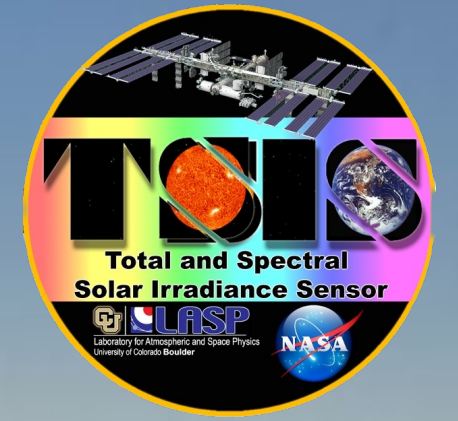


# TSIS-1 SIM Science Data Processing Update



## 2023 Sun-Climate Symposium

OCTOBER 16-20, 2023  
FLAGSTAFF, ARIZONA

Penton, Béland, Brooks, Chambliss, Charbonneau, & Peck

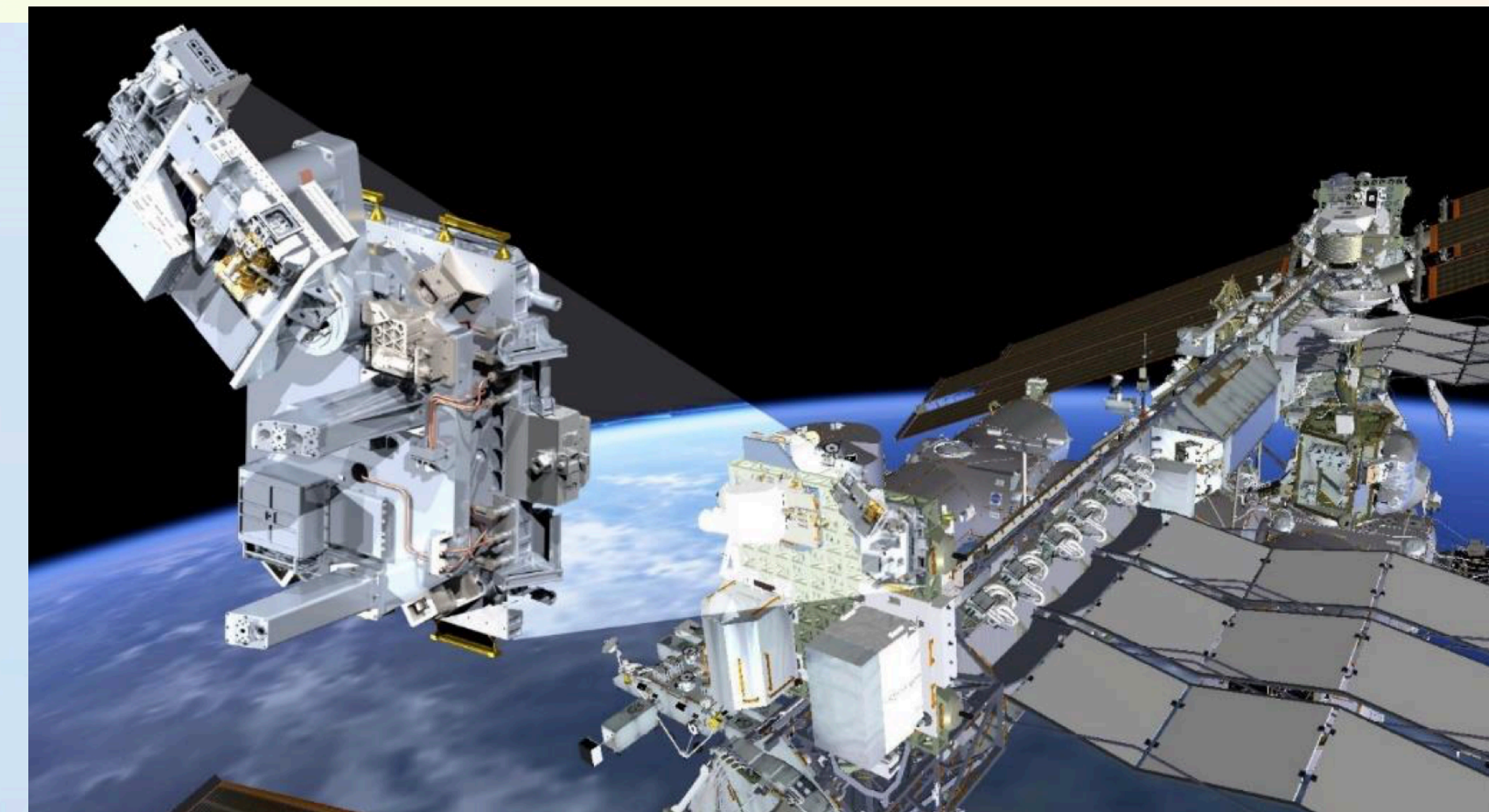
TSIS-1 PI : Tom Woods

TSIS-1 SIM Instrument Scientist : Erik Richard

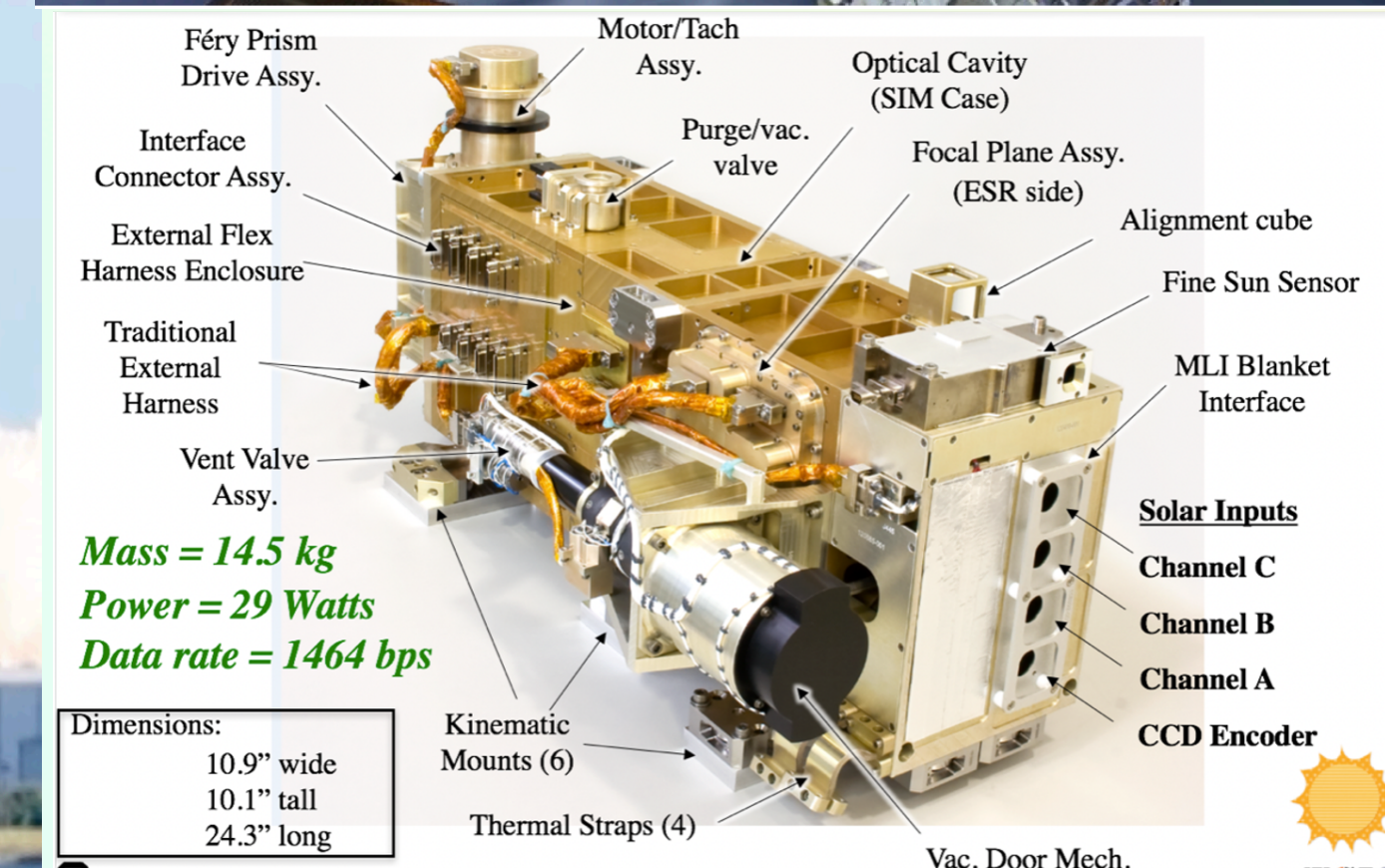
# Introduction to TSIS-1 SIM

The Total and Solar Irradiance Sensor (TSIS-1) operates on the International Space Station (ISS) from the ELC-3 (ExPRESS Logistics Carrier, STS-134). TSIS was launched on Dec 15, 2017 on a SpaceX Falcon 9.

TSIS-1 measures TSI with the TIM (Total Irradiance Monitor) and SSI with SIM (Spectral Irradiance Monitor).



**TIM**



**Mass = 14.5 kg**  
**Power = 29 Watts**  
**Data rate = 1464 bps**

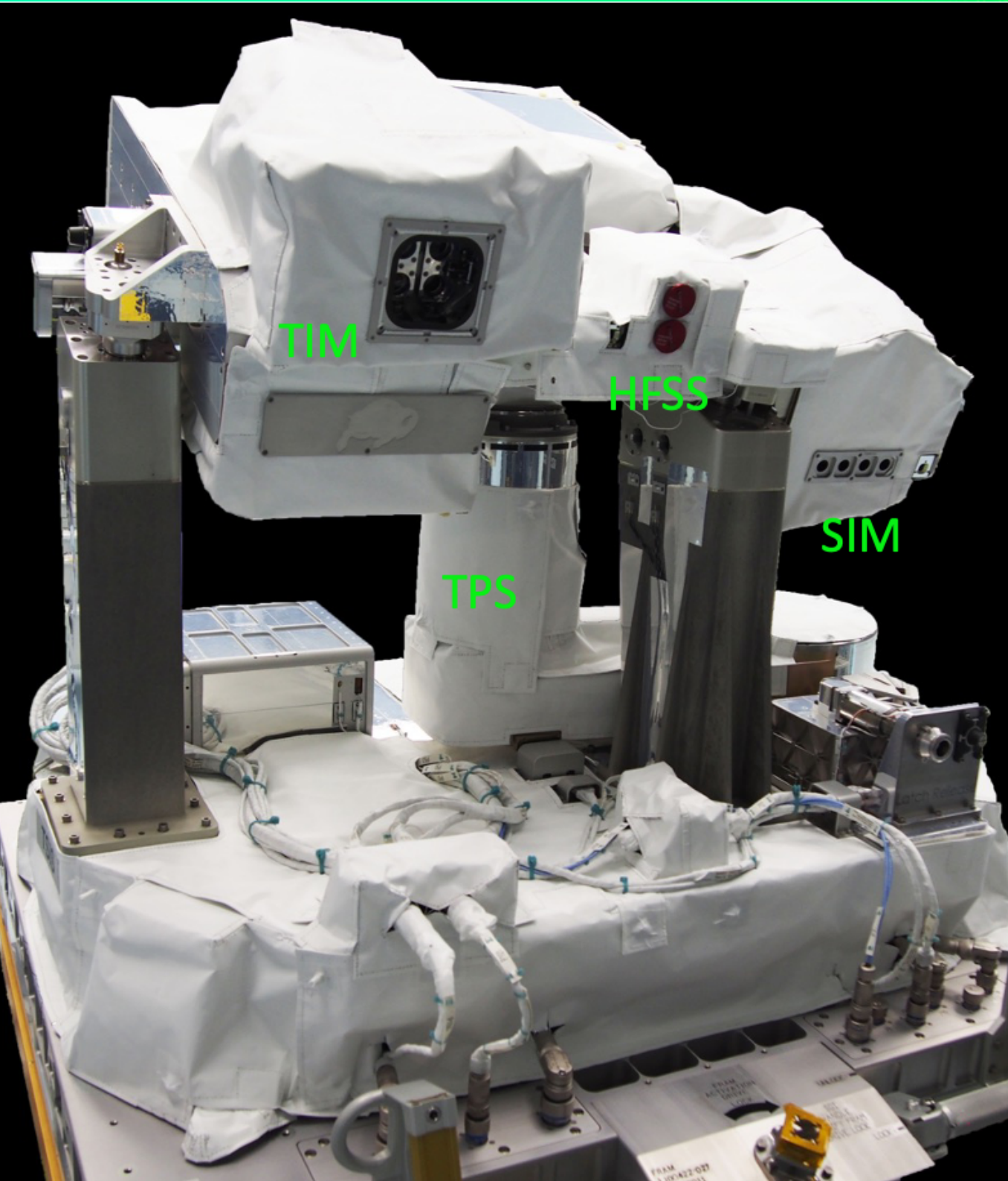
**Dimensions:**  
10.9" wide  
10.1" tall  
24.3" long

**SIM**

# Introduction to TSIS-1

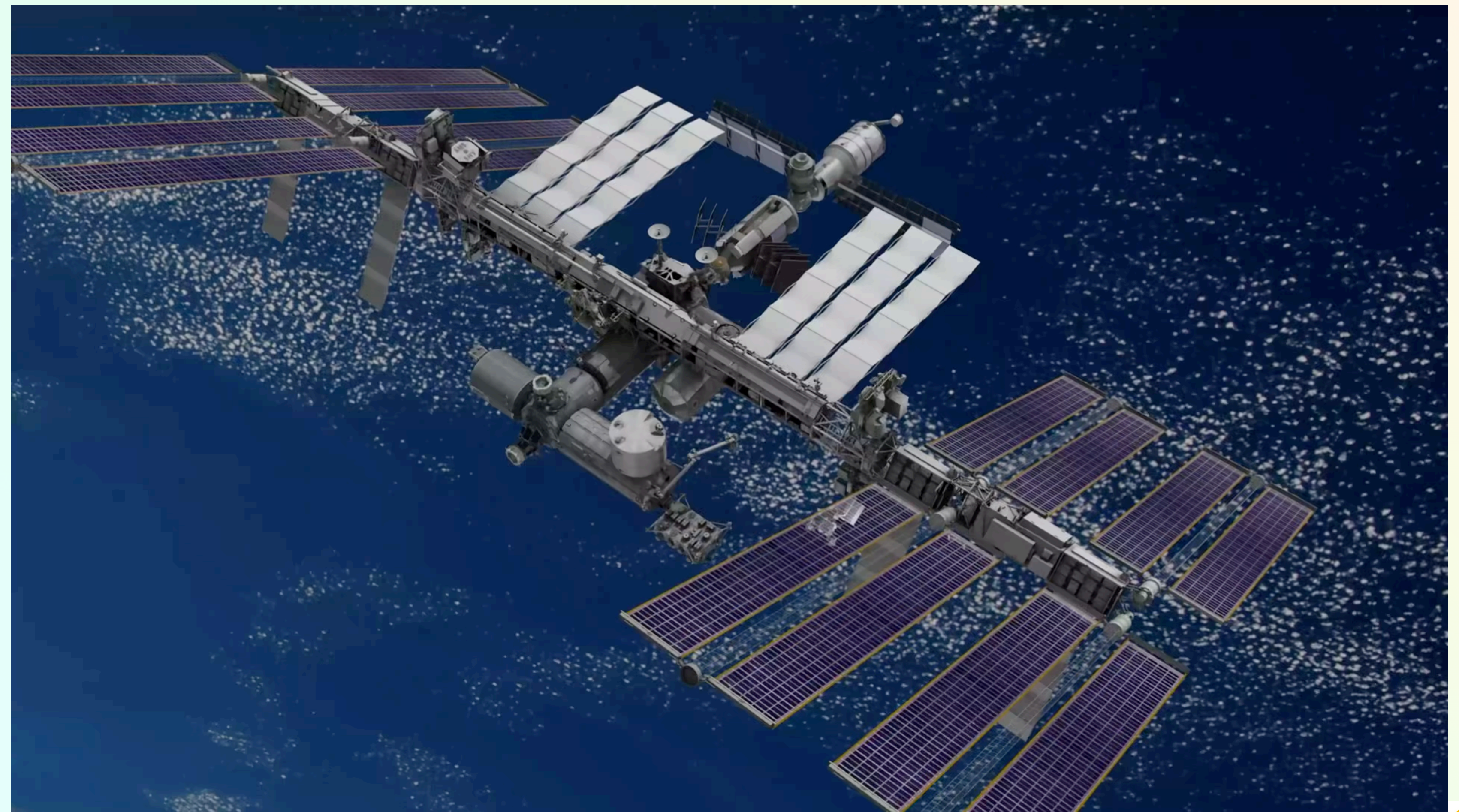
The TIM+SIM optical bench is mounted on a two-axis gimbal known as the thermal pointing system (TPS).

