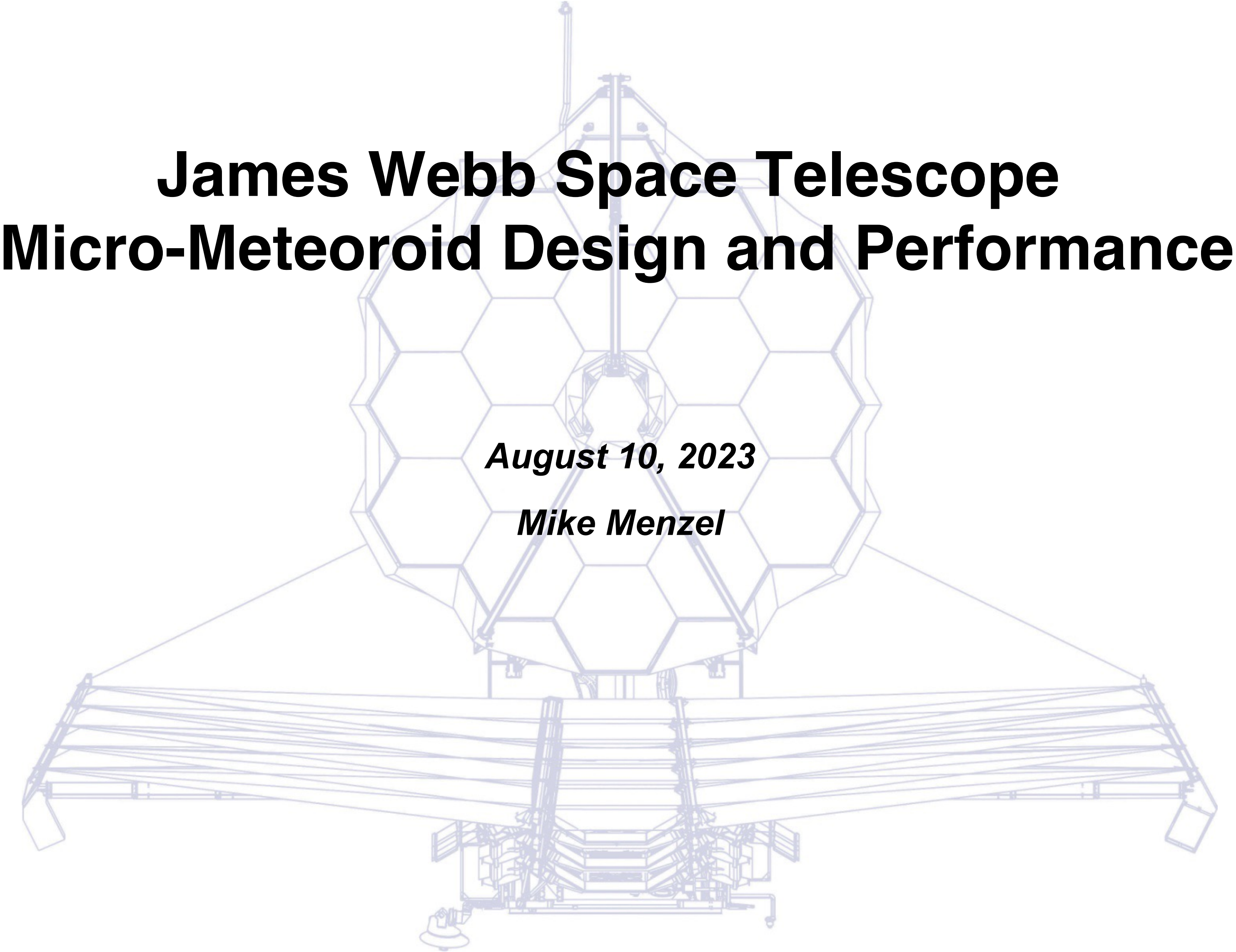


# James Webb Space Telescope Micro-Meteoroid Design and Performance

*August 10, 2023*

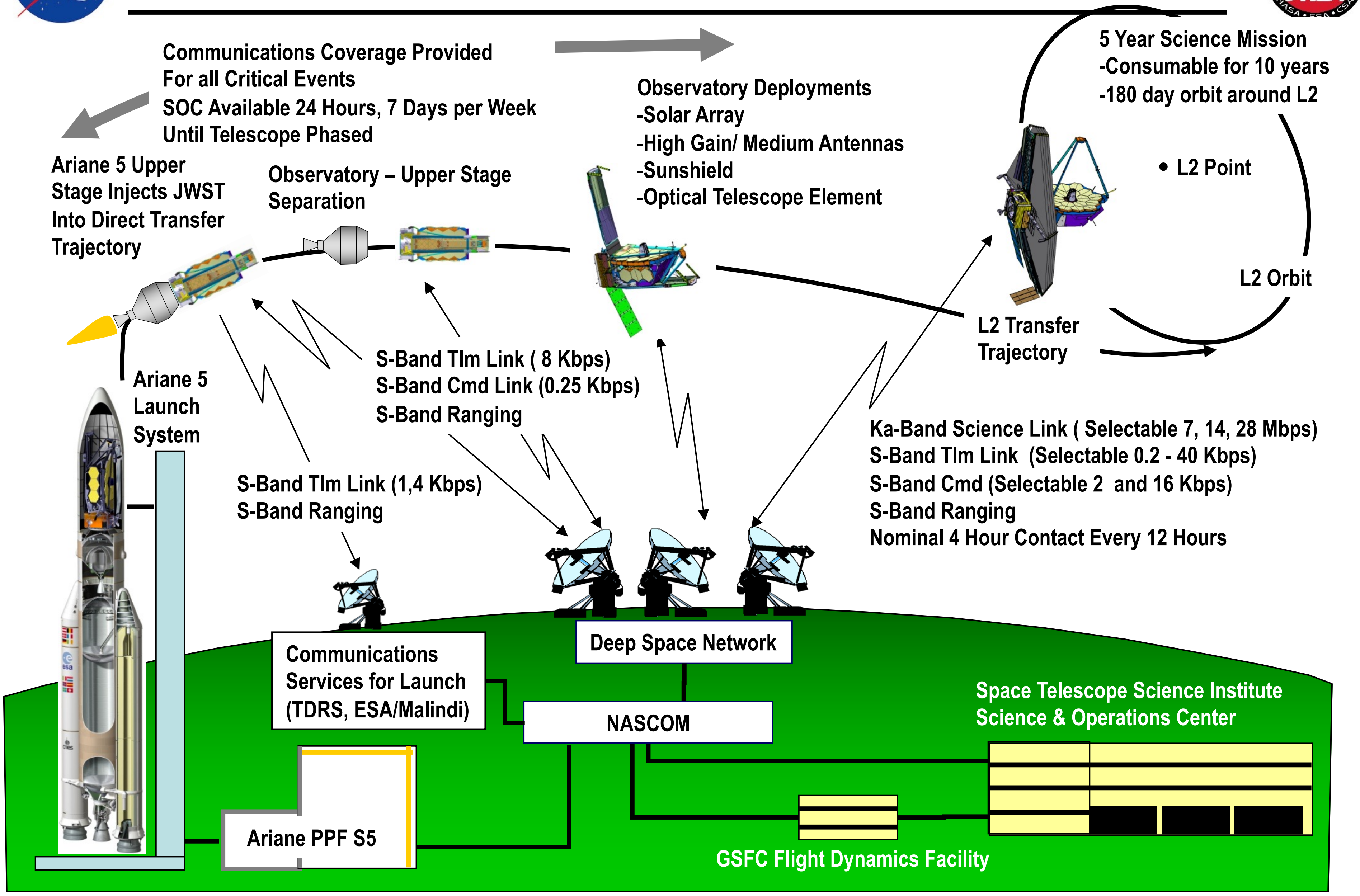
*Mike Menzel*

# Summary

- **The James Webb Space Telescope (JWST) has been operating in space for over a year and 8 months. Given its capability to measure nanometer (nm) wavefront errors (WFE) on its Primary Mirror (PM), JWST offers a unique opportunity to record Micro-Meteoroid (MM) impacts.**
- **As of this date 43 such events have been recorded on the PM, and all but one resulted in WFE well within pre-launch expectations.**
- **Even after these the overall performance of the observatory is over 2 times better than its requirements.**
- **This presentation will cover the following topics:**
  - Mission Description
  - The Predicted MM Environment
  - JWST On-Orbit MM Events and Analyses to Date
  - MM Mitigations and Future Efforts
  - Conclusion

# Mission Description

# JWST System Architecture



Communications Coverage Provided
