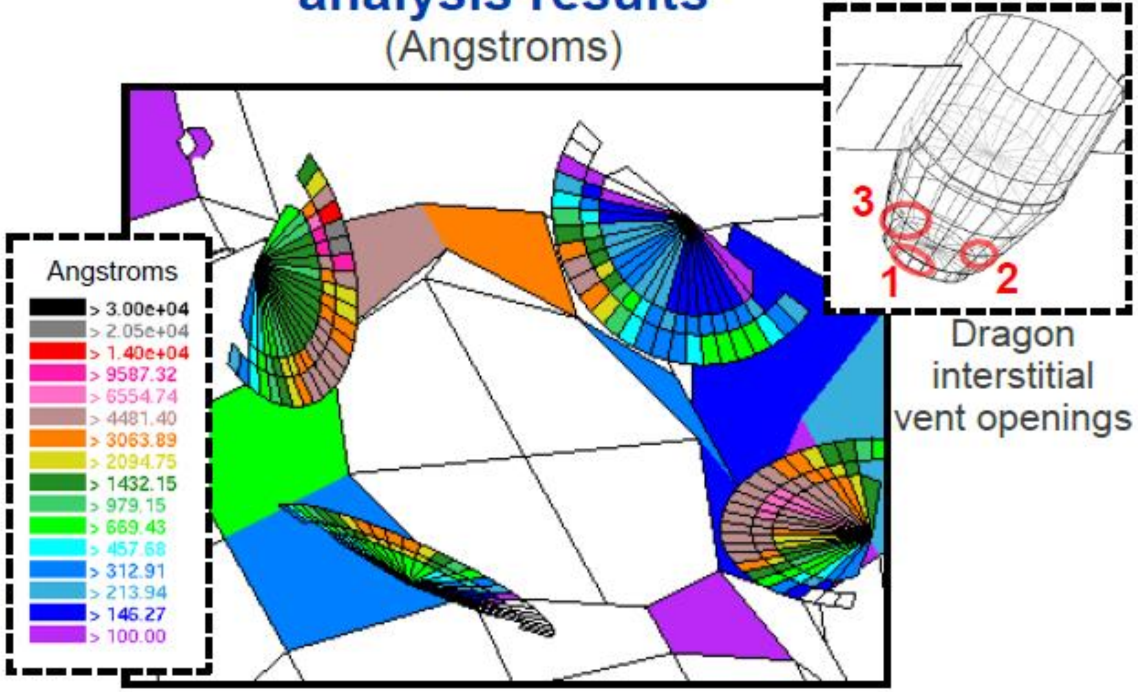


Image Courtesy of the NASA
Image Science and Analysis Group

Dragon materials outgassing analysis results
(Angstroms)