Solar pointing is controlled by 1 of 2 High-rate Fine Sun Sensors (HFSS)



ISS orbits the Earth ~15.5 times a day

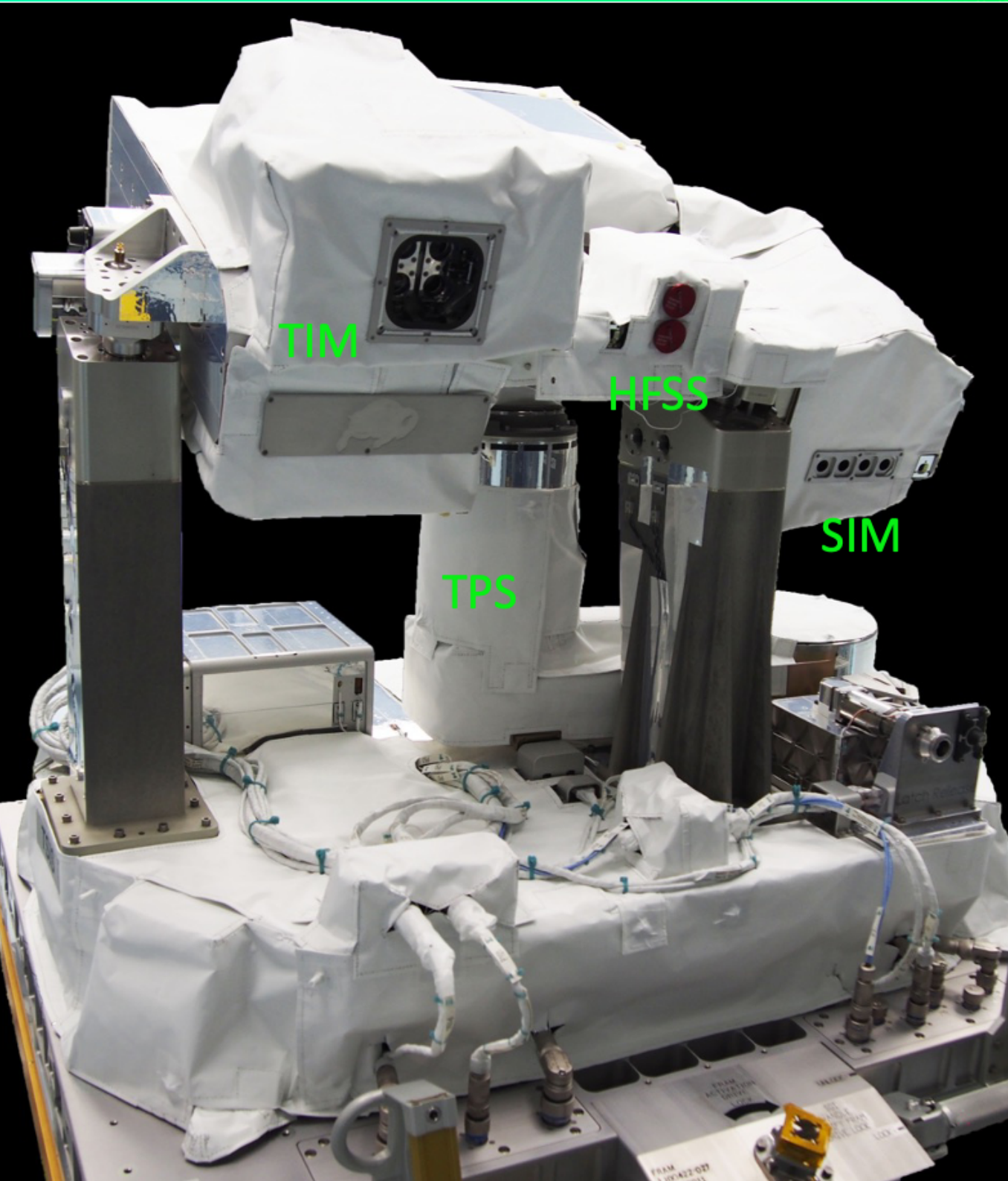
~45 min/orbit for science



# Introduction to TSIS-1

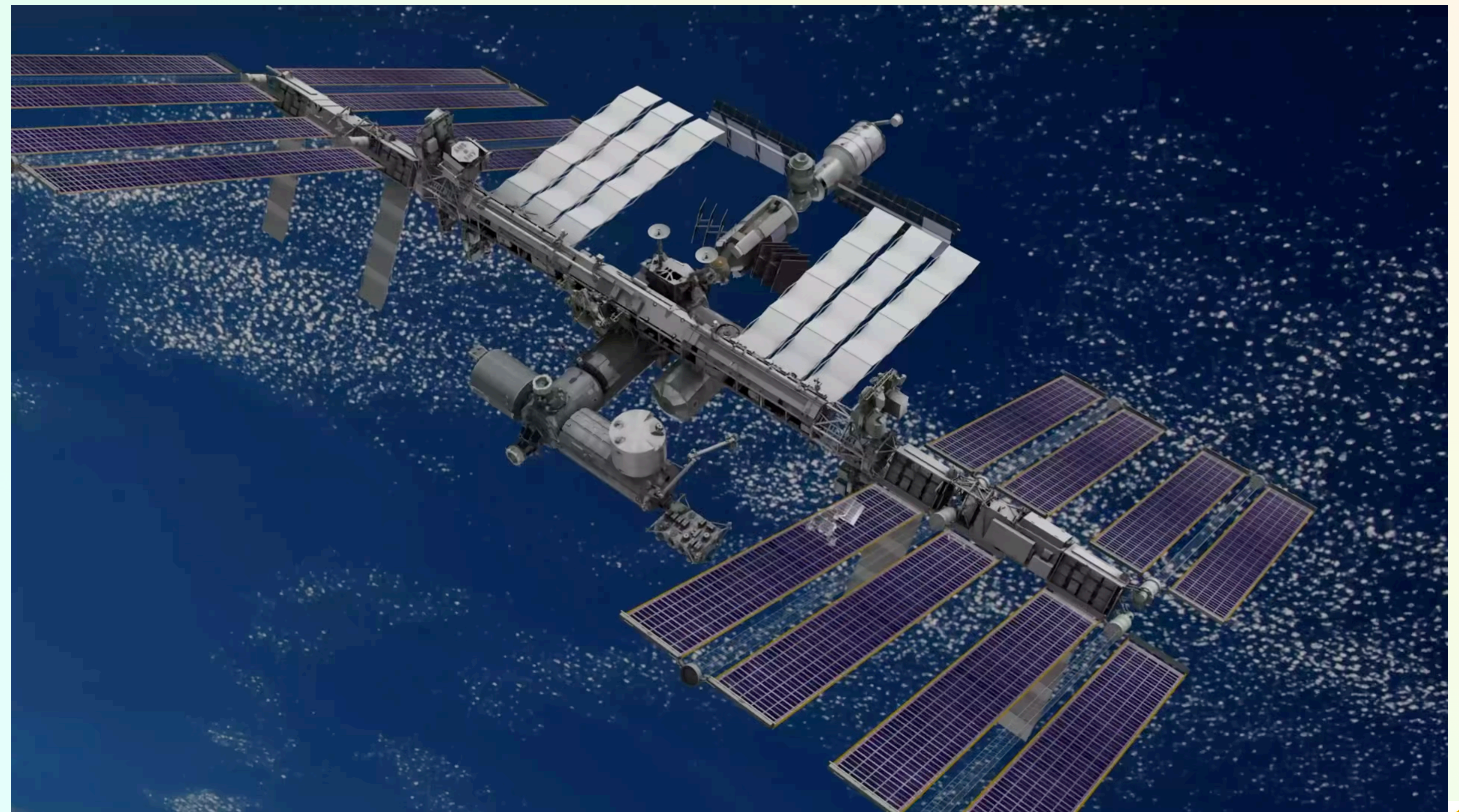
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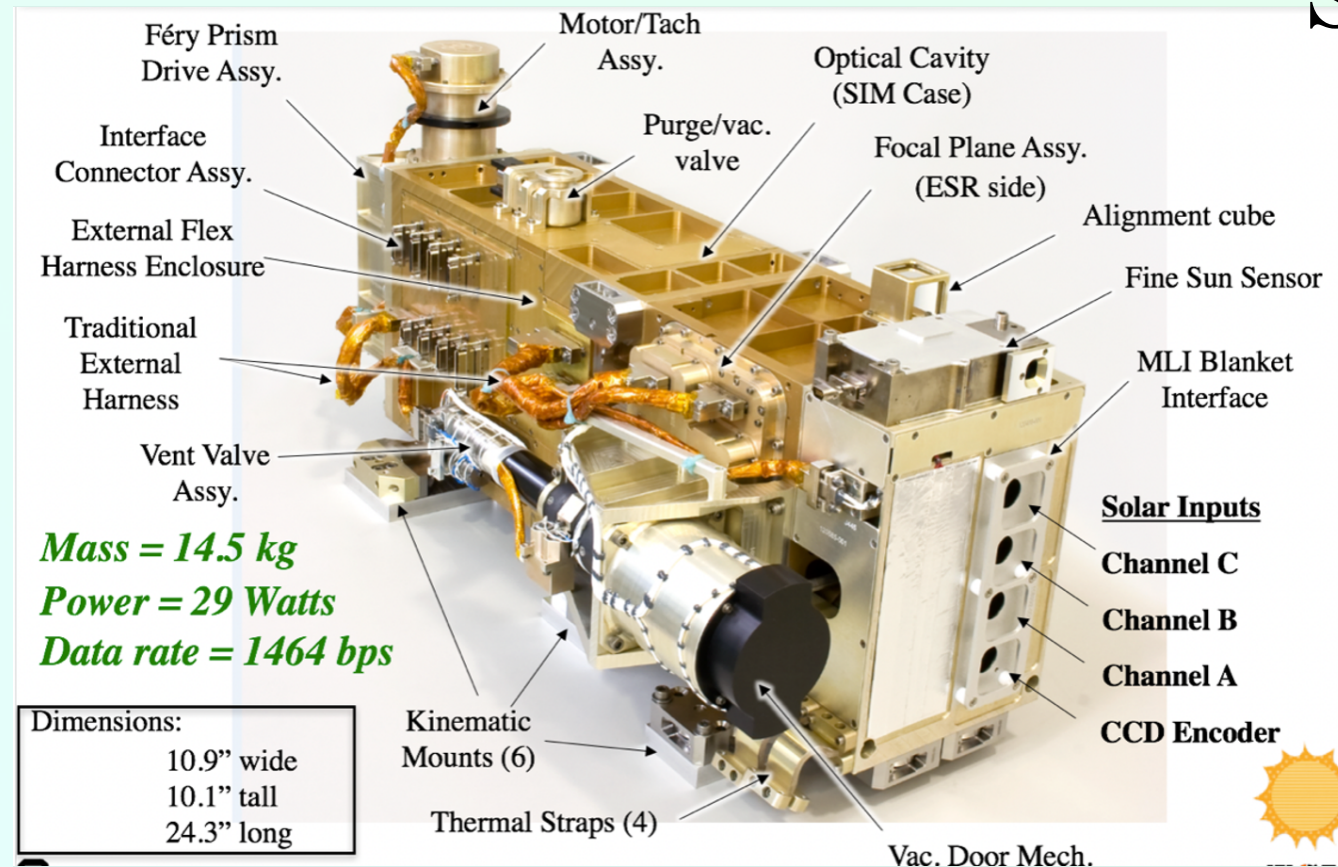
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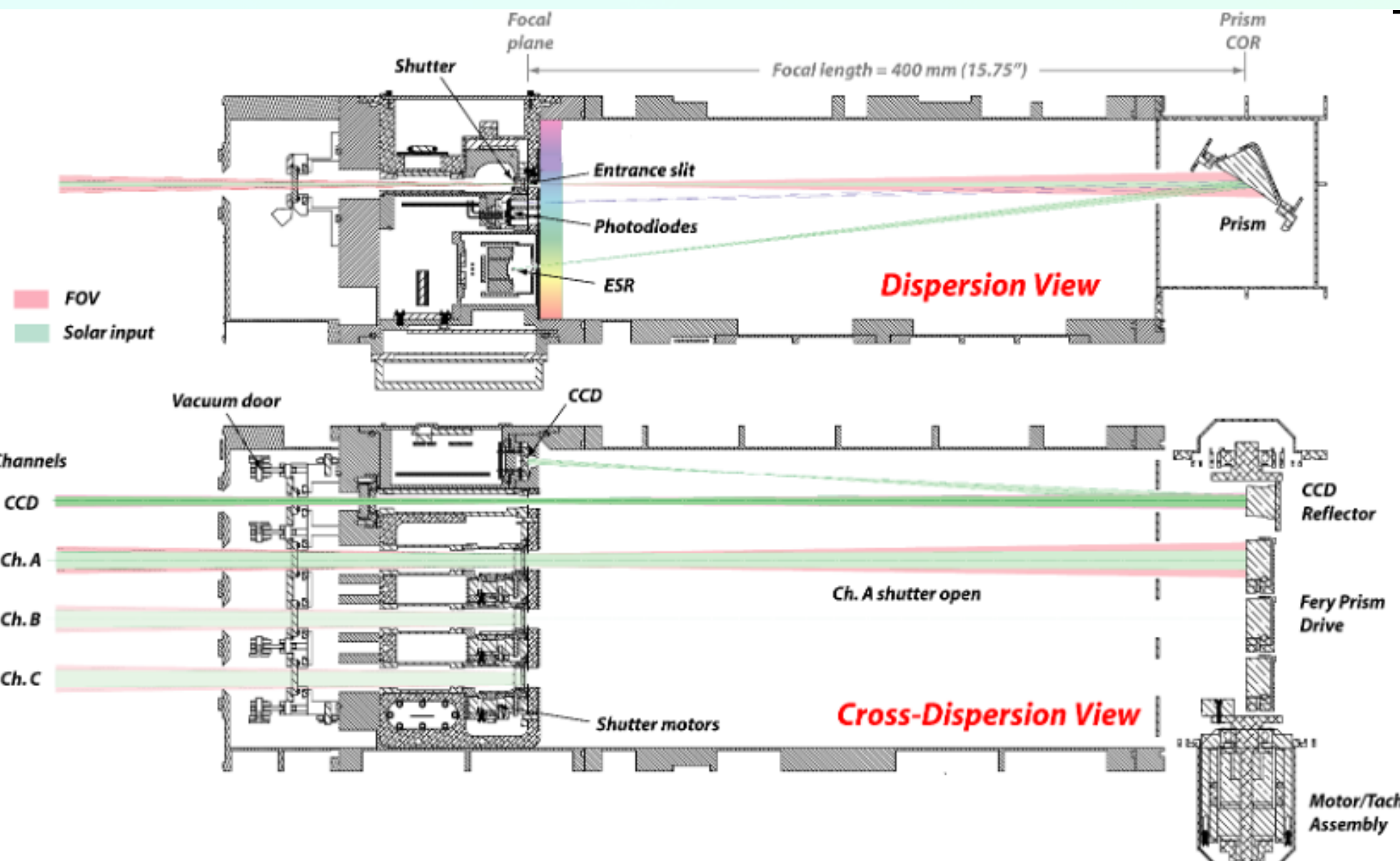


# Introduction to TSIS-1 SIM

SIM is a 3-channel Spectrometer (1 wavelength at a time). Each channel contains:



- UV diode (200 - 312 nm)
- VIS diode (312 - 950 nm)
- IR diode (950 -1620 nm)
- ESR (Electronic Substitution Radiometer) 1620-2402 nm
- A Féry Prism that degrades (becomes opaque) with usage

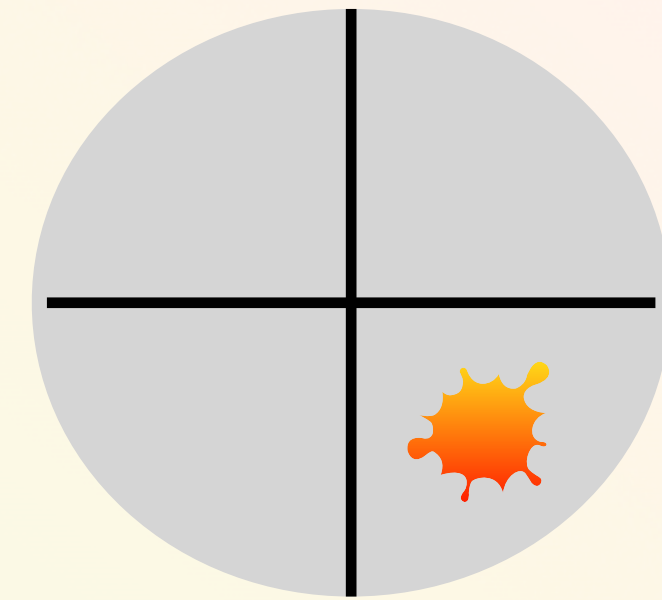


- ChA is the prime channel and takes 2 full spectra a day
- ChB and C are used to monitor ChA degradation
- ChB takes a full spectrum every 3-4 weeks
- ChC takes a full spectrum twice a year when the Earth is at 1AU (early April and early October)
- Each ChC spectrum triggers a recalibration of the entire mission, and an new data release
- Observing schedule is limited by ISS operations/obstructions