For all Critical Events
SOC Available 24 Hours, 7 Days per Week
Until Telescope Phased

Ariane 5 Upper
Stage Injects JWST
Into Direct Transfer
Trajectory

Observatory – Upper Stage
Separation

Observatory Deployments
-Solar Array
-High Gain/ Medium Antennas
-Sunshield
-Optical Telescope Element

5 Year Science Mission
-Consumable for 10 years
-180 day orbit around L2

L2 Transfer
Trajectory

Ariane 5
Launch
System

S-Band Tlm Link ( 8 Kbps)
S-Band Cmd Link (0.25 Kbps)
S-Band Ranging

S-Band Tlm Link (1,4 Kbps)
S-Band Ranging

Ka-Band Science Link ( Selectable 7, 14, 28 Mbps)
S-Band Tlm Link (Selectable 0.2 - 40 Kbps)
S-Band Cmd (Selectable 2 and 16 Kbps)
S-Band Ranging
Nominal 4 Hour Contact Every 12 Hours

Communications
Services for Launch
(TDRS, ESA/Malindi)

Deep Space Network

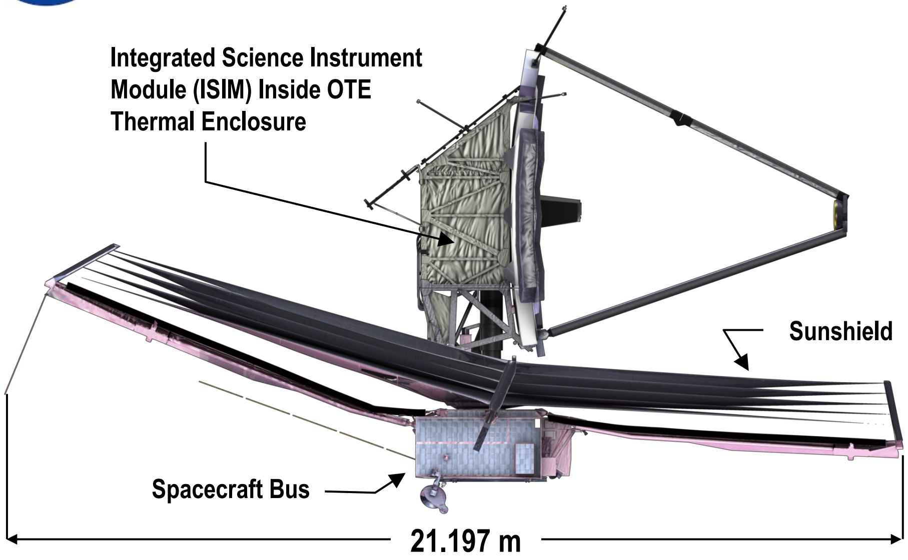
NASCOM

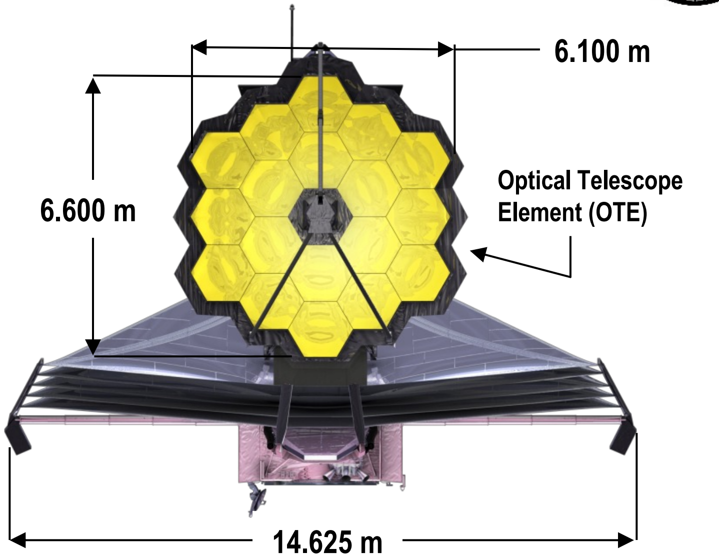
Space Telescope Science Institute
Science & Operations Center