Dragon interstitial vent openings

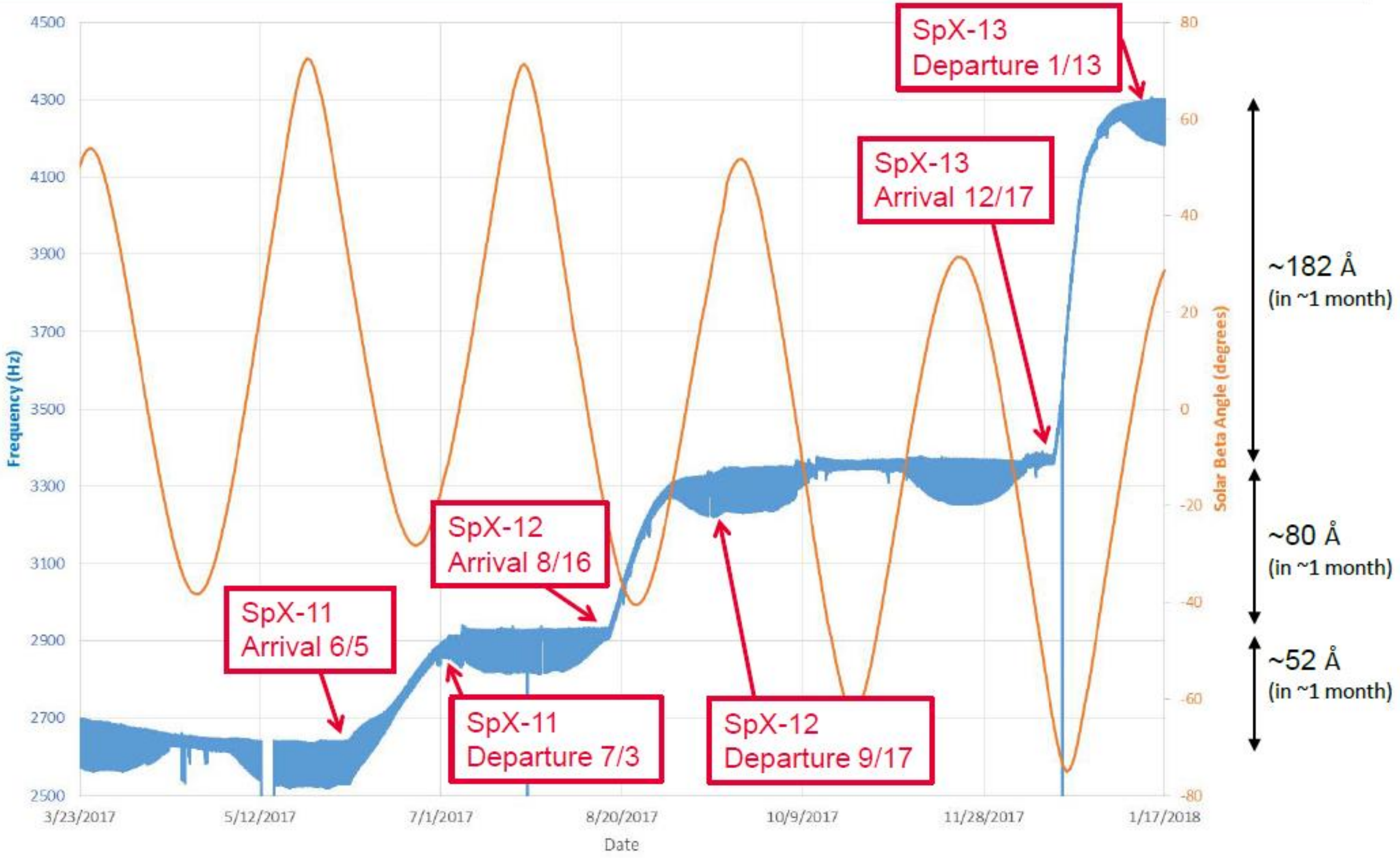
Contamination Measurements

- ISS now has active contamination monitoring, following the arrival of the Stratospheric Aerosol and Gas Experiment III (SAGE III) in Feb. 2017.

  Note: SAGE III is a NASA Langley payload that measures scattering of solar radiation in the Earth's atmosphere (i.e., limb scattering) to determine the amounts of its components.

- SAGE III houses eight Thermoelectric Quartz Crystal Microbalances (TQCMs) as part of a contamination monitoring package. Initial observations:
  - The majority of ISS permanent modules and visiting vehicles are having minimal contributions to contamination.
  - However, the SAGE III TQCMs have consistently measured higher than expected contamination levels while the Dragon cargo vehicle is present at ISS.
- The SAGE III TQCM data indicates that there is a Dragon material outgassing source that needs to be identified and evaluated for impacts to ISS payload sites and hardware.

Performance Vs. Expectation
Example SAGE III TQCM Frequency Data



Visiting Vehicle Empirical Assessment

- In parallel with the on-going investigation, Space Environments has developed an empirical Dragon contamination model based on the SAGE III TQCM measurements.
- Empirical model used to assess Dragon materials outgassing induced contamination to ISS hardware and payload sites.
- Assessment showed that only 7 of the 56 USOS hardware and active payload sites sensitive to induced contamination could experience exceedances of the system level requirement (130 Å/year).
- The empirical data can be used for hardware impact assessments, payload placement studies, and other system integration activities until the contamination source(s) and corrective actions are ultimately identified.
- This investigation highlights the importance of well characterized vacuum-exposed materials and operating temperature data for visiting vehicles.

Contamination Anomaly Summary

- The Space Environments Team has developed visiting vehicle requirements and methodologies to address the increasingly complex challenge of integrating multiple visiting vehicles while maintaining ISS contamination control requirements.
  - Visiting vehicle providers supply contamination characterization data (e.g., vacuum exposed materials, thruster plumes, vacuum venting, particulates).
  - The Space Environments Team performs integrated analyses, addressing visiting vehicle induced contamination to ISS and unpressurized cargo.
- On-orbit measurements have confirmed the visiting vehicle analysis and integration approach.
- **Early and close coordination with visiting vehicle providers on external contamination requirements and data deliveries is essential for early identification of potential issues and successful integration with ISS.**