# Since last Sun-Climate Symposium (May 2022)

On 2022-03-19, contamination from Soyuz MS-21 docking reduced counts on the HFSS-B quad diode

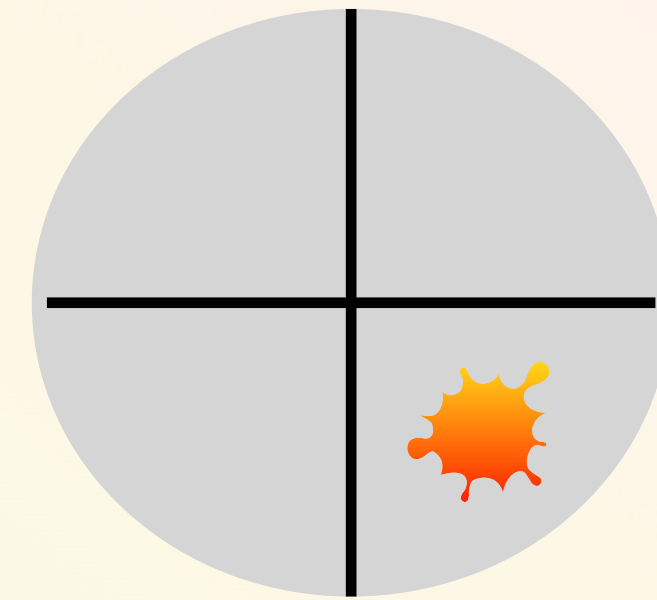
- Resulted in all SIM observations from 2022-03-19 to 2022-05-19 being offset by 1 arcmin
  - This included the Apr 2022 ChC observations (unusable)
- TSIS-1 SIM V07 data release was halted, and no data published after 2022-03-19
- On 2022-05-19, pointing was switched to the backup HFSS (HFSS-A)



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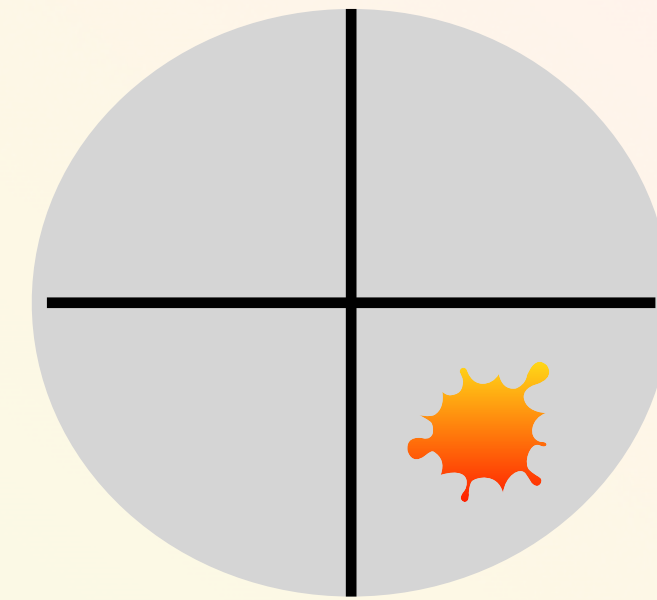
In June 2022, we commissioned a series of recovery exposures to derive a spectral correction for the off-pointed data

- 2 sets of back-to-back HFSS-B(OFF) and HFSS-A ChA/ChB spectra, 2 weeks apart to quantify solar variability
- On 2022-08-11, TSIS-1 SIM V08 was released, with HFSSB-B(OFF) data fully corrected for off-pointing
  - Adds L3 data quality flags (including one for HFSS-B(OFF) spectra) & adds baseline (filtering) spectrum (safety net)
- On 2022-08-18, another contamination event affected HFSS-A (just after RS EVA-54 and SpX-25 thruster test)
  - minor (5 arcsecond) compared to HFSS-B offset (60 arcseconds), ok to proceed, but correction desired

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After ChC scans in 2022-10, the TSIS-1 SIM V09 data release of 2022-11-15 added a new column to the data record

- `ADDITIONAL_UNCERTAINTY` : reports the uncertainty associated with the HFSS-B(OFF) spectral corrections



# V08/09 : Correcting the HFSS-B(OFF) pointed SIM data in V07

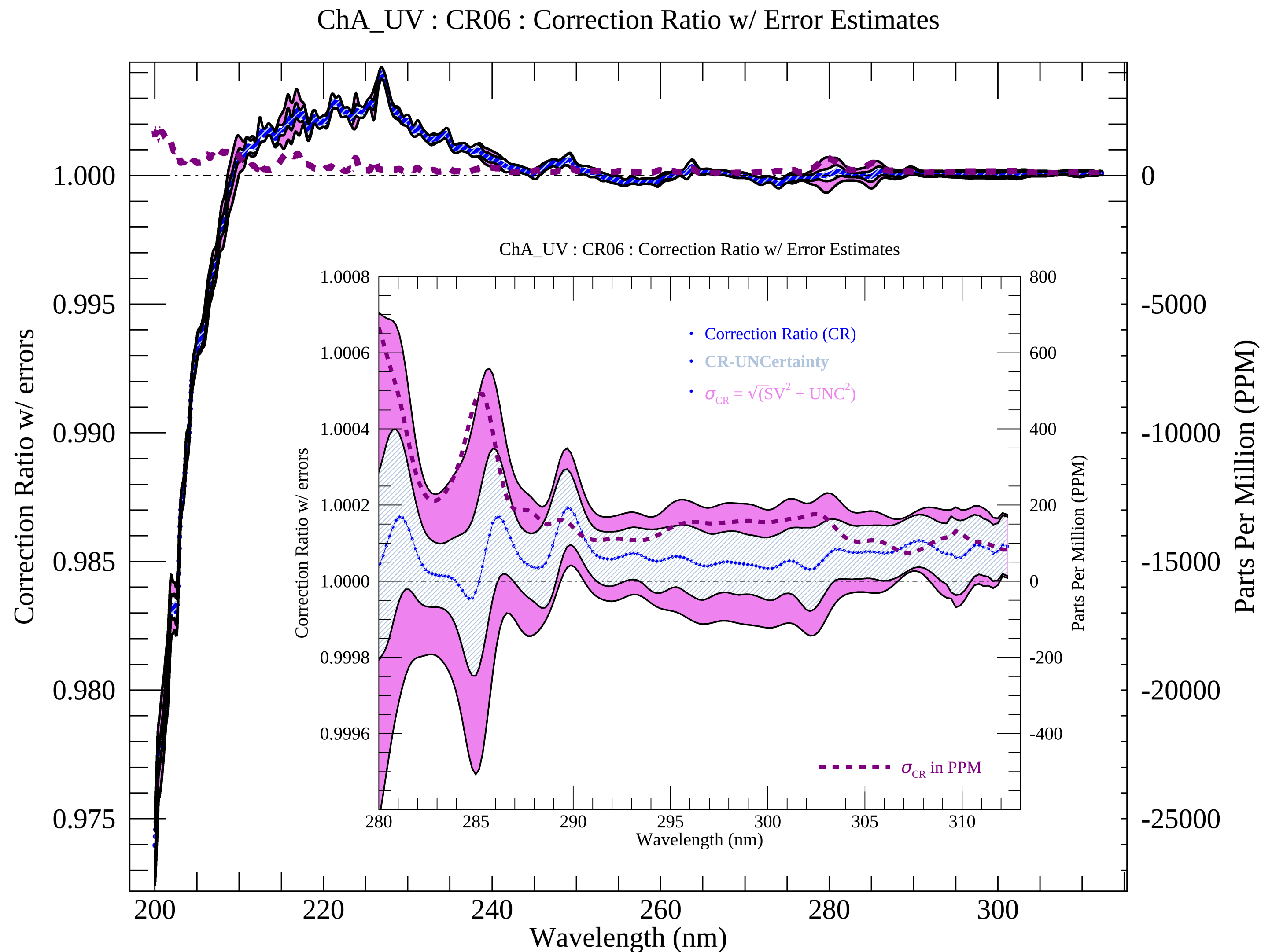
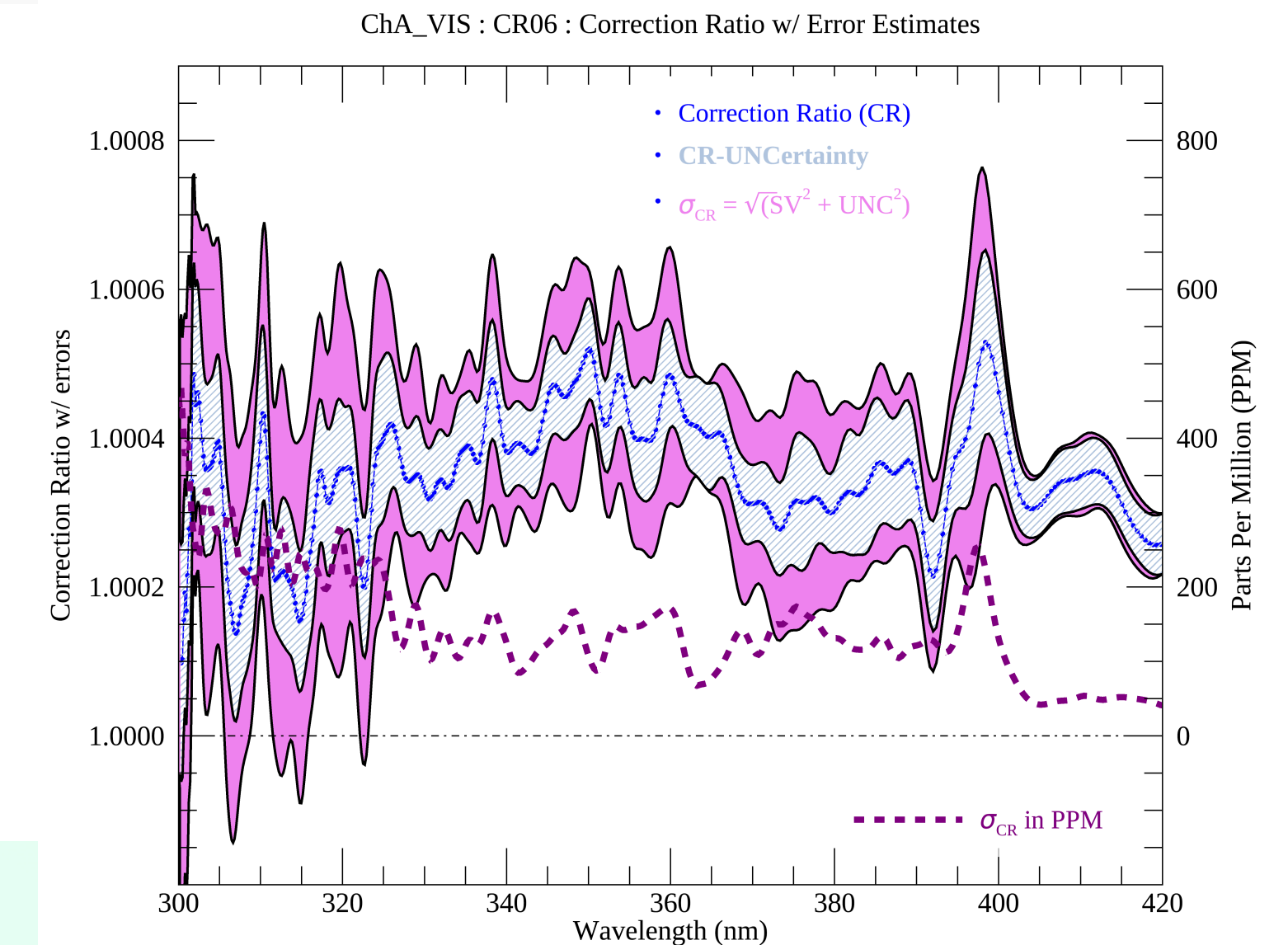


Figure shows the HFSSB-(OFF) pointing SSI correction and uncertainty for the UV diode of TSIS-1 SIM Channel-A .

**Without correction, V07 SSI measurements were off by as much as 2.5% (25,000 ppm)**

Uncertainties are a combination of based of published V08 SSI uncertainties + solar variability between calibration observations



## VIS-B Correction

# V08/09 : Correcting the HFSS-B(OFF) pointed SIM data in V07

TIM TSI shown in background (not used in calibration)

TSIS-1 SIM L2 : 1479 < T1D < 1692 : ChA\_VIS 365.98 ± 0.08 nm : CorrIRR

TSIS-1 DAY (T1D)

1500

1550

1600

1650

HFSS-B(OFF)  
Pointing  
3/19 -- 5/19/22

HFSS-A Pointing >= 5/19/2022

1363.0

1362.5

1362.0

1361.5

P09 CORR

P07 CORR

**TSIS-1 SIM V09  
@ 366 nm tracks  
TSI during  
contamination,  
HFSS-B(OFF)  
pointing.**

ChA\_VIS : Solar Spectral Irradiance  
(SSI,  $W m^{-2} nm^{-1}$ )

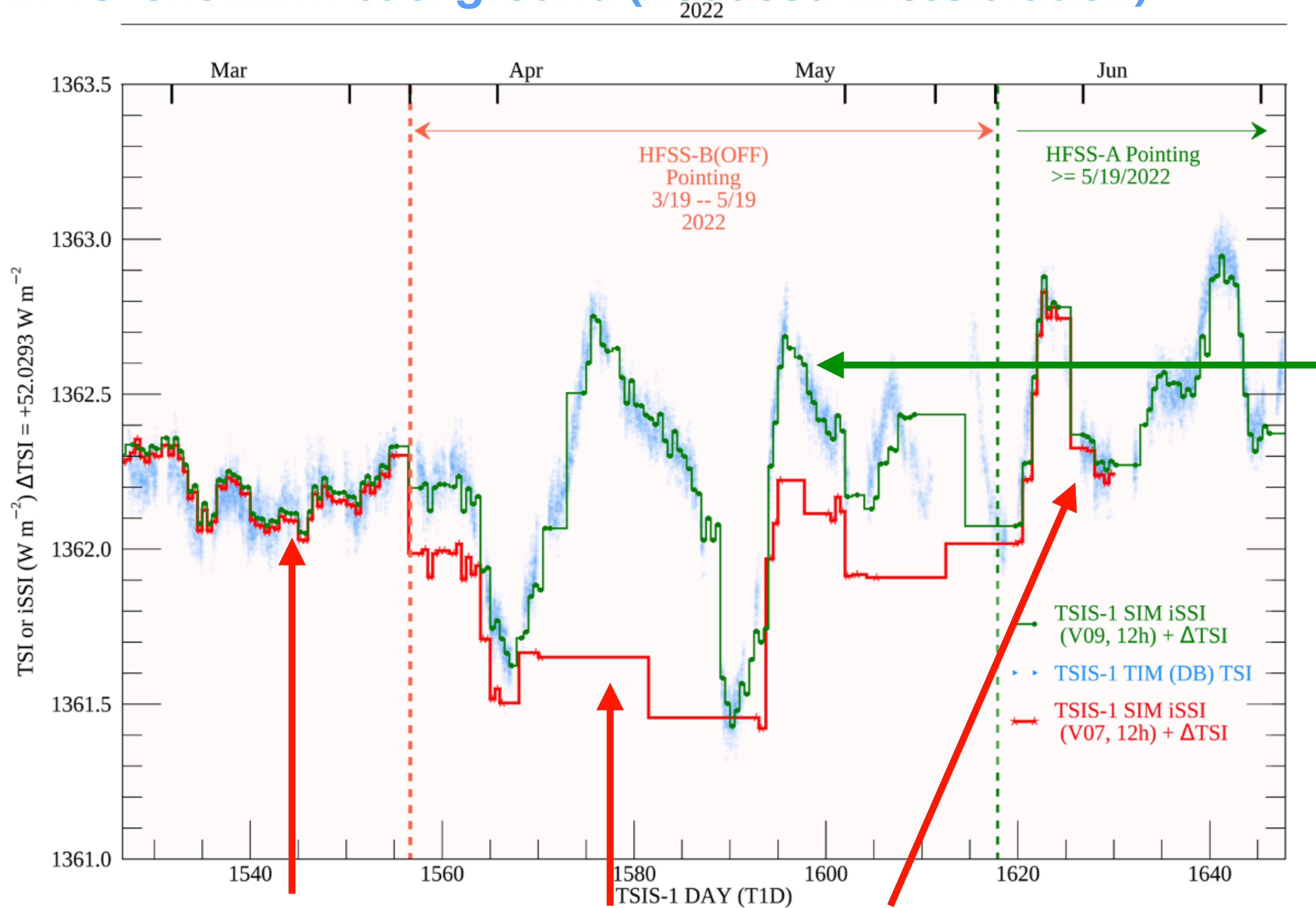
TSIS-1 TIM TSI ( $W m^{-2}$ )