Ariane PPF S5

GSFC Flight Dynamics Facility

# Observatory Design, Capabilities and Susceptibilities





## Design Parameter

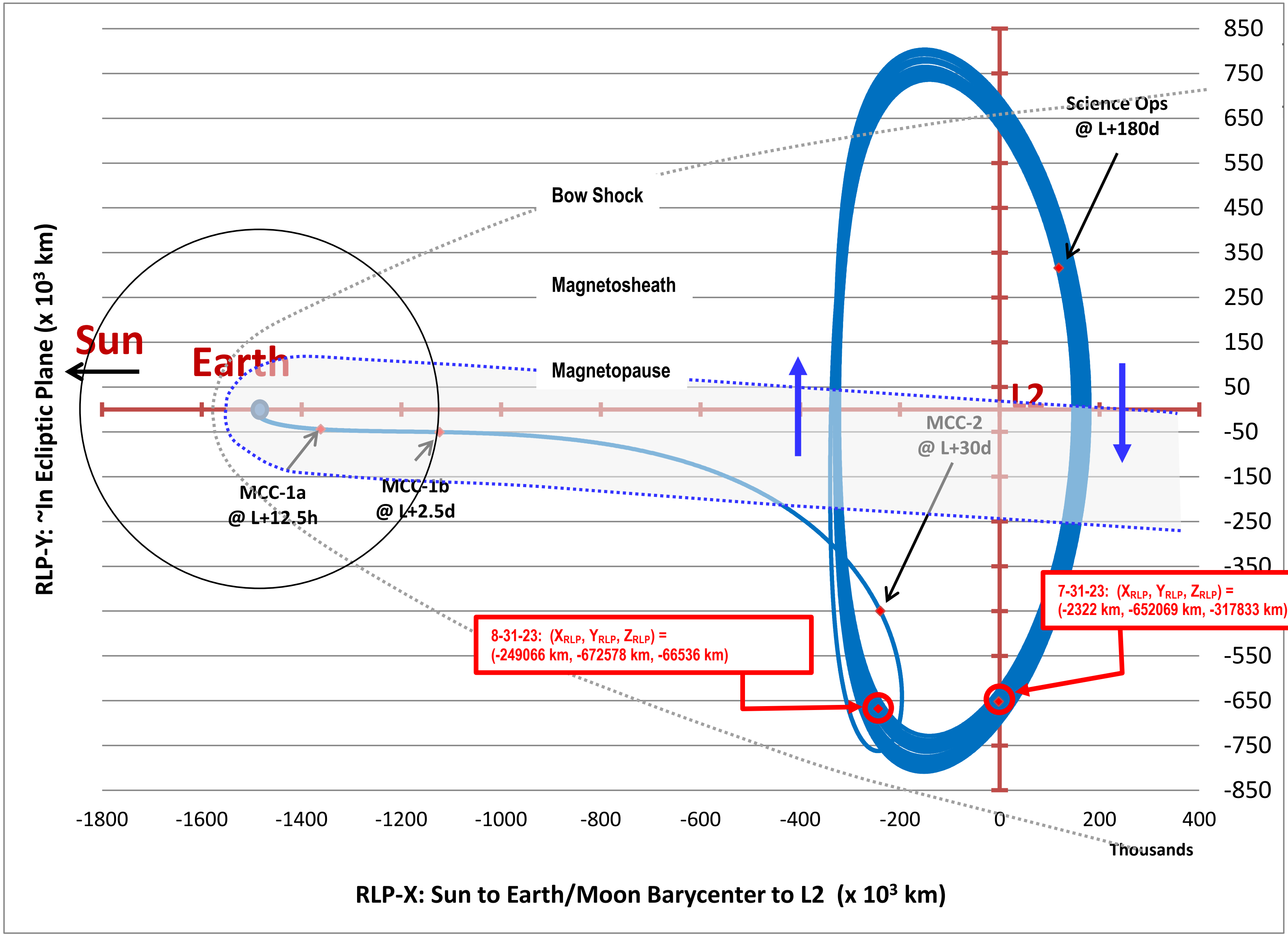
- **Optical Telescope Element (OTE) diffraction limited at 2 micron wavelength**.
  - 25 $m^2$ , 6.35 m average diameter aperture. (Actual aperture 25.8 $m^2$)
  - Instantaneous Field of View (FOV) ~ 9' X 18'.
  - Deployable Primary Mirror (PM) and Secondary Mirror (SM).
  - 18 Segment PM with 7 Degree of Freedom (DOF) adjustability on each.
- **Integrated Science Instrument Module (ISIM) containing 4 cryogenic science instruments (SIs) to observe in the near and mid infrared.**
  - The FGS provides fine guidance error signals to maintain pointing
  - The NIRCam functions as the on-board wavefront sensor for initial OTE alignment and phasing and periodic maintenance.
- **Deployable sunshield for passive cooling of OTE and ISIM.**
- **Mass: < 6310 kg. (Actual Mass at launch 6161 kg)**
- **Power Generation: 2138 Watts Solar Array, and a 105.6 AHr Lithium Ion battery**
- **Data Capabilities: 471 Gbits on-board storage, 229 Gbits / 12 hours science data.**
- **Science Data Downlink: 28 Mbps.**
- **Life: Designed for 10.5 years of operation.**

## Micro-Meteoroid Features

- **Susceptibilities:**
  - Exposed Primary and Secondary Mirrors, due to lack of protective barrel. A protective barrel was not possible in order to allow passive cooling of the OTE to cryogenic temperatures.
  - Five 2 or 1 mil thick coated Kapton sunshield layers to provide insulation from solar radiation to passively cool OTE and ISIM.
  - External electrical cables between the Science Instruments and their Focal Plane Electronics (FPE)

- **Capabilities / Design Mitigations;**
  - NIRCam provides nm class WFE sensing of the OTE optical train. Sensing operations are conducted every 2 days. Sensing data cannot provide direct information on the time or direction of the impact.
  - PM segments have 7 Degree of Freedom corrections that can be employed to correct certain MM induced WFE's.
  - WFE budget allocated 31 nm for MM degradation
  - The Sunshield thermal design included allocated margin for predicted MM generated heat leaks from impact holes.
  - External cables wrapped with protective Nextel fabric similar to that used on Space Station.

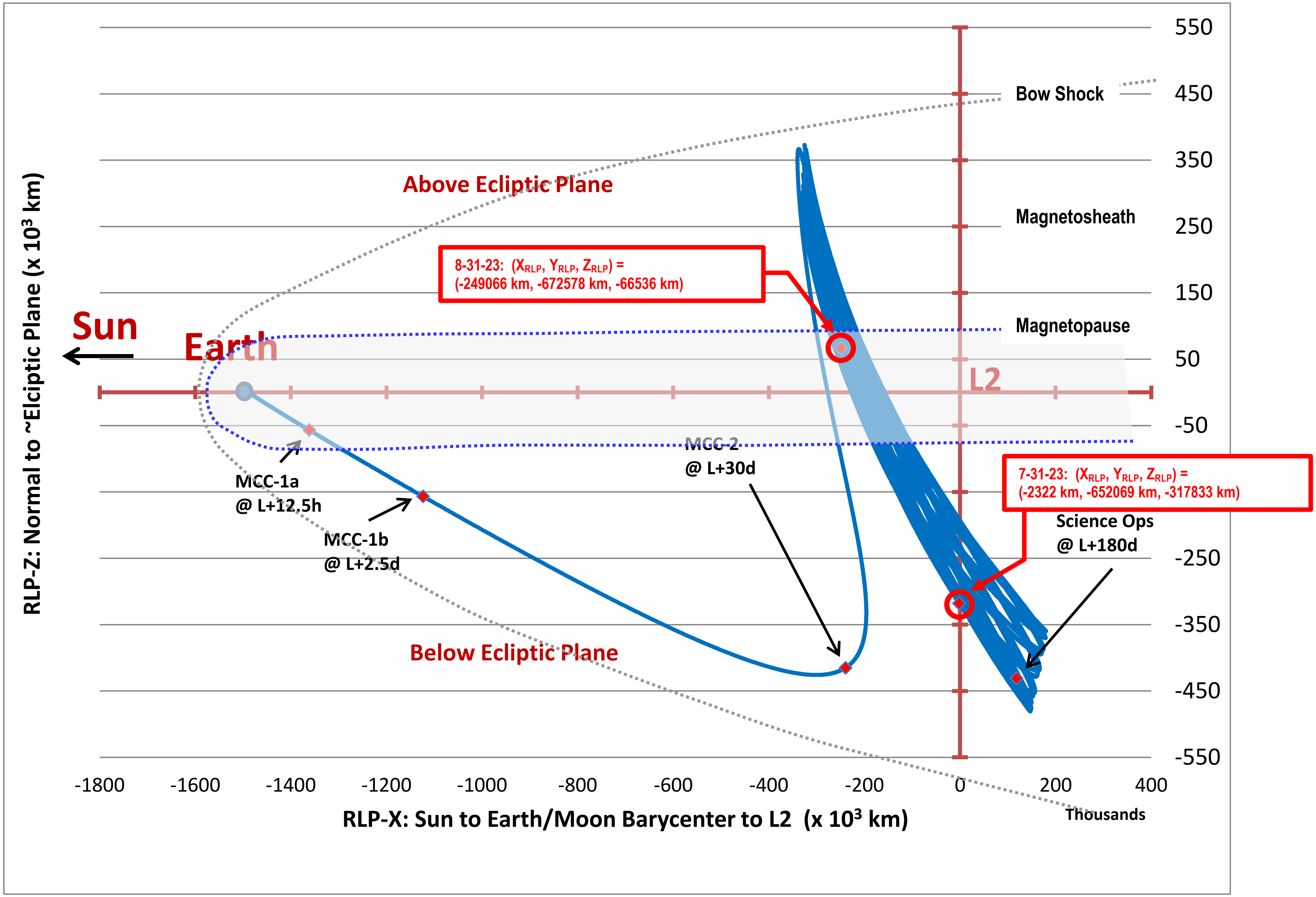
# Predicted Mission Trajectory August 2023 (1 of 2)



8-31-23: $(X_{RLP}, Y_{RLP}, Z_{RLP})$ = (-249066 km, -672578 km, -66536 km)

7-31-23: $(X_{RLP}, Y_{RLP}, Z_{RLP})$ = (-2322 km, -652069 km, -317833 km)

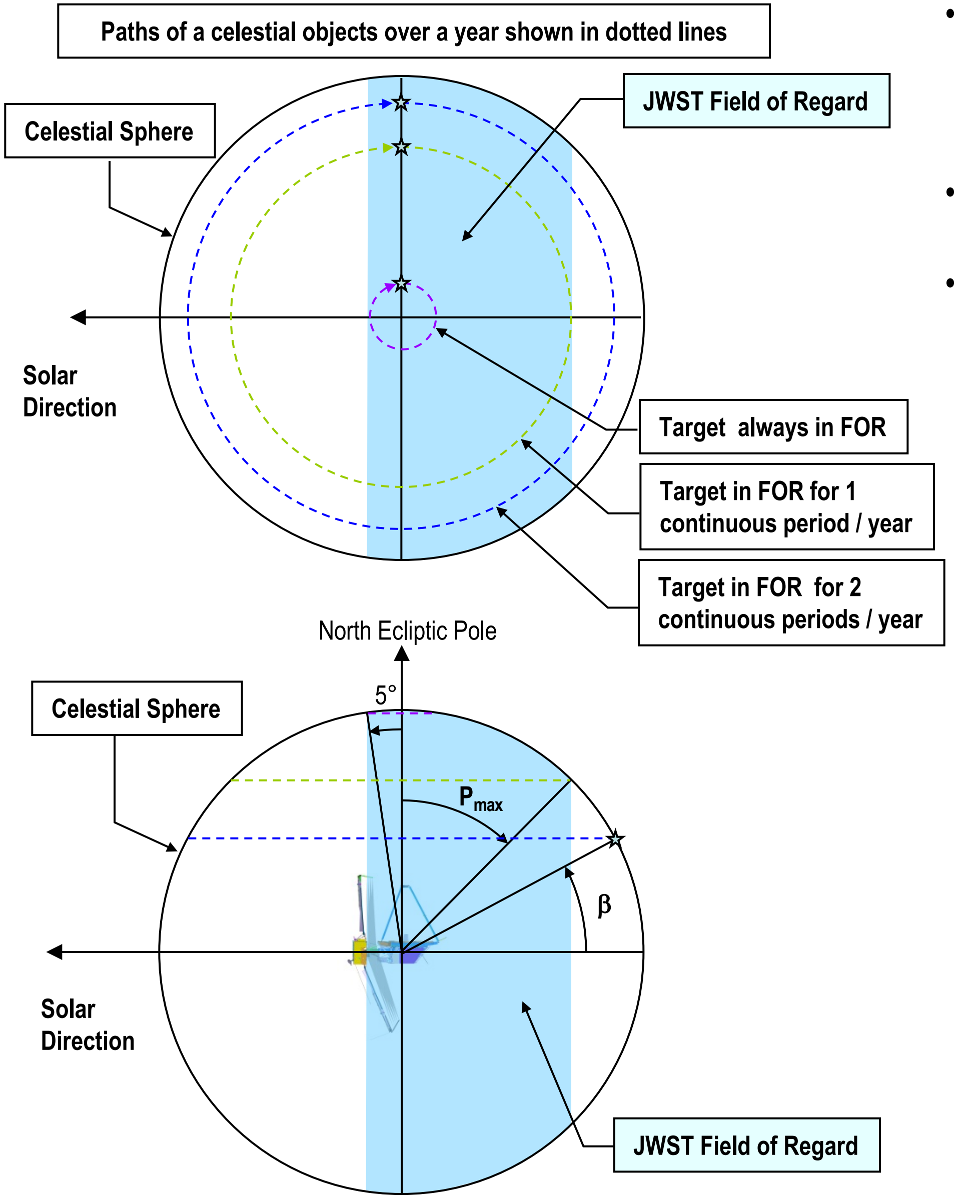
# Predicted Mission Trajectory August 2023 (2 of 2)