Jan 2022 Apr Jul

**V07 @ 366 nm tracks TSI before contamination, significantly offset during, recovers after.**

# V08/09 : Correcting the HFSS-B(OFF) pointed SIM data in V07

TIM TSI shown in background (not used in calibration)



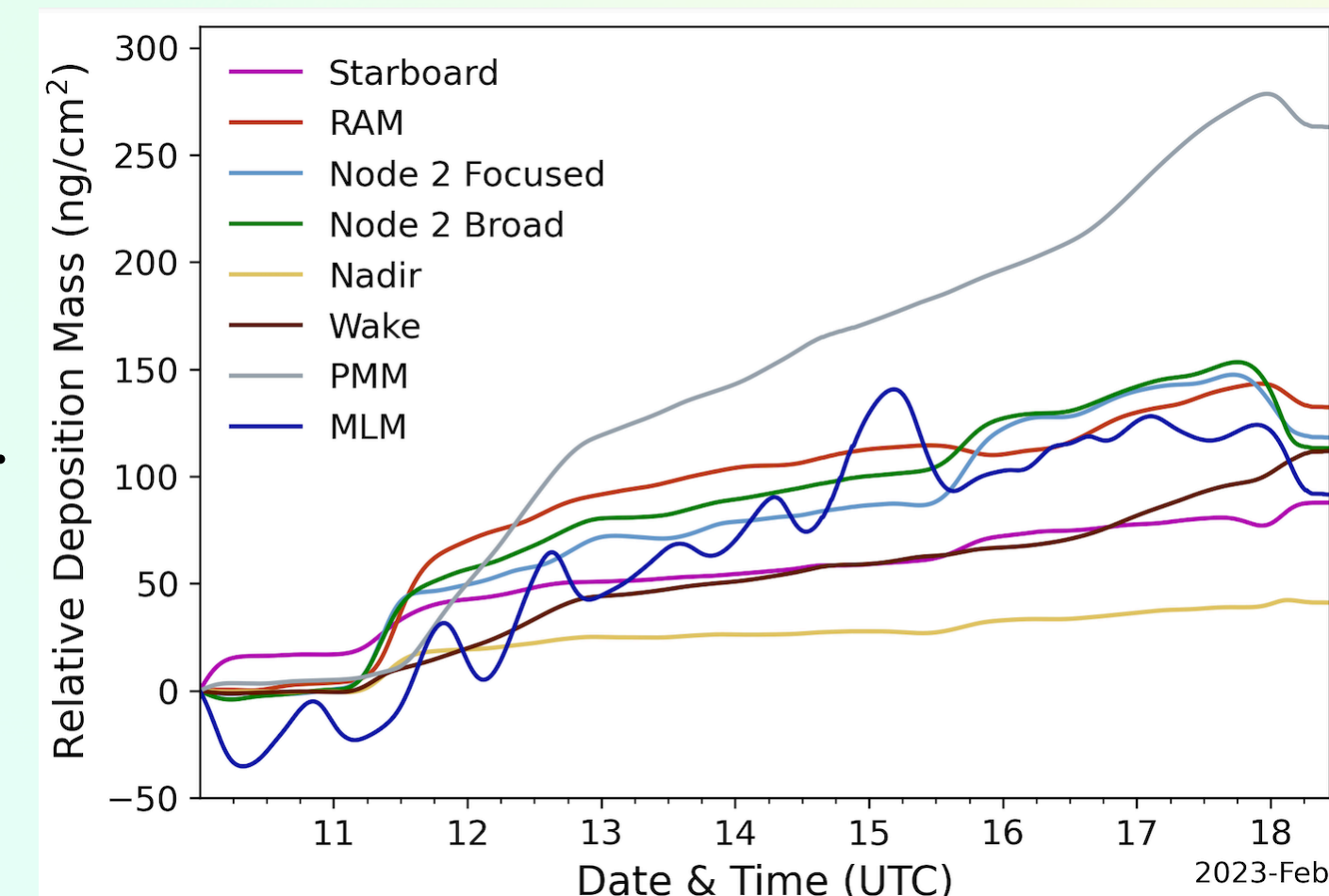
Integrating SSI from 200-2402 nm (iSSI) allows the best comparison of the effectiveness of the V08/V09 spectral corrections.

**TSIS-1 SIM V09 iSSI tracks TSI during contamination, HFSS-B(OFF) pointing.**

**V07 @ 366 nm tracks TSI before contamination, significantly offset during, recovers after.**

# TSIS-1 SIM Update for Fall 2022 / Spring 2023

- 2022-11-15 : V09 released
- 2022-12-15 : MS-22 major leak
  - Fortunately, no SIM impact
- 2023-02-09 : HFSS-A/B realigned
  - HFSS-B now a viable backup
- 2023-02-11: Another MS-21 Leak
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- 2023-04 : Successful ChC Scans
- 2023-05-31 : V10 released
  - ESR ( $> 740$  nm) wavelength alignment now uses IR prism offset corr.
  - Updated IR prism degradation corrections for 950-1620 nm
  - New prism degradation correction for ESR 1620–1845 nm
  - Updated baseline (filtering) spectrum using V10 data



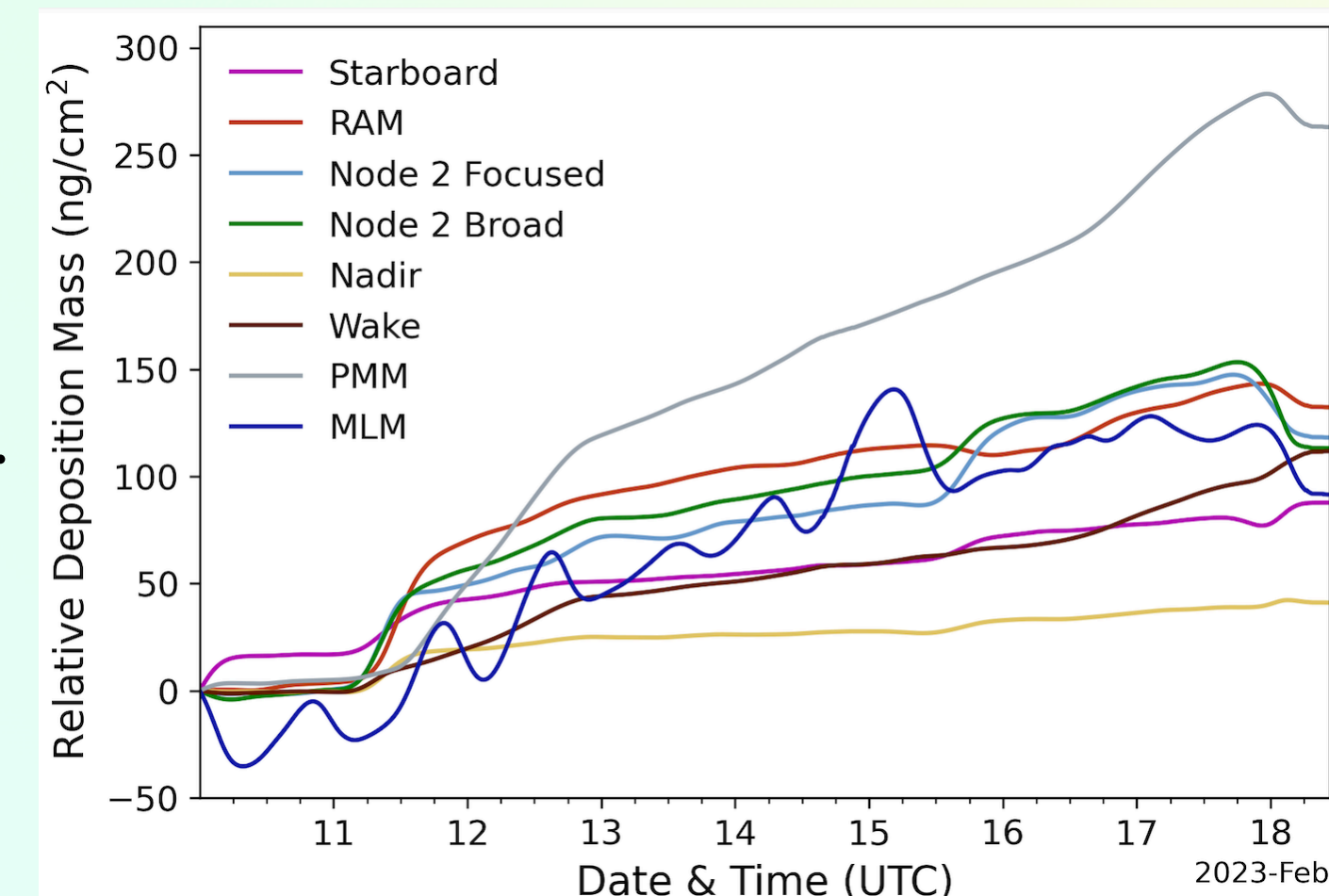
SAGE III (ELC-4)

Monitored significant contamination on the panels facing multiple directions

Up to 300 ng/cm<sup>2</sup>

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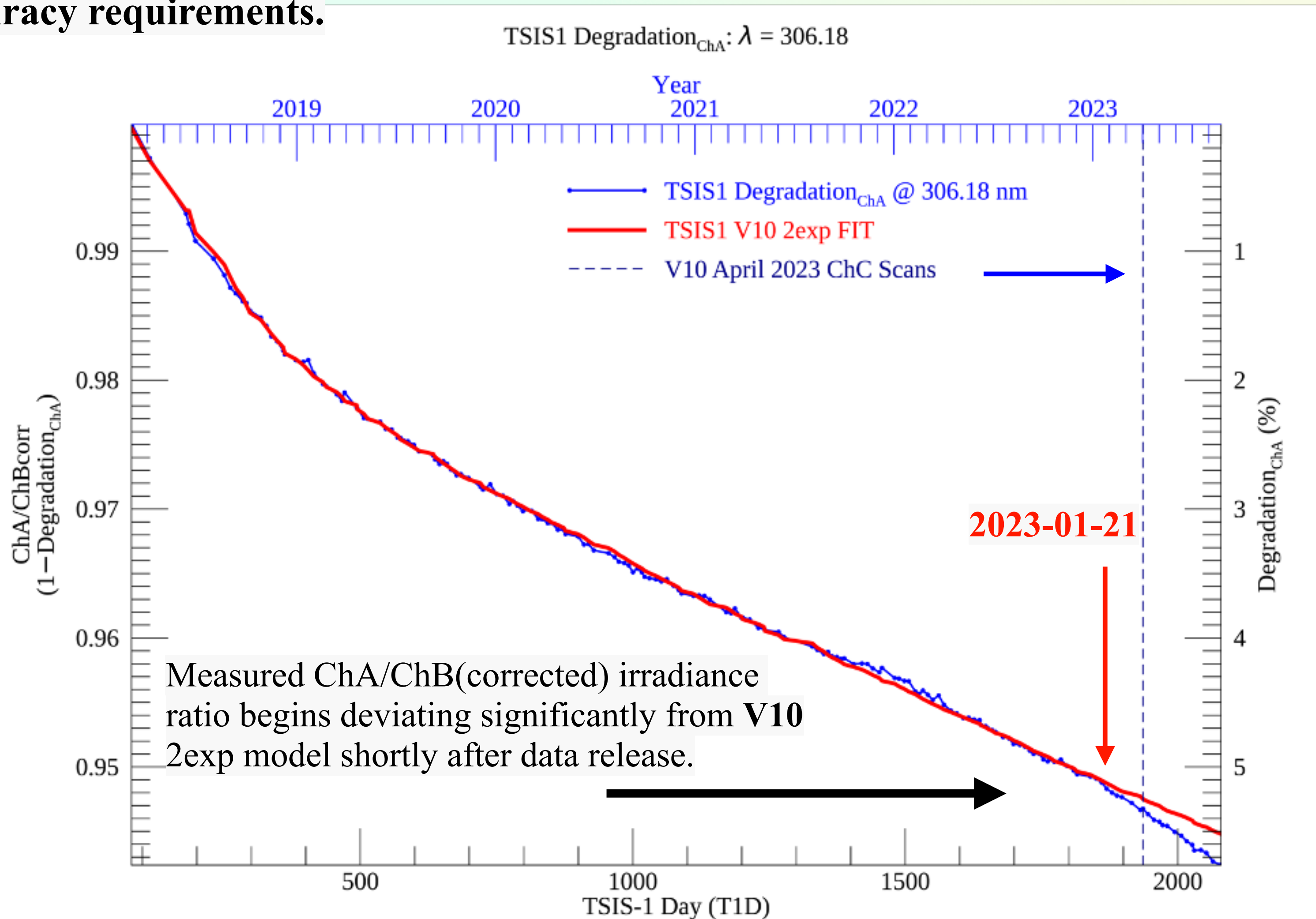
**SAGE III (ELC-4)**

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# TSIS-1 SIM V10 halted on 2023-08-10

Shortly after V10 release, the observed ChA/B irradiance ratios slowly deviated from the V10 2-term exponential prism degradation models used to **extrapolate** between semi-annual ChC scans. **Action was needed to prevent reported irradiances from exceeding accuracy requirements.**



Ratio change is due to increased ChA prism transmission loss, due to increased Solar activity during solar maximum

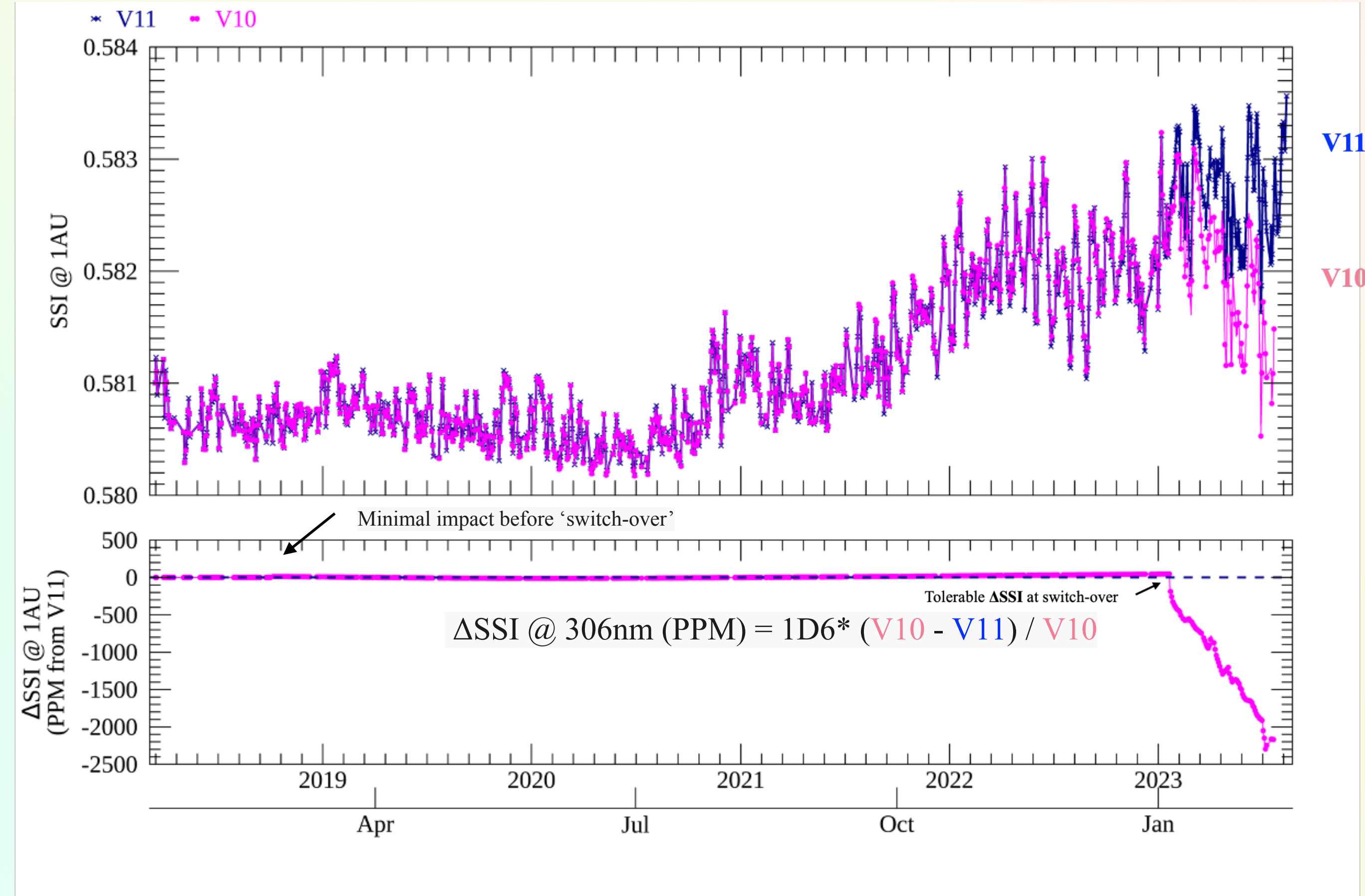
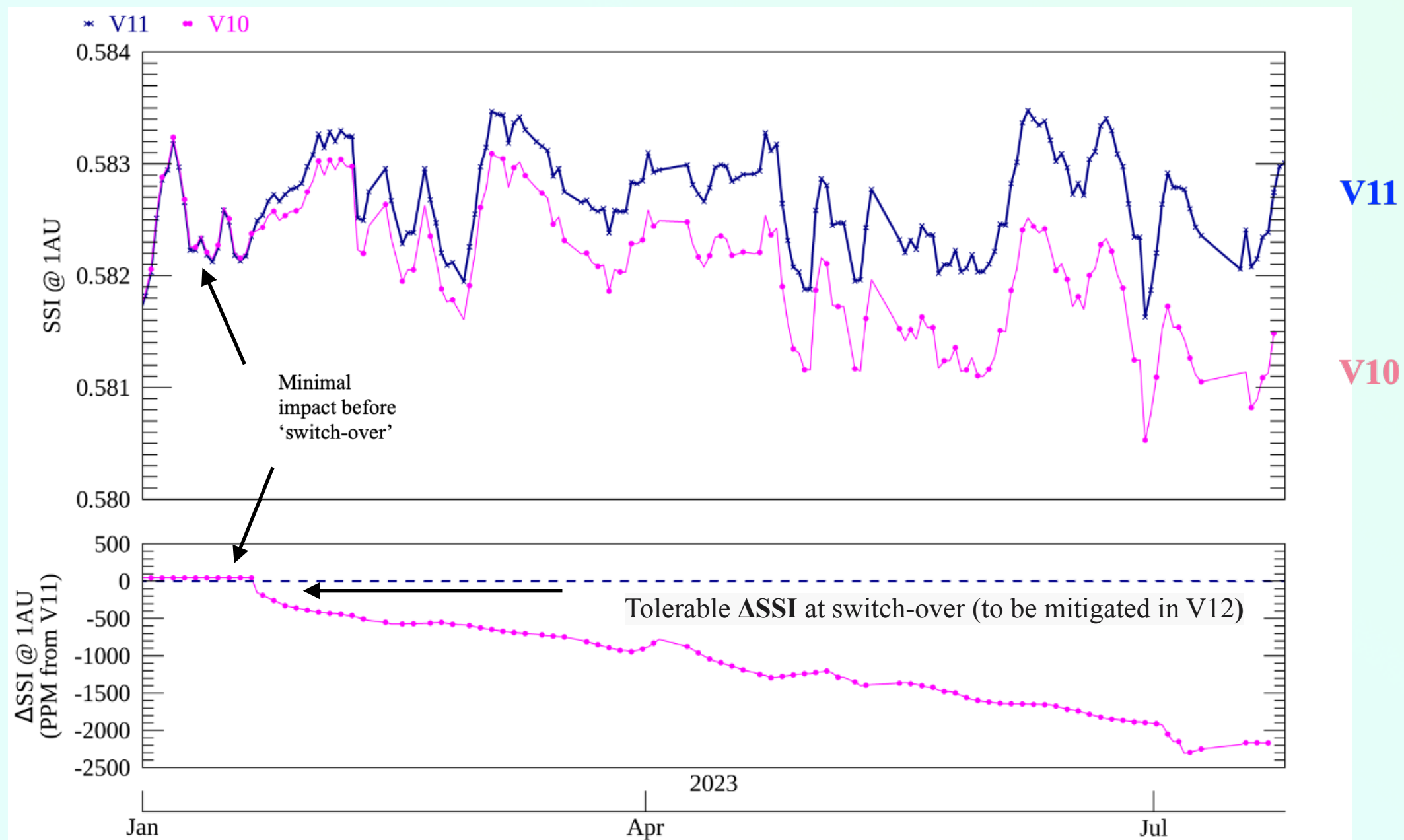
Currently only seen for  $\lambda < 800$  nm on the most used channel, ChA.