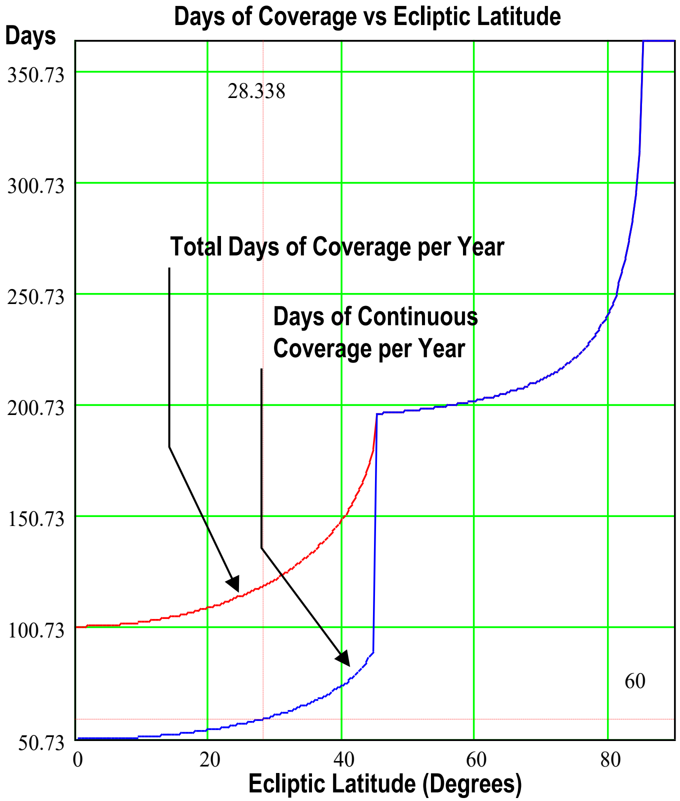
8-31-23: ($X_{RLP}$, $Y_{RLP}$, $Z_{RLP}$) = (-249066 km, -672578 km, -66536 km)

7-31-23: ($X_{RLP}$, $Y_{RLP}$, $Z_{RLP}$) = (-2322 km, -652069 km, -317833 km)

# JWST Field of Regard and Celestial Coverage



- **Field of Regard (FOR) requirements drive slew angles.**
  - MR- 106 (CVZ) drives min pitch of -5° (toward the sun).
  - MR-105 (50% of sphere visible for 60 consecutive days). drives required max pitch angle of 45° (away from the sun)
- **These pitch angles result in a total celestial coverage of 39.8%, satisfying MR-104 (FOR >35% of celestial sphere).**
- **10 day exposure time requirement (MR-177) satisfied by ±5° roll capability of the observatory about the OTE boresight.**



# Predicted Micro-Meteoroid Environment

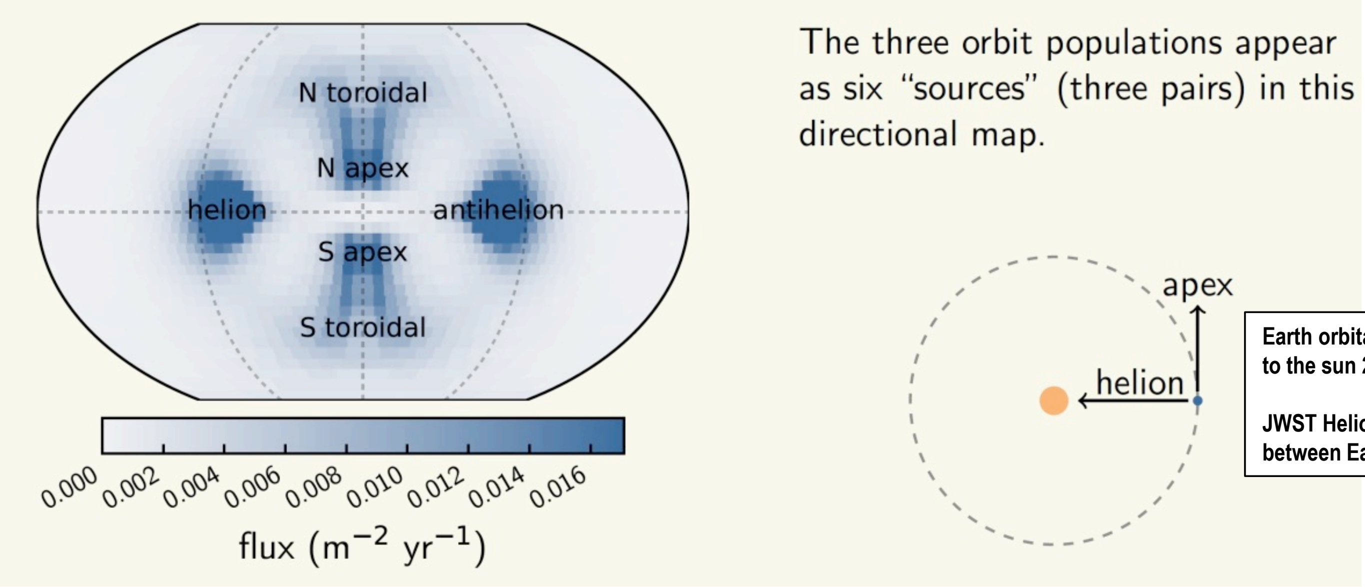
# Micro-Meteoroid Environment (1 of 6)

- **The Micro-Meteoroid environment consists of two major types:**
  - Sporadics:  An overall pervasive background of meteoroids, relatively time constant but not isotropic.
  - Showers:  Predictable meteoroid trails produced by comets.  Shower activity peaks as the Earth and or spacecraft passes thru the trail on a yearly basis.
  - The primary risks to spacecraft comes from the Sporadics.

- **The Sporadic Meteoroids have three orbital populations, that produce a non-isotropic distribution of particle fluxes, velocity and energy distributions.**
  - Helion and Anti-Helion from short period comets.
  - Apex, (North and South) from long period comets.
  - Toroidal (North and South) from Halley type comets.

# Micro-Meteoroid Environment: Sporadics (1 of 2)

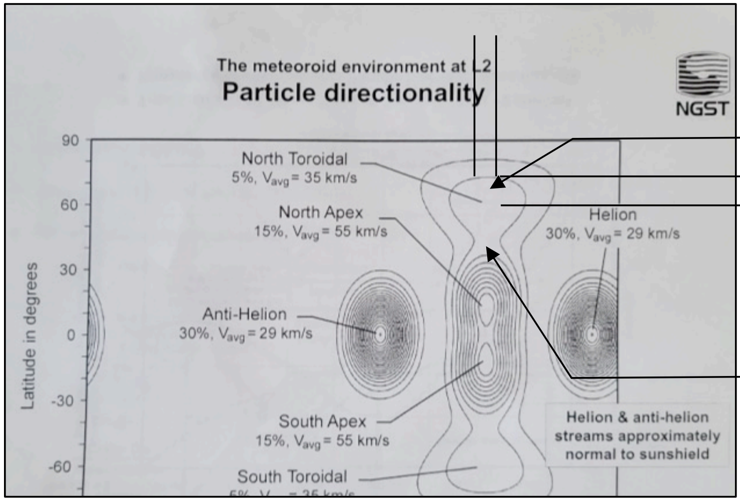
## Sporadic Meteor Population Flux and Velocities



The three orbit populations appear as six "sources" (three pairs) in this directional map.

Earth orbital velocity relative to the sun 29.7 km/s.

JWST Heliocentric velocity varies between Earth Velocity +/-0.34 km/s.



North Apex Lobe

- Between Ecliptic Latitude +5° and +20°
- Between 264° and 276° from the Sun Direction in Ecliptic Longitude

South Apex Lobe

- Between Ecliptic Latitude -5° and -20°
- Between 264° and 276° from the Sun Direction in Ecliptic Longitude

- The average velocity of the Sporadic meteoroids in a Heliocentric coordinate system is ~ 30 km/s.
- JWST has approximately the same orbital velocity as the earth in the earth in this coordinate system 30 km/s.
- MM velocities relative to JWST can be has high as 60 to 70 km/s in the Apex or "Ram" direction

# Micro-Meteoroid Environment: Sporadics (2 of 2)

- **The distribution of Sporadic MM masses is given by the Grun Model as shown on the upper right.**
  - Graph shows number of flux of particles (#/m$^2$/y) with masses equal to or greater than mass on x axis.
  - Majority of MM's have masses 10$^{-6}$ g of greater.
  - With an average velocity of ~30 km/s this corresponds to MM energies of ~0.5J.
  - With an area of 25 m$^2$ this would indicate the JWST PM should see ~25 hits per year (roughly 2 per month with energies .5 J or above)
- **The illustration on the bottom right shows the estimates of the MM densities for Helion – Anti-Helion and Apex populations.**
  - $T_j$ is the Tisserand Parameter
  - At these densities the particle diameters for a 10$^{-6}$g MM is 0.1 to 0.2 mm.