**Mitigated in V11 by ending degradation model extrapolation on 2023-01-21, replaced by actual measurements ('piece-wise' linear, ~ the blue data)**

# V11 : Mitigating the V10 Prism Degradation Issue (306 nm)

## V11 Timeline

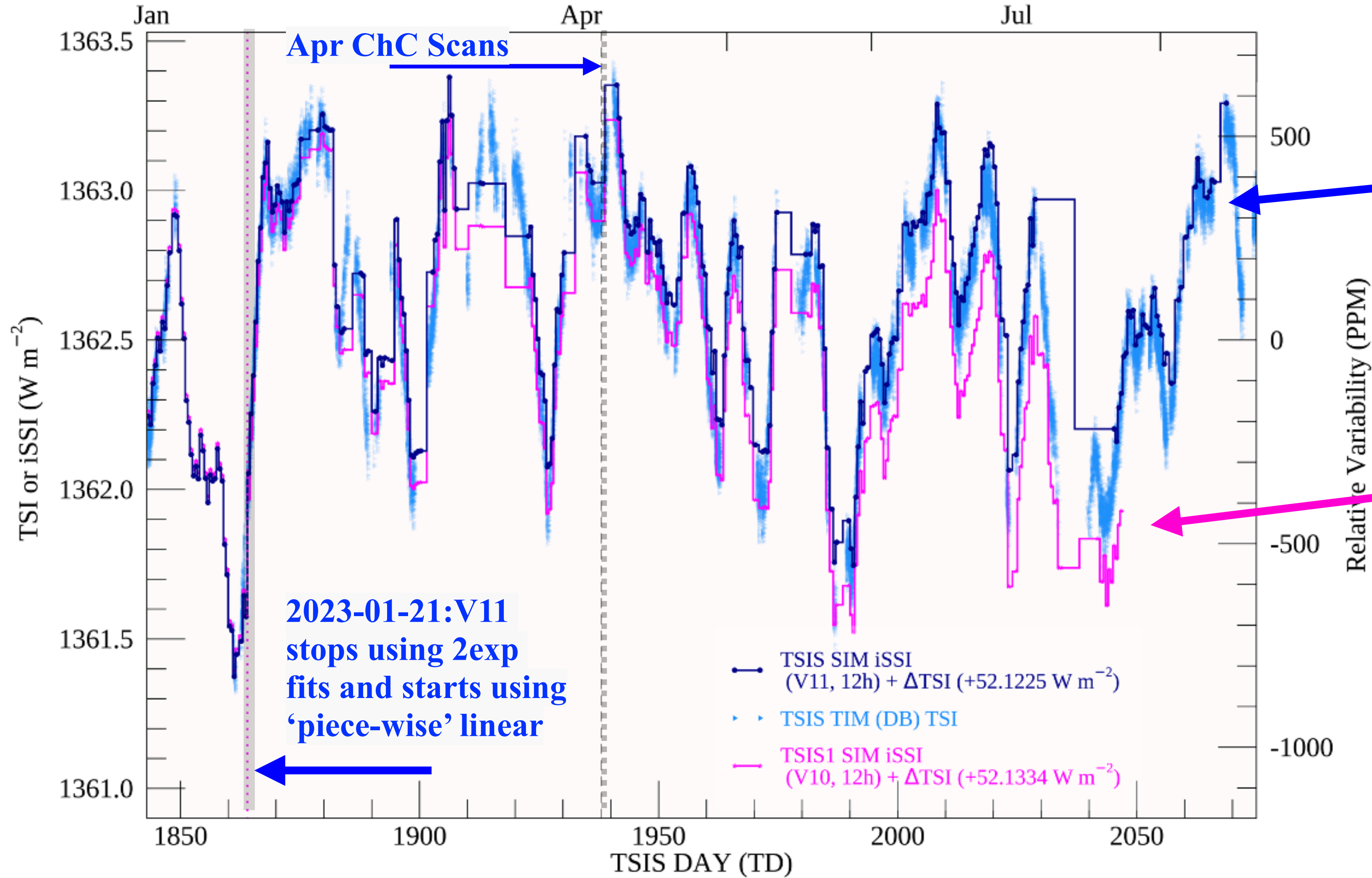
- **2023-08-10** - V10 issue discovered
- **2023-08-17** - V10 data release halted
  - Alert published on all data delivery portals
  - Published data rolled back/truncated to 2023-03-07 (date at which ½ accuracy requirement exceeded)
- **2023-08-30** - V11 replaces V10
  - V11 replaces extrapolation with ‘piece-wise’ linear (actual measurements) after 2023-01-21



V11 alleviates the V10 prism degradation rate change issue

# V11 : Mitigating the V10 Prism Degradation Issue (iSSI vs TSI)

TIM TSI shown in background (not used for calibration)



V11 iSSI tracks TIM-TSI extremely well

V10 iSSI increasingly divergent from TIM-TSI: -400 PPM on 2023-08-10



# TSIS-1 SIM update for September/October 2023

- 2023-09-02 : SIM DSP (digital signal processor) hang halts SIM science operations
  - non-stop telemetry indicates instrument is otherwise healthy (temps and voltages)
- 2023-09-29 : Mission Extension Approved (at 50% budget)
  - Includes exploring an 2400-2800 nm extension

- 2023-10-04 : October ChC scans aborted

- 2023-10-09 : Major MLM Leak

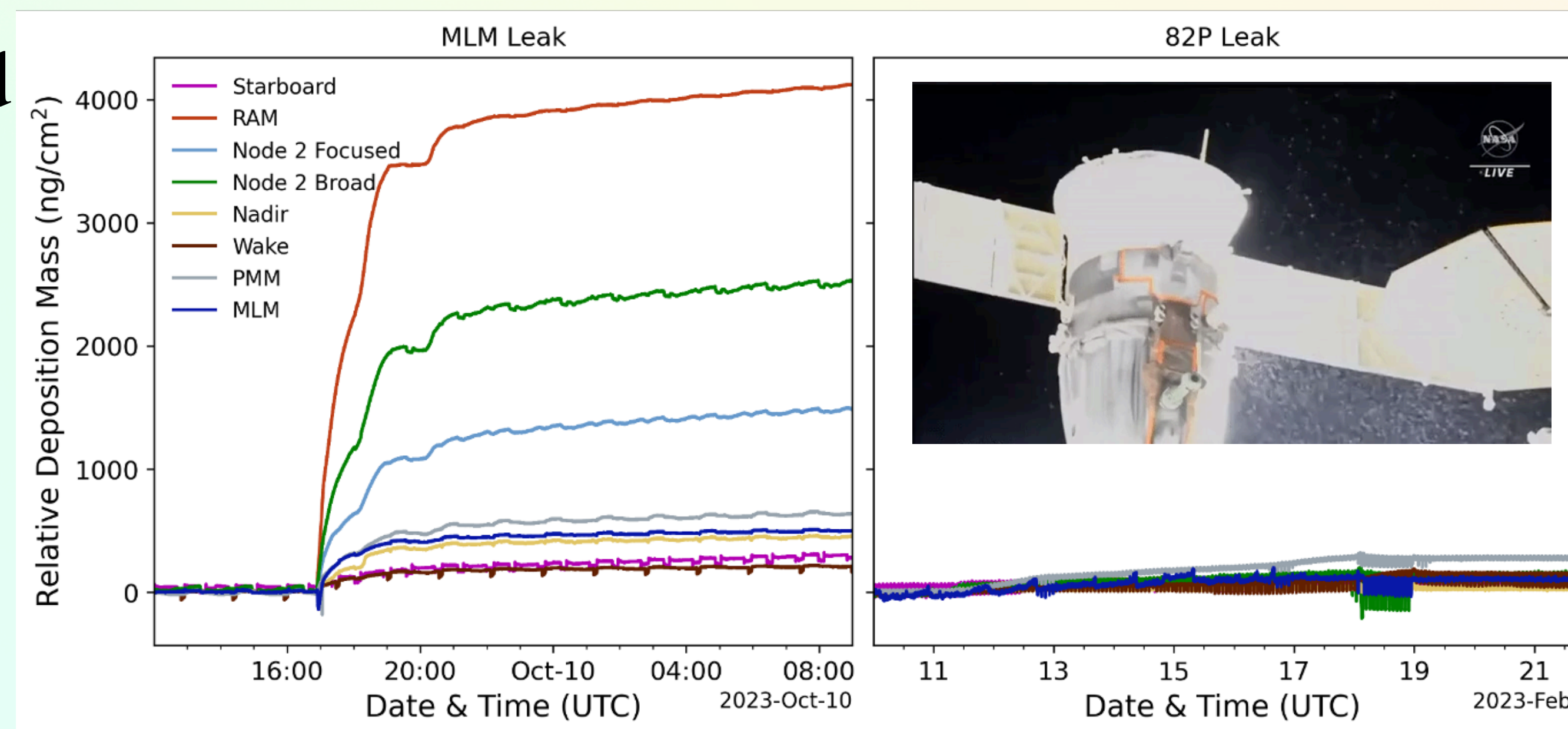
- Multipurpose Laboratory Module = Nauka
- Up to 4000x worse than MS-22 (82P) leak !
- 70+ liters of coolant
- Amazingly, no SIM impact detected (FSSs or CCD)

- 2023-10-14 : SIM DSP 'un-hung'

- 2023-10-17 : 3 days ago - SIM Dark exposures successfully executed - full functionality

- 2023-10-18 : 2 days ago - SAGE III shows contamination down to acceptable levels

- 2023-10-20 : Today - SIM resumes science operations at 12:16 PM MT



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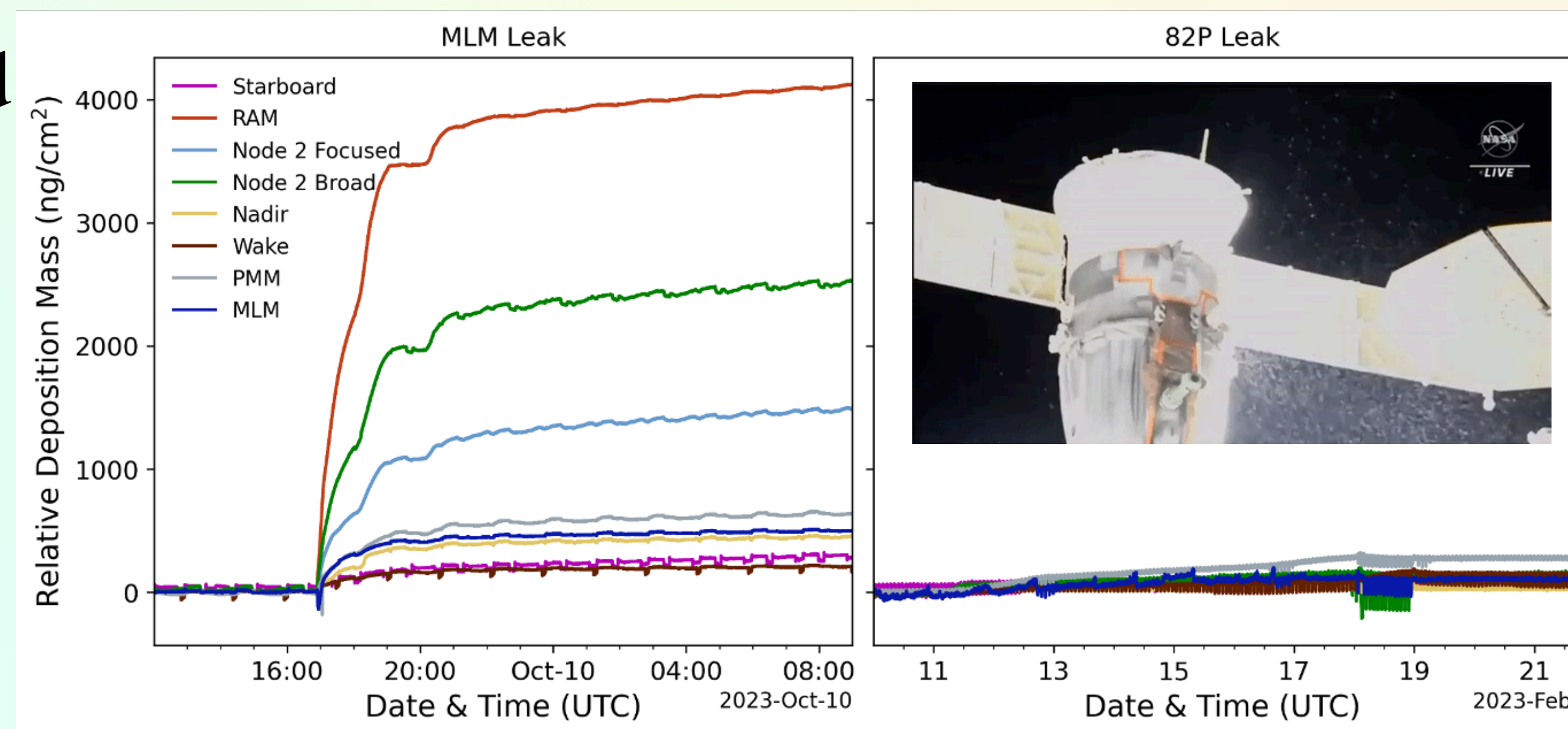
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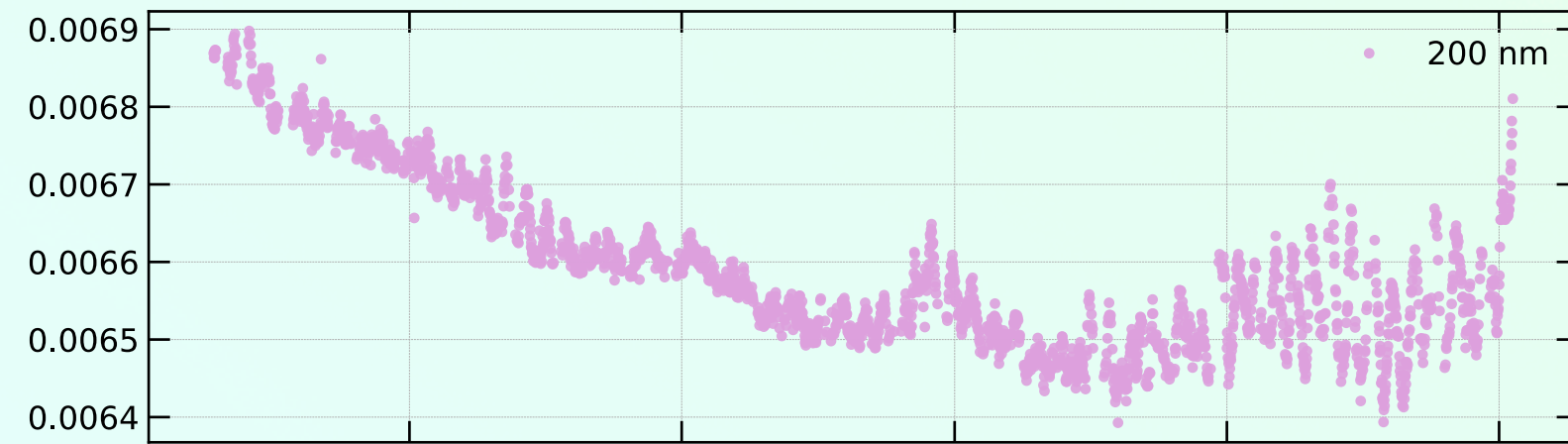