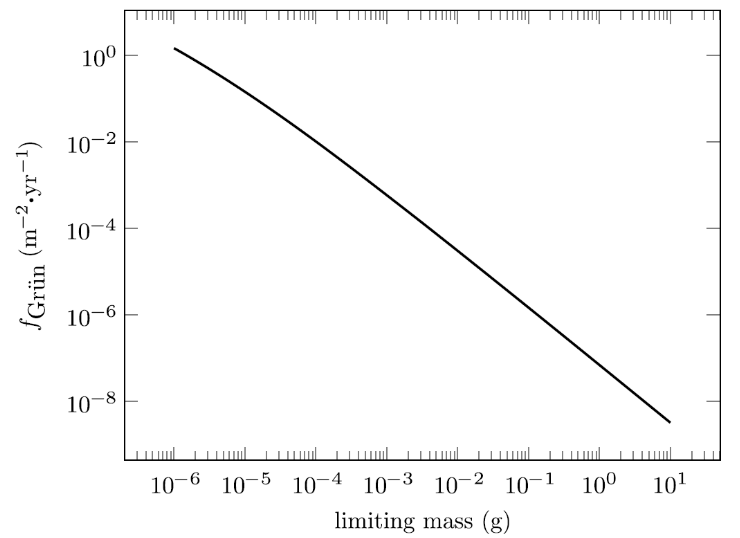
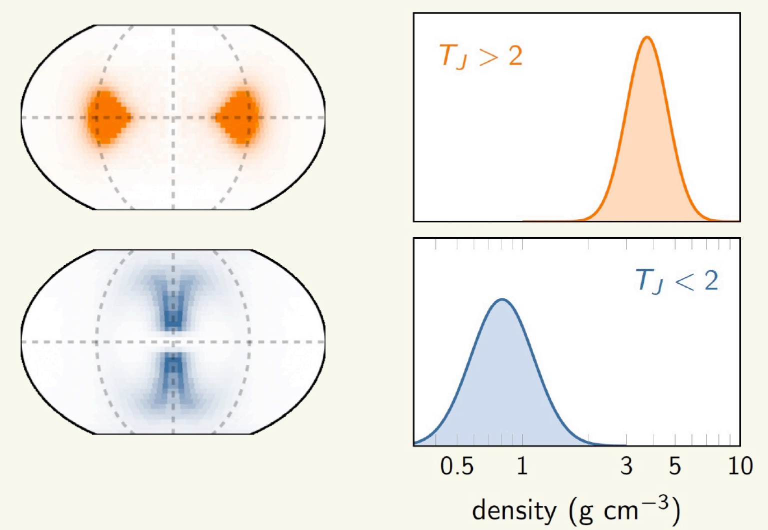
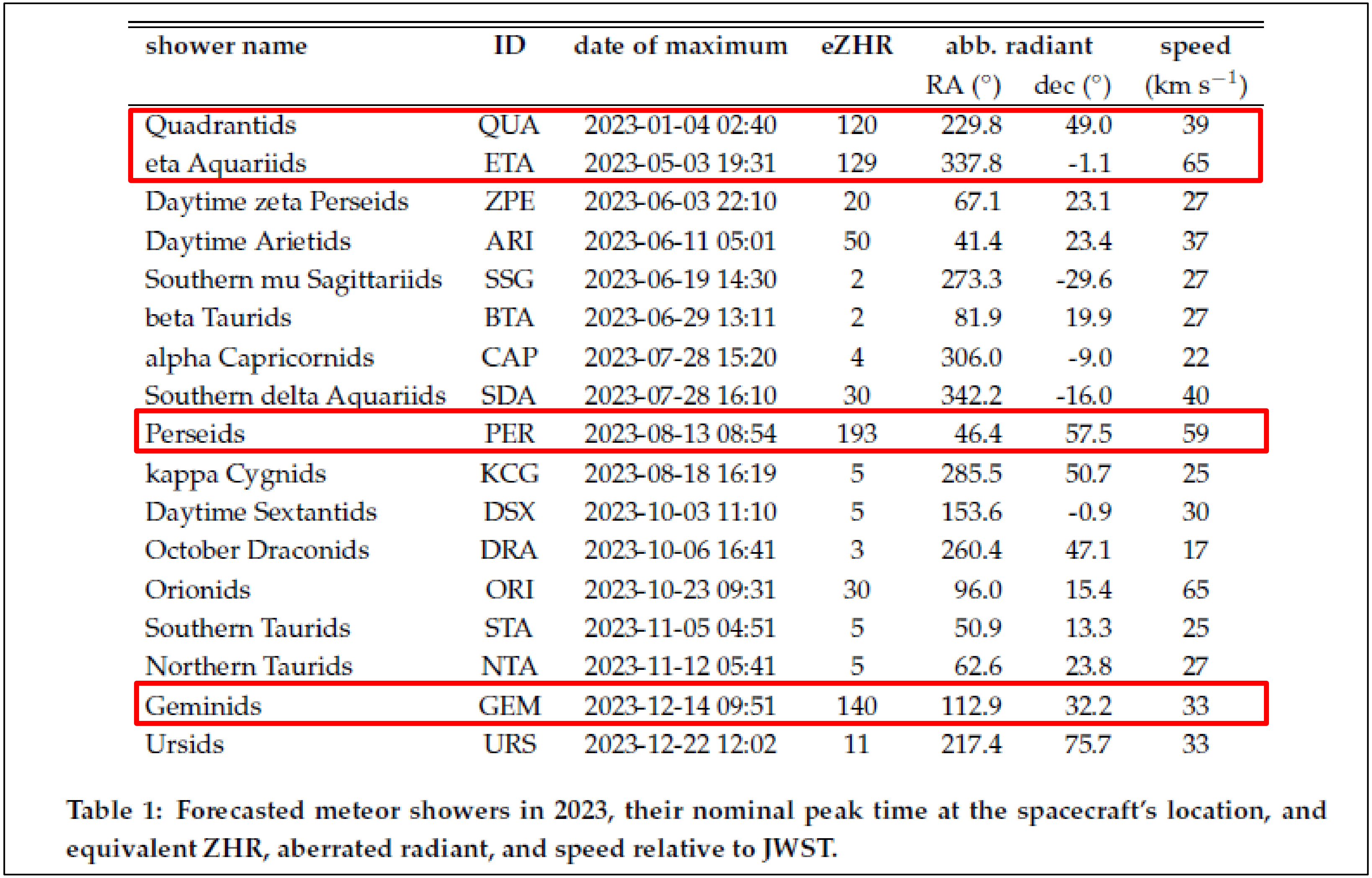


**Fig. 1** Meteoroid flux at 1 au according to Grün et al. [6].



# Micro-Meteoroid Environment: Showers (1 of 2)

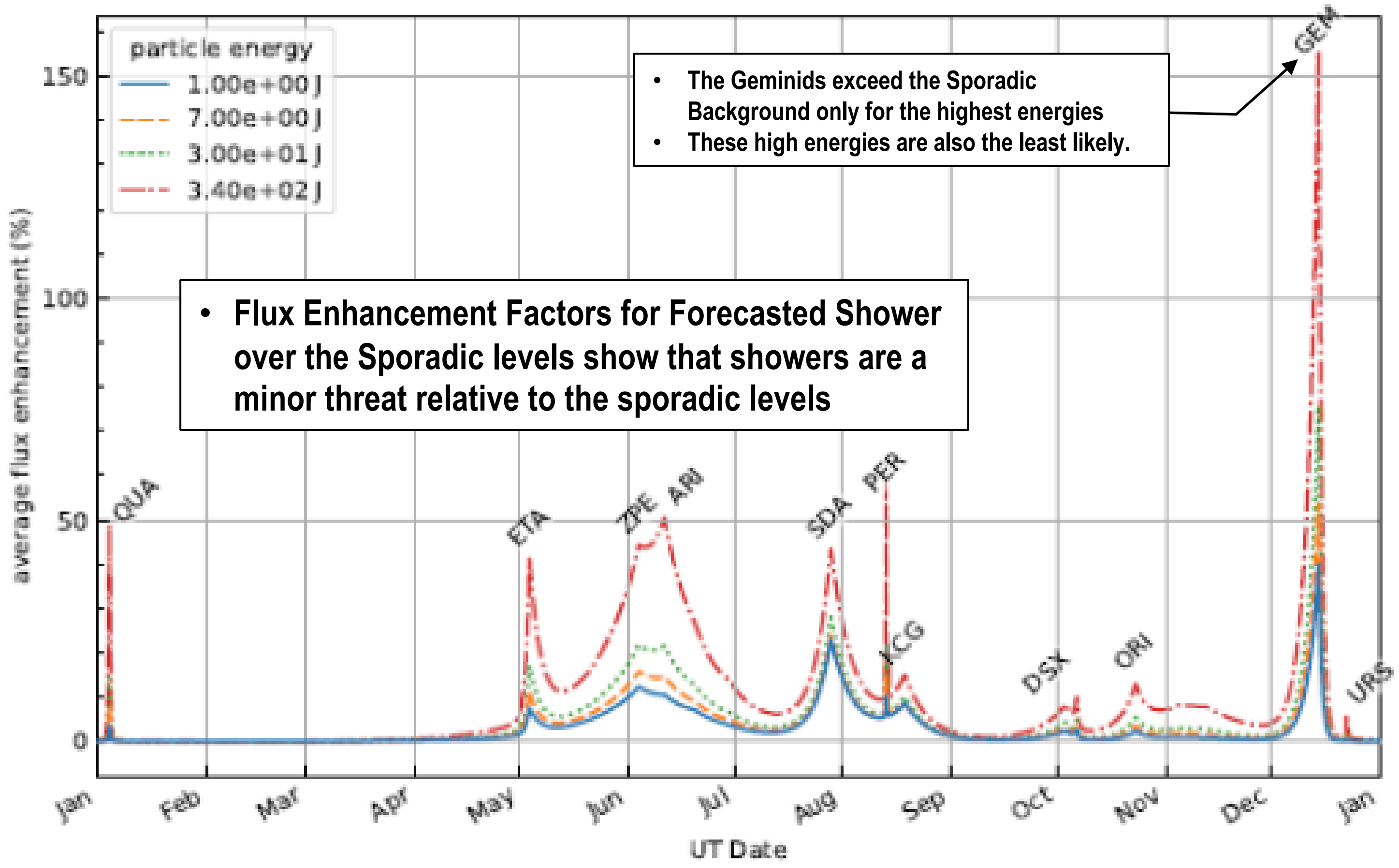
## Key Meteor Shower Forecasts For JWST for 2023 from the MEO



| shower name | ID | date of maximum | eZHR | abb. radiant | | speed |
|---|---|---|---|---|---|---|
| | | | | RA (°) | dec (°) | (km $s^{-1}$) |
| Quadrantids | QUA | 2023-01-04 02:40 | 120 | 229.8 | 49.0 | 39 |
| eta Aquariids | ETA | 2023-05-03 19:31 | 129 | 337.8 | -1.1 | 65 |
| Daytime zeta Perseids | ZPE | 2023-06-03 22:10 | 20 | 67.1 | 23.1 | 27 |
| Daytime Arietids | ARI | 2023-06-11 05:01 | 50 | 41.4 | 23.4 | 37 |
| Southern mu Sagittariids | SSG | 2023-06-19 14:30 | 2 | 273.3 | -29.6 | 27 |
| beta Taurids | BTA | 2023-06-29 13:11 | 2 | 81.9 | 19.9 | 27 |
| alpha Capricornids | CAP | 2023-07-28 15:20 | 4 | 306.0 | -9.0 | 22 |
| Southern delta Aquariids | SDA | 2023-07-28 16:10 | 30 | 342.2 | -16.0 | 40 |
| Perseids | PER | 2023-08-13 08:54 | 193 | 46.4 | 57.5 | 59 |
| kappa Cygnids | KCG | 2023-08-18 16:19 | 5 | 285.5 | 50.7 | 25 |
| Daytime Sextantids | DSX | 2023-10-03 11:10 | 5 | 153.6 | -0.9 | 30 |
| October Draconids | DRA | 2023-10-06 16:41 | 3 | 260.4 | 47.1 | 17 |
| Orionids | ORI | 2023-10-23 09:31 | 30 | 96.0 | 15.4 | 65 |
| Southern Taurids | STA | 2023-11-05 04:51 | 5 | 50.9 | 13.3 | 25 |
| Northern Taurids | NTA | 2023-11-12 05:41 | 5 | 62.6 | 23.8 | 27 |
| Geminids | GEM | 2023-12-14 09:51 | 140 | 112.9 | 32.2 | 33 |
| Ursids | URS | 2023-12-22 12:02 | 11 | 217.4 | 75.7 | 33 |

Table 1: Forecasted meteor showers in 2023, their nominal peak time at the spacecraft's location, and equivalent ZHR, aberrated radiant, and speed relative to JWST.

# Micro-Meteoroid Environment: Showers (2 of 2)



- The Geminids exceed the Sporadic Background only for the highest energies
- These high energies are also the least likely.

- **Flux Enhancement Factors for Forecasted Shower over the Sporadic levels show that showers are a minor threat relative to the sporadic levels**

Figure 2: Meteor shower flux enhancement relative to the sporadic meteoroid flux over the course of 2023 for JWST, averaged over 1-hour intervals.

# Meteoroid Engineering Model

- **JWST worked with the Meteoroid Environment Office (MEO) at MSFC to compute the expect L2 MM flux levels.**
- **Employed the Meteoroid Engineering Model (MEM) Rev 1c for the final pre-launch verification calculations.**
- **At the present time MEO has updated MEM to Rev 3.**
    - Differences are described in article shown on the right.
    - Differences between MEM 1C and MEM 3 are relatively minor with respect to JWST predicts

JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 57, No. 1, January–February 2020

Check for updates

## NASA's Meteoroid Engineering Model 3 and Its Ability to Replicate Spacecraft Impact Rates

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https://doi.org/10.2514/1.A34561

**Meteoroids pose one of the largest risks to spacecraft outside of low Earth orbit. To correctly predict the rate at which meteoroids impact and damage spacecraft, environment models must describe the mass, directionality, velocity, and density distributions of meteoroids. NASA's Meteoroid Engineering Model (MEM) is one such model; MEM 3 is an updated version of the code that better captures the correlation between directionality and velocity and incorporates a bulk density distribution. This paper describes MEM 3 and compares its predictions with the rate of large particle impacts seen on the Long Duration Exposure Facility and the Pegasus II and III satellites.**

### Nomenclature

$a$ = semimajor axis
$b$ = unitless parameter that relates $\Delta$, $y$, $x$, and $t_t$
BH = Brinell hardness
$c$ = speed of sound in meteoroid
$c_t$ = speed of sound in target
$c_{0,t}$ = speed of sound in unstressed target material
$d$ = meteoroid diameter
$d_c$ = crater diameter
$d_0$ = crater diameter without supralinearity correction
$E$ = Young's modulus
$E_t$ = Young's modulus of target
$e$ = orbital eccentricity
$F$ = flux
$F_c$ = crater- or damage-limited flux
$F_G$ = Grün et al. [6] flux
$F_m$ = mass-limited flux
$f$ = supralinearity correction
$G$ = gravitational constant
$h$ = altitude
$h_1$ = altitude of 100 km
$h_2$ = altitude of 100,000 km
$i$ = orbital inclination
$M_\odot$ = mass of the Sun
$M_\oplus$ = mass of the Earth
$m$ = meteoroid mass
$N_{c,i}$ = number of craters on side $i$
$P$ = probability
$p_c$ = crater depth
$Q$ = aphelion distance
$q$ = perihelion distance
$R_\oplus$ = radius of the Earth
$r$ = heliocentric distance
$s_t$ = stress factor of target
$t_t$ = target thickness
$v$ = meteoroid velocity
$v_{esc}$ = local escape velocity
$v_f$ = meteoroid speed with gravitational focusing