1. Remove the need to extrapolate prism degradations (in time)
  - A. Replace 2-exponential models with polynomials or separate fits over independent time epochs (in development)
  - B. After the latest ChC scan, only actual measurements will be used
    - 'piece-wise' linear interpolation
2. Report 'TRUE\_EARTH' irradiance
  - A. Current irradiance is '1AU' normalized to highlight solar variability
  - B. Irradiance @ Earth important for climate studies/earth science
  - C. TSIS-1 TIM already provides similar TSI data product (w/uncertainties)
    - Implementation will mirror TSIS-1 TIMs
3. Continued evolution of software for multi-mission use (TSIS-2)
4. Continued mitigation of annual signals seen in time series

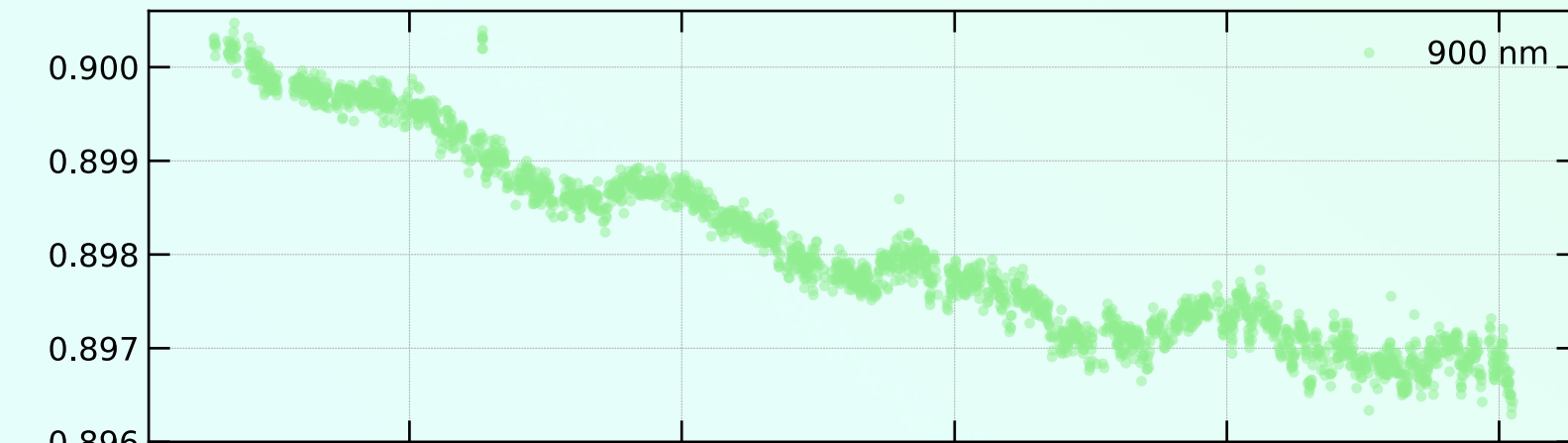
# V12 : Investigating Removal of Instrumental Annual Oscillations

## V11

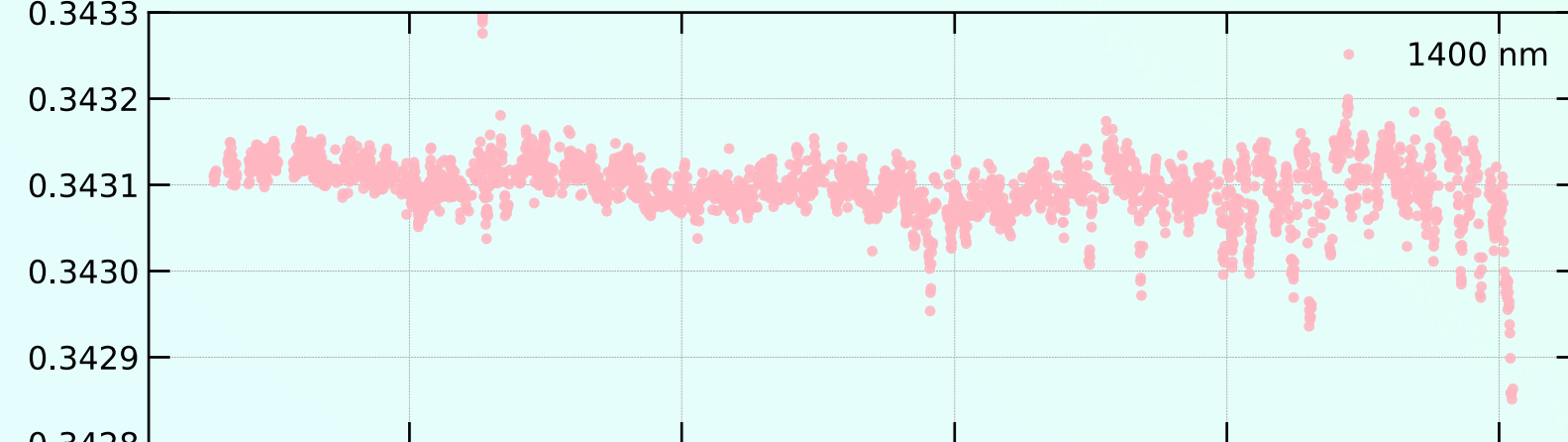
UV Diode



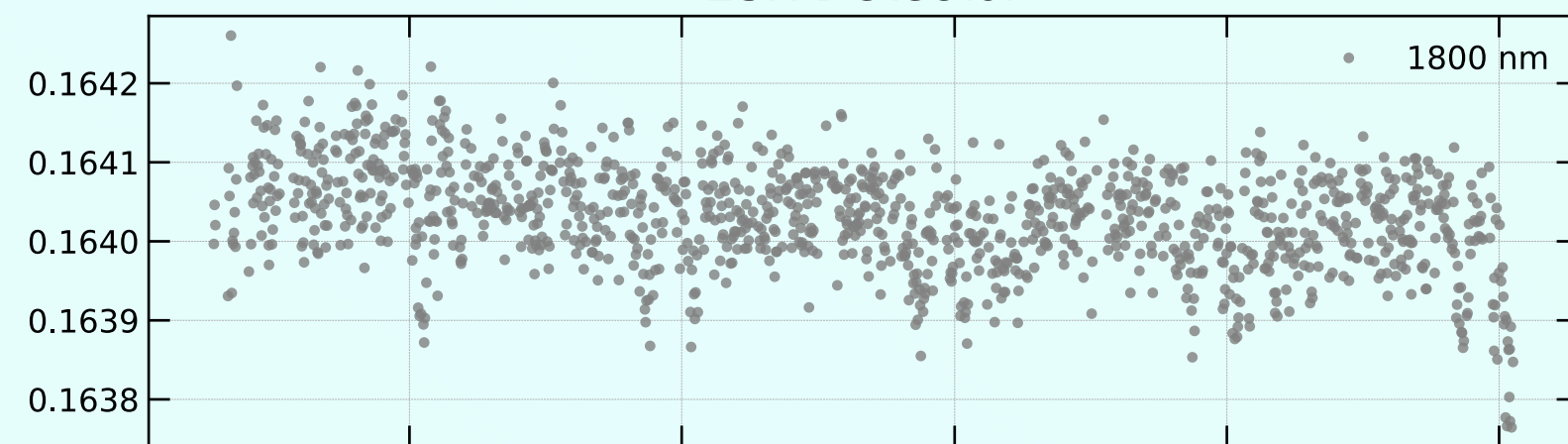
Vis Diode



IR Diode



ESR Detector



Investigating two main improvements:

- 1) Improving diode temp. dependence,  $dR/dT$
- 2) Improving the diffraction correction using the true solar radius instead of the average

L2 data shown in figures  
(no prism degradation correction)

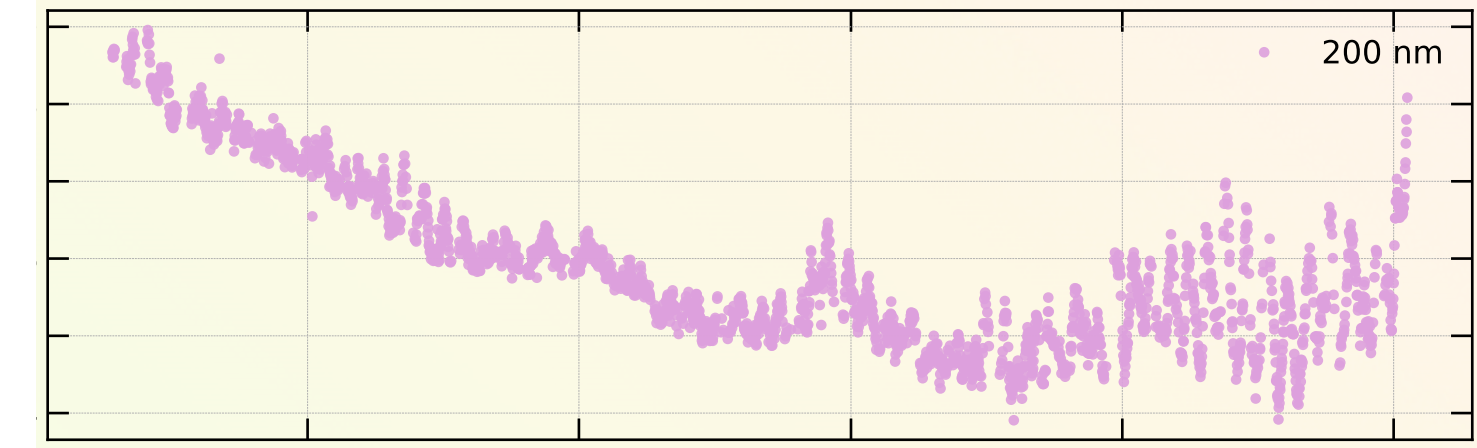
VIS diode improvement is  $\sim 100\%$  via  $dR/dT$

IR and ESR improvements are mainly from diffraction correction

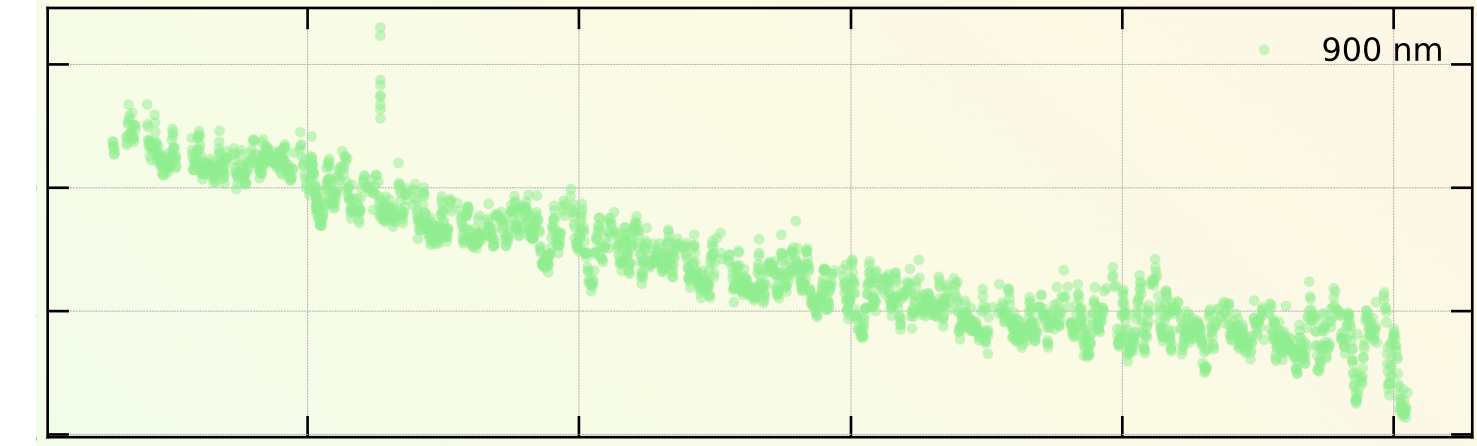
There is almost no change to the UV, but future improvements to  $dR/dT$  should help.

## V12beta

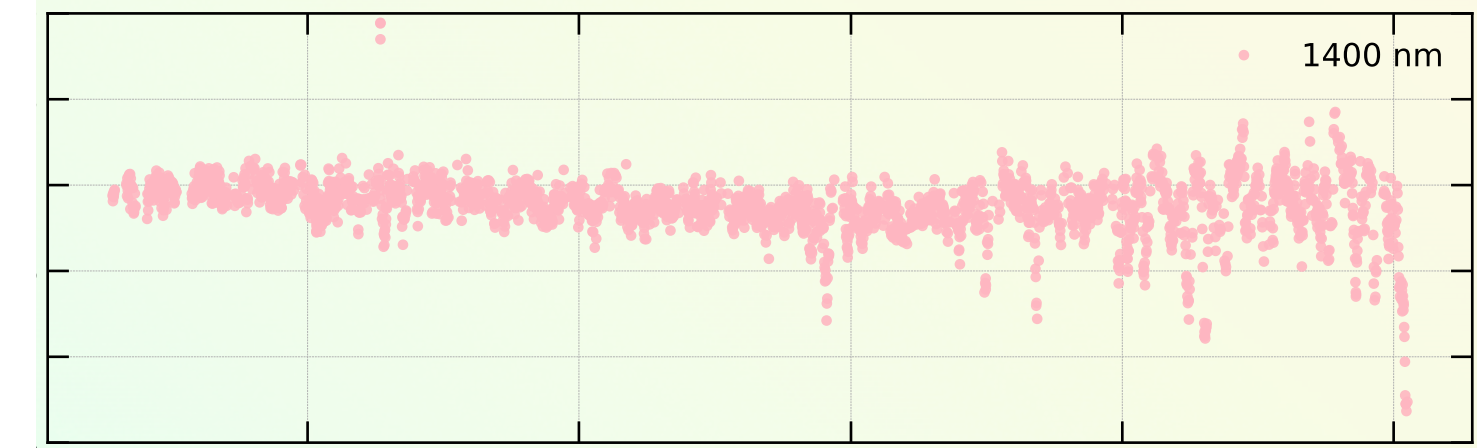
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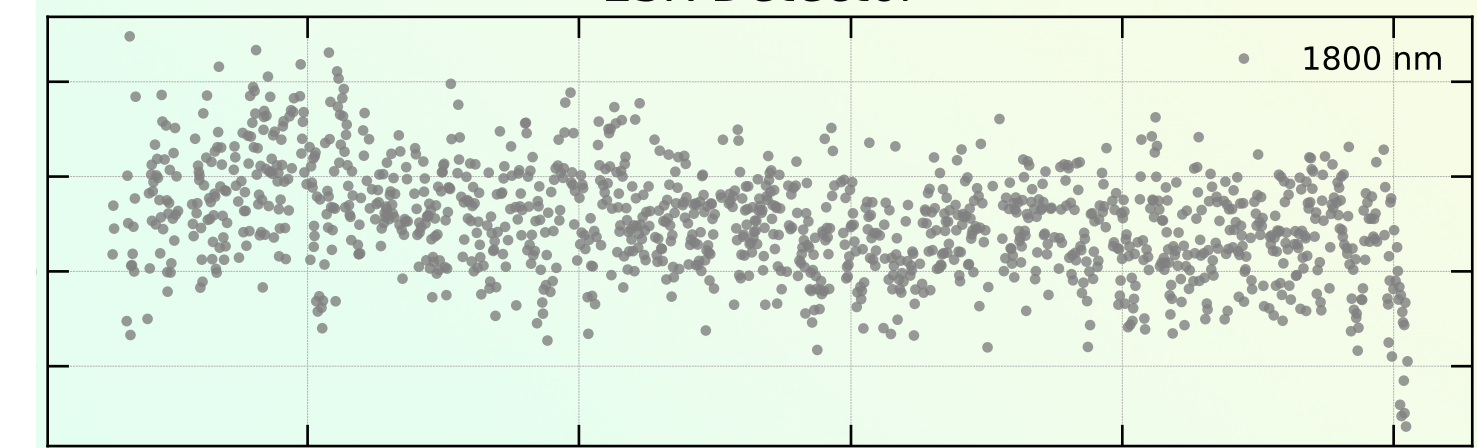
Vis Diode



IR Diode



ESR Detector



# TSIS-1 SIM SDP Posters Presented at SCS 2023

**Life on the ISS:**  
**The Challenges Faced by the TSIS-1 Mission Due to Observing Onboard the ISS**  
 Keira J. Brooks, Michael Chambliss, Stéphane Béland, Luke A. Charbonneau, Odele Coddington, Cody Folgmann, Charles Labonde, Robby Mendoza, Courtney L. Peck, Steven V. Penton, Jason Price, Erik Richard, Lucas Sackrison  
 LASP (Laboratory for Atmospheric and Space Physics) – University of Colorado at Boulder

For the last five years, TSIS has collected data from its observing platform on the ISS. The location of the instrument has presented a unique set of challenges to the operations, systems engineering, and data analysis that is required in order to continue the solar irradiance data record and provide the highest quality data.

Early in the mission, learning how the seasonal changes in the length of time the instruments are sun-illuminated during an orbit and different solar viewing windows impact scheduling was particularly challenging, while the continued and frequent changes to the ISS schedule, requires constant attention and adjustment by the Operations team.

Additionally, recent leaks in docked vehicles, ISS power outages, and debris from ISS activities have all affected the TSIS-1 team from recovering the instruments to adding processing steps to ensure data quality.

The daily solar observing success rate for TSIS prime mission was 86% for TIM and 85% for SIM. While for space-based most missions, this is less than optimal, for TSIS, given the scheduling challenges, this is quite impressive.

**Impacts to Operations: Scheduling**  
 One of the main challenges of having the ISS as the TSIS-1 platform is that due to the position of TSIS-1 on the ISS, there are times of the year in which it is impossible to take science data due to obstructions, glints, and other impacts of the hardware around the instruments. This was discovered very early on in the mission, and adjustments to scheduling had to be made to ensure optimal science data collection.

Due to the location of TSIS-1 on the ISS, there are many obstructions that block the sun, and how much they block the sun can depend on the time of year and other factors. In the figure above, we see how an angle,  $\beta$ , is used to indicate the viewing window of the TSIS-1 instruments. In the figure to the right, this angle is shown on the y-axis and we see a mapping of ISS components in the TSIS-1 field of view. Outside of  $\beta \pm 40$  degrees, our viewing window, and therefore the ability to take all scans as expected, decreases.

If, at any point, additional ISS components, for example the Canadarm, are moved into the field of view of TSIS-1, this also impacts the scheduling window and the amount of science data we can take.

**Impacts to Operations: Outages**  
 Two main reasons for planning TSIS outages: concern for contaminants and ISS required outages for safety.

**Contaminant concerns arise when:**

1. A vehicle docking or berthing/capture
2. A vehicle is undocking or unberthing/release
3. A vehicle relocate
4. EVA maneuver of any kind
5. ISS vents substances
6. EVA that involves risk of contaminant release or foreign object debris risks

**ISS safety outages:**  
 These occur when there is a safety risk to the crew or hardware. At these times TIM & SIM are powered off and are powered on immediately after their conclusion.

1. EVA activity in the vicinity of ELC3
2. Robotics activity in the vicinity of TSS

**Unplanned Outages**  
 In the event of unplanned outages, TIM & SIM are shuttered as soon as Ops is aware of the event. Such events have included leaks and unexpected power loss.

Major unplanned events that have impacted TSIS operations:

- December 2022: Soyuz MS-22 coolant leak
- February 2023: Progress 82 cargo ship coolant leak
- August 2023: Unexpected loss of ELC-3 (where TSIS is located) power
- October 2023 (ongoing): MLM coolant leak

**Outage tracking**  
 The TSIS-1 operations team has an internal ISS Dynamic Ops Log which tracks events (both planned and unplanned).

**Planned Outages**

**Unplanned Outages**

**Additional updates made as a result of this event:**

- Added quality flags
- Adjustment to the pointing flags
- Adjustments made to the HFS-8 so that if used in the future, it will be pointed correctly

## Life on ISS in tough - K. Brooks

**Solar Irradiance Monitor (SIM) instrument calibration techniques on the TSIS-1 missions**  
 Michael Chambliss, Luke A. Charbonneau, Alan Hoskins, Stéphane Béland, Keira J. Brooks, Odele Coddington, Courtney L. Peck, Steven V. Penton, Erik Richard, Thomas Woods  
 University of Colorado Boulder – Laboratory for Atmospheric and Space Physics (LASP)

**Introduction**  
 The Solar Irradiance Monitor (SIM) measures solar solar part of the Total and Spectral Irradiance Sensor (TSIS-1) mission and its successor the high degree of accuracy produced by SIM to meet its has developed a high-fidelity and its Spectral Radiometry. The SRF at LASP is used to of the instrument using both NIST-traceable detector called Radiometer). Upgrades and beam made since TSIS-1 was, the addition of SNACR, method of calibration is very IS-2 SIM.

**Calibration in SRF**  
 The TSIS-2 calibration campaign spanned multiple months and hundreds of calibration scans in total covering a wide array of different wavelengths. The SRF facility at LASP contains a Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) Laser system that allows the calibration team to generate stable laser sources of various wavelengths and polarizations. At the end of the system is a mirror which can point the beam at either SNACR or SIM. Additionally, a fast-steering mirror paints a rectangular pattern on the aperture slits of the detectors multiple times per second to mimic a diffuse source like the Sun instead of the point like laser source.

**SIM Scans**  
 During a scan on the SIM instrument the FPD drive is rotated causing the dispersed laser to scan across one of the detectors. Below is the resulting signal measured by the VIS diode for a typical scan with a laser at 532nm. The key values derived from each scan are the CCD centroid position and the irradiance of the scan derived from the integral of the signal.

**SIM Irradiance Calibration**  
 For each SIM scan we can calculate an initial irradiance value by converting the measured signal to power via the detector response function and applying the aperture area. However, this leaves out several key corrections such as dispersion and prism transmission. Using our instrument model, we can derive values for these corrections to get an accurate irradiance value to compare with the measured irradiance on SNACR. Using these comparisons, we iteratively optimize the physical parameters of our SIM instrument model in order to get our calculated irradiance values to match SNACR as closely as possible. Any remaining difference can be corrected via a calibration function.

**Improving Solar Spectral Irradiance Calibrations Through Analysis of TSIS-1 SIM Measurement Artifacts**  
 Courtney L. Peck<sup>1</sup>, Stéphane Béland<sup>1</sup>, Keira J. Brooks<sup>1</sup>, Michael Chambliss<sup>1</sup>, Luke A. Charbonneau<sup>1</sup>, Odele Coddington<sup>1</sup>, Steven V. Penton<sup>1</sup>, Erik Richard<sup>1</sup>  
<sup>1</sup>Laboratory for Atmospheric and Space Physics (LASP), University of Colorado - Boulder

**SIM Instrument Overview**  
 The Spectral Irradiance Monitor (SIM) instrument onboard the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission measures solar spectral irradiance (SSI) from 200 nm to 2400 nm using:

- Three channels to monitor instrument degradation each with a Féry prism for dispersion
- Three photodiode detectors:
  - Ultraviolet (UV: 200 nm – 311.5 nm)
  - Visible (Vis: 311.5 nm – 950 nm)
  - Infrared (IR: 950 nm – 1620 nm)
- An absolute electrical substitution radiometer (ESR: 200 – 2400 nm)

**Determining the Source of the Annual Signal**  
**METHODOLOGY**

- Use Version 11 L2 SIM data to isolate the annual trends in the UV, Vis, IR, and ESR measurements separately (i.e., not using L3 degradation-corrected data)
- Characterize the amplitude of the annual signal at each wavelength using a detrending algorithm (Python statsmodels package)

As shown (left), the amplitude of the annual signal is uniquely wavelength-dependent for measurements from the three photodiodes (top) and the ESR (bottom).

- The amplitude in the Vis and IR photodiode measurements closely resembles the diode responsivity temperature dependence (dR/dT), indicating a potential error in this calibration
- The amplitude in the ESR measurements increases with wavelength, suggesting a possible error in the diffraction correction

**DIODE RESPONSIVITY TEMPERATURE DEPENDENCE (dR/dT)**  
 Since the photodiode temperature has a strong annual variability, errors in dR/dT calibration could manifest as an annual signal in the photodiode measurements

We tested the effect of changes in the dR/dT calibration values on the amplitude of the annual signal

- The dR/dT calibration is used to correct for the diode responsivity to convert from diode Amps to Watts
- The dR/dT values are also used in an intermediate step to perform the wavelength alignment for each scan

**DIFFRACTION CORRECTION**  
 Given the larger dispersion angle off the prism for the ESR, errors in the diffraction calculation will be:

- Larger in the ESR than the photodiode measurements
- Larger in the IR photodiode measurements than in the UV or Vis

We tested the impact of adding the true solar radius in the diffraction calculation where it was previously using an average radius

**Results**  
**Residual errors in the dR/dT calibration values causes annual signals in the photodiode measurements**

- Modifying the dR/dT calibration values for the Vis photodiode measurements greatly reduced the annual signal at all wavelengths longward of ~700 nm
- The modified dR/dT values were derived from the pre-flight calibration measurements, which will need to be refined to remove the residual annual signals remaining in the photodiode measurements

**Improving the diffraction correction reduces the annual signals for long wavelengths**

- The diffraction correction was updated to use the true solar size instead of an average solar size
- This change reduced the annual amplitude in the IR and ESR measurements by ~50% for most wavelengths
- While reduced, the annual signals in the ESR measurements remain, particularly from ~1500–1800 nm, and are currently thought to be due to the lack of accurate wavelength-alignment for ESR measurements

**Conclusions and Future Work**  
 We have determined the dominant sources of the annual signal artifact in the TSIS-1 SIM data, finding it to be due in part to errors in dR/dT calibration values and a simplification used in the diffraction calculation

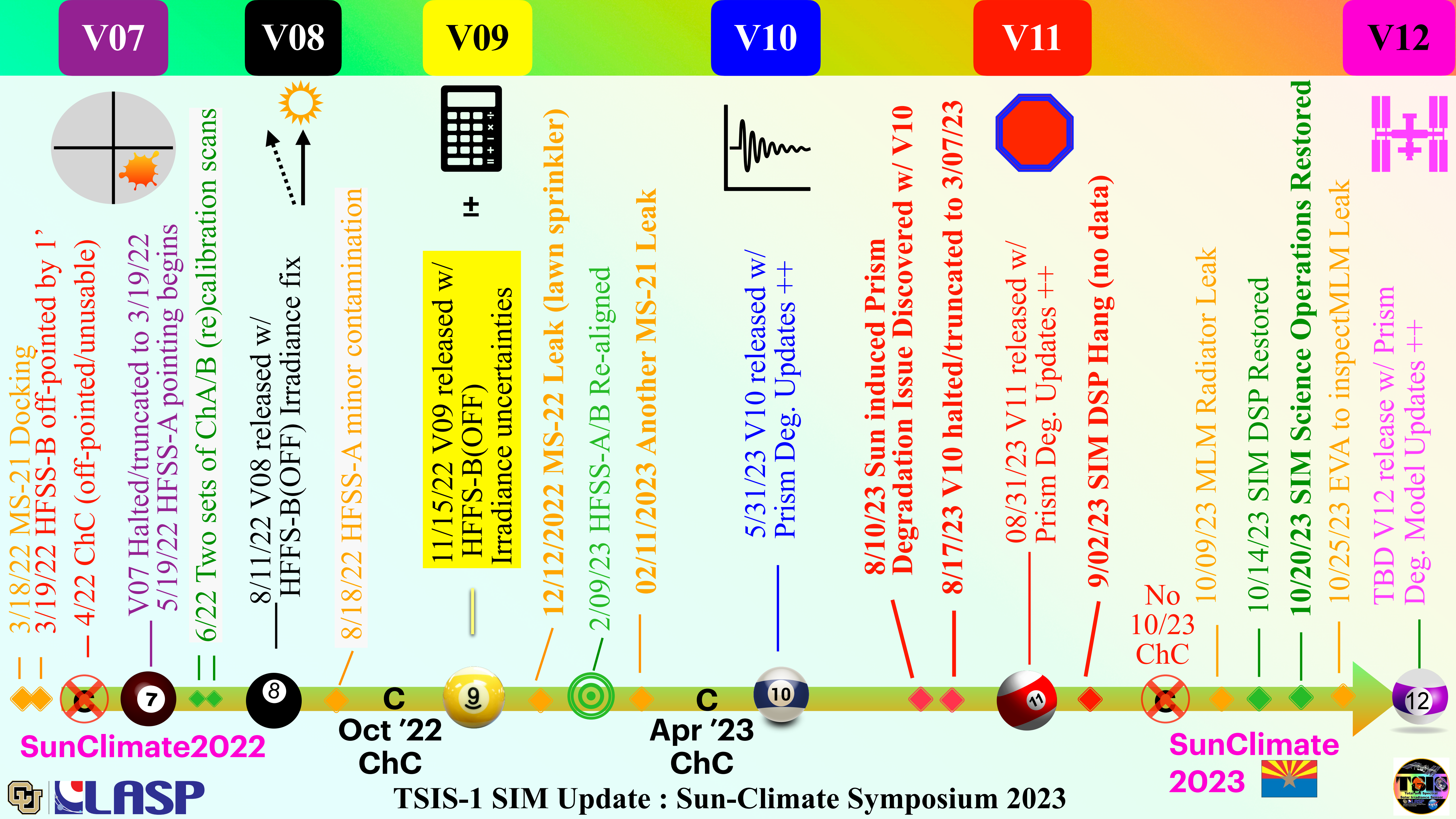
Future work includes:

- Rederiving dR/dT to ensure accuracy and reduce the remaining annual signal in the photodiode measurements
- Investigating the remaining annual signal from ~1500–1800 nm, including exploring methods for wavelength alignment for the ESR scans
- Apply corrections in new data version release, which will be made available at <https://lasp.colorado.edu/tsis/data/>

## Further improvements are on the way - C. Peck

## How we calibrate - M. Chambliss and L. Charbonneau





V07

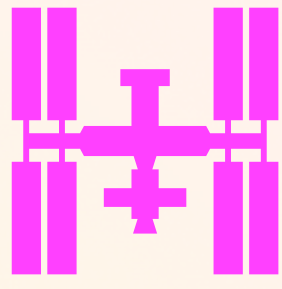
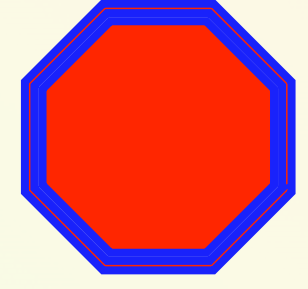
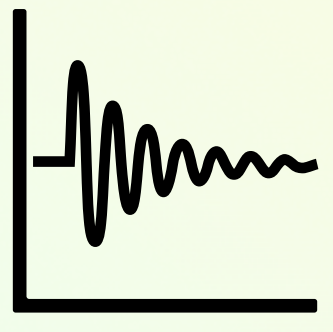
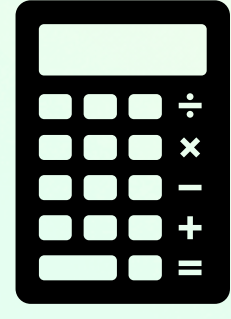
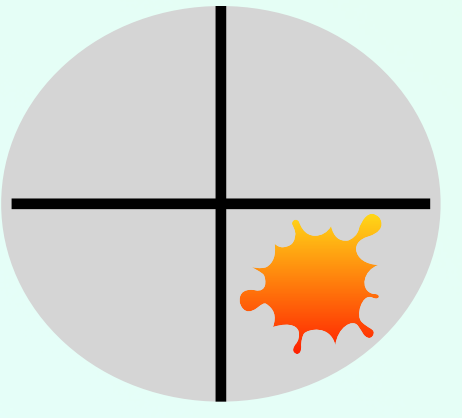
V08

V09

V10

V11

V12



SunClimate2022

SunClimate 2023

TSIS-1 SIM Update : Sun-Climate Symposium 2023



# BACKUP SLIDES

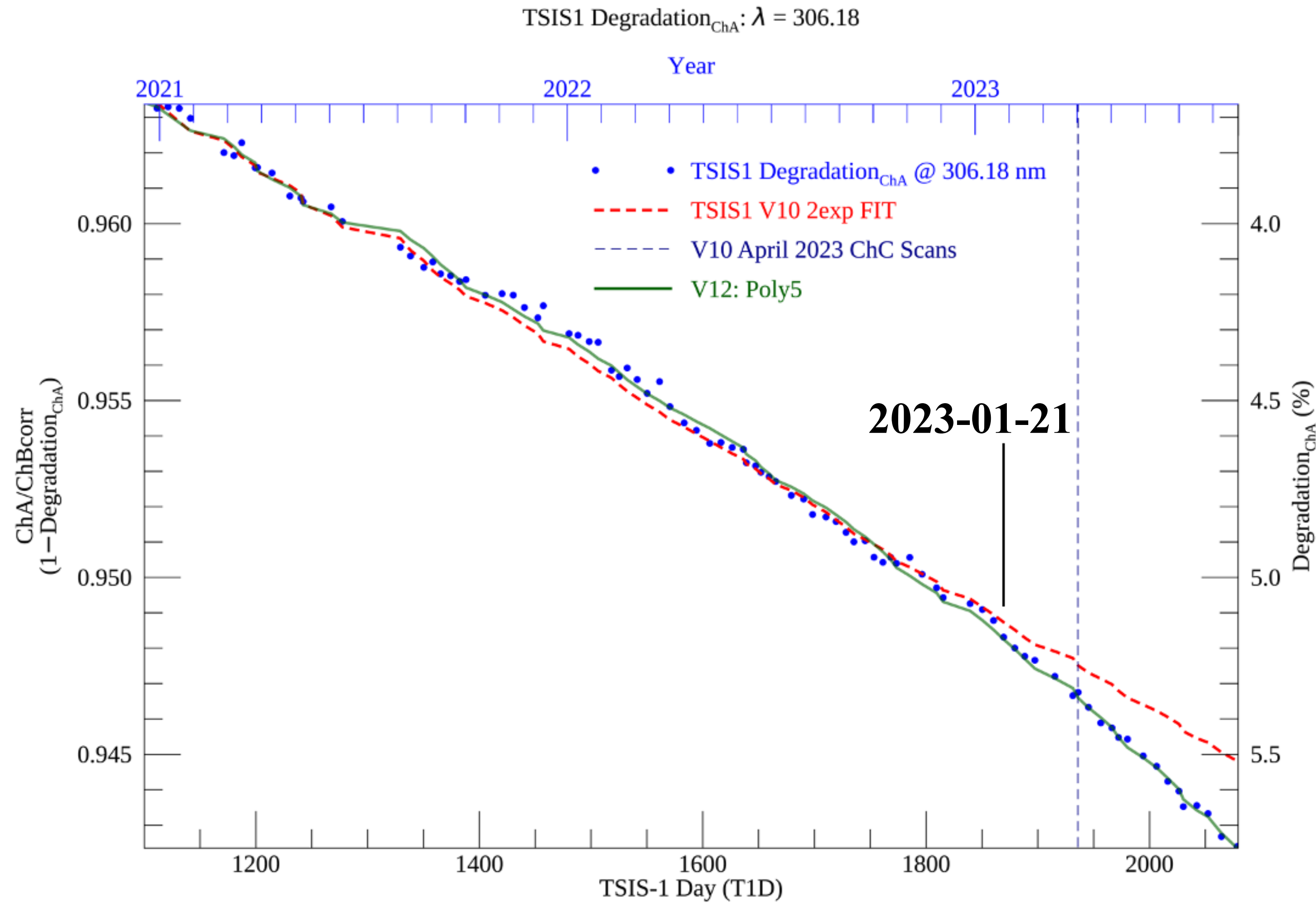
# V12 : Changes to Prism Degradation Models to handle V10/11 Issues

Example for wavelength < 800 nm, after :  
 ChA(uncorrected)/ChB(corrected) Prism Degradation Correction

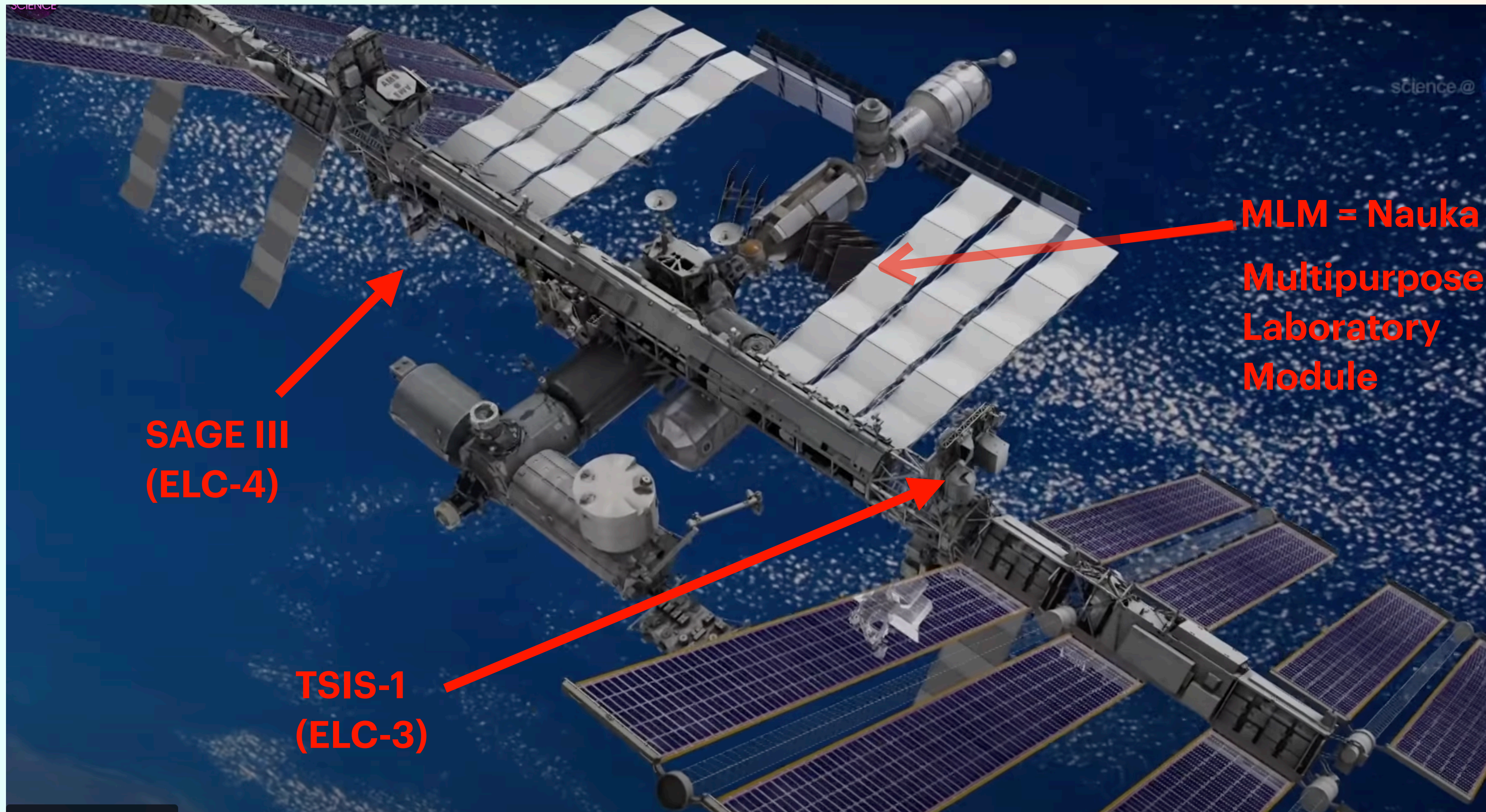
	<b>V10</b>	<b>V11</b>	<b>V12 (beta)</b>
<b>Data up to latest ChC Scan (or 2023-01-21, V11)</b>	2-term exponential model	2-term exponential, BUT only < 2023-01-21, where model deviates from ChA/B measurements	Polynomial fits (N<6) and/or fits over multiple time ranges
<b>Data after latest ChC Scan (or 2023-01-21, V11)</b>	<b>Extrapolation</b> of 2-term exponential model after latest ChC	Uses ChA/ChB measurements (piece-wise linear) AFTER 2023-01-21	Uses ChA/ChB measurements (piece-wise linear) AFTER last ChC (no extrapolation)



# V12 : Example of Polynomial ChA Prism Degradation Fit\* at 306 nm



\*Polynomial (n=5) fit is made as a function of solar exposure, but displayed here vs calendar time/ TSIS-1 Day

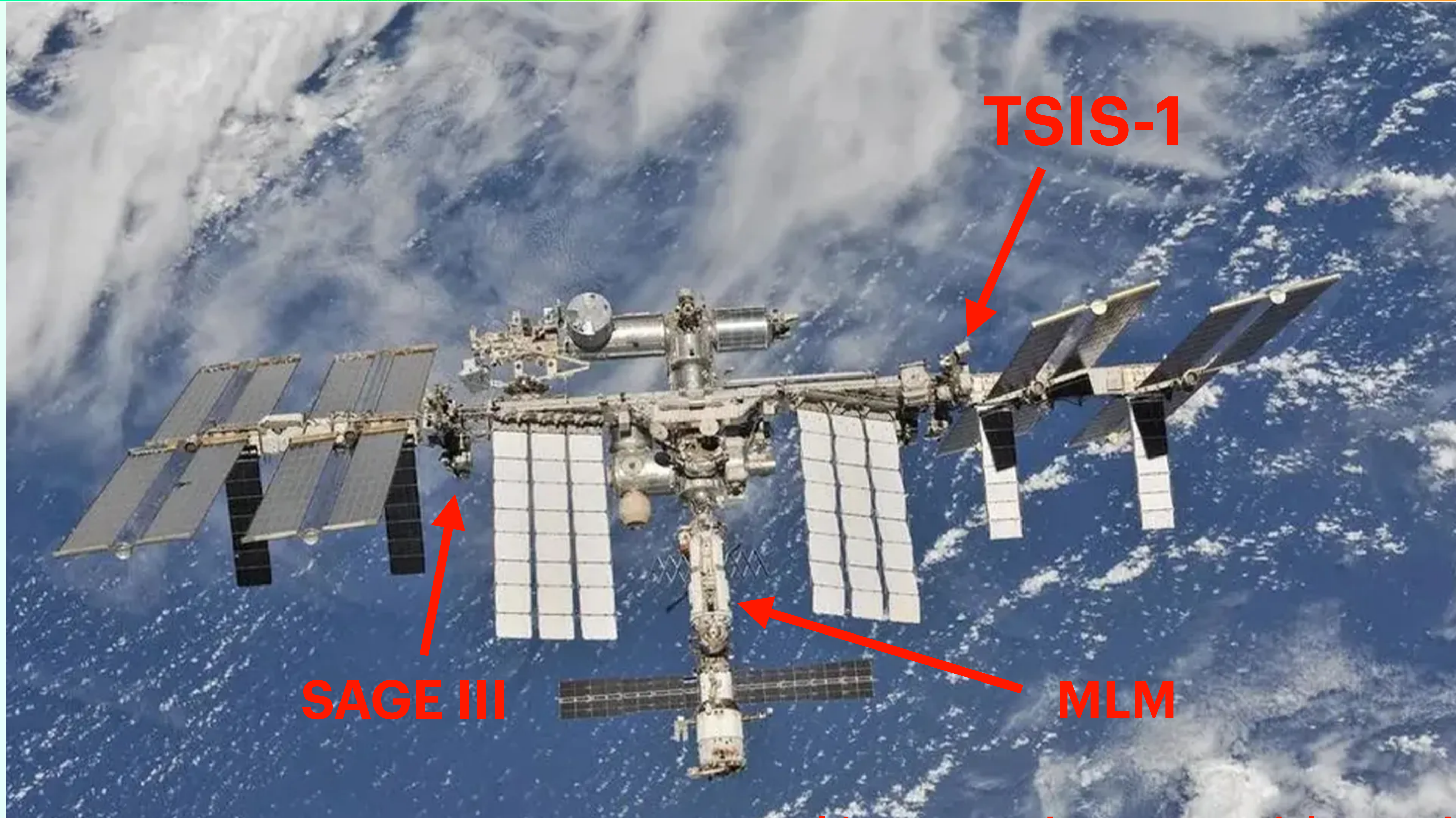


**SAGE III  
(ELC-4)**

**TSIS-1  
(ELC-3)**

**MLM = Nauka  
Multipurpose  
Laboratory  
Module**

# TSIS-1 & SAGE III in relation to the MLM (Nauka)



**SAGE III**

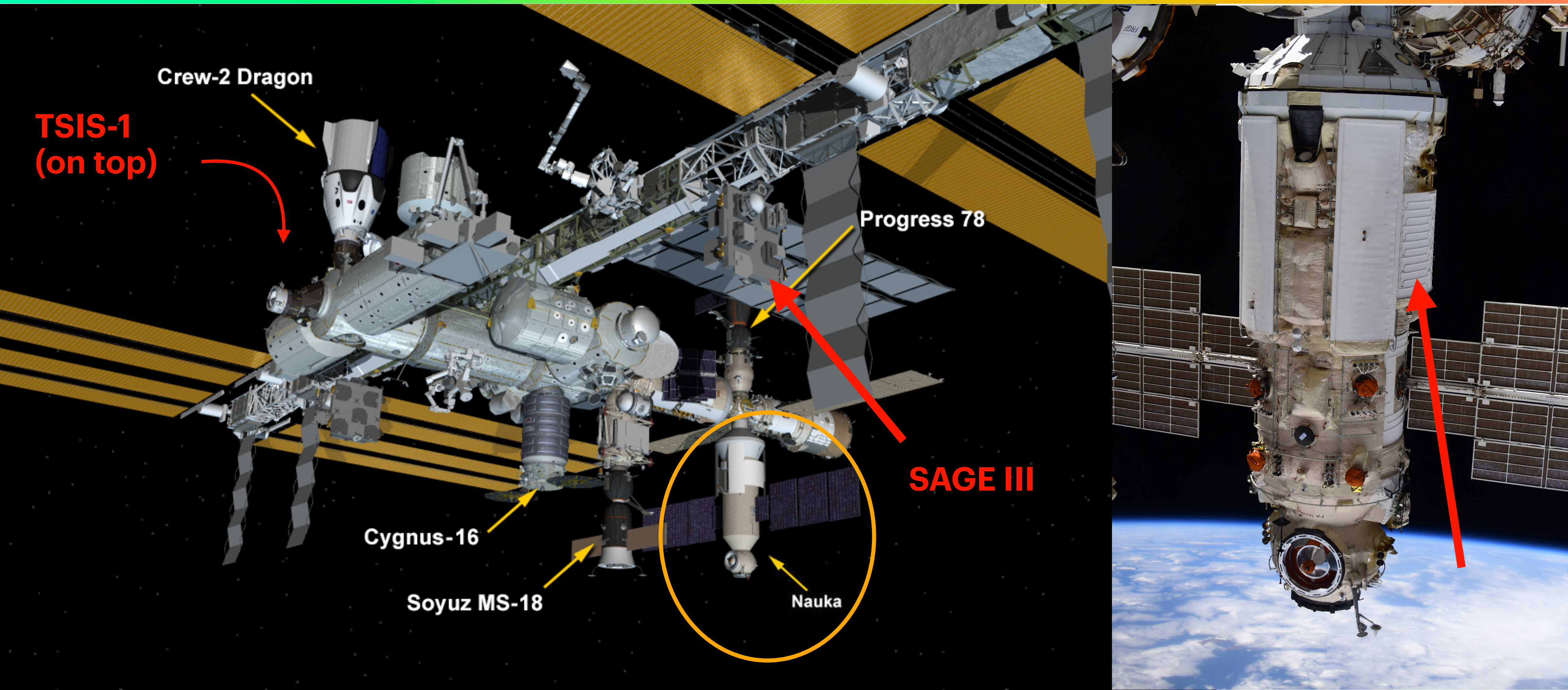
**TSIS-1**

**MLM**

**Multipurpose Laboratory Module = Nauka**

**TSIS-1 SIM Update : Sun-Climate Symposium 2023**

# TSIS-1 & SAGE III in relation to the MLM (Nauka)



# TSIS-1 & SAGE III in relation to the MLM (Nauka)

Multipurpose Laboratory Module (MLM) Spare Radiator External Coolant Leak Radiator was installed during RS EVA #56 summer 2022, but was not in use at the time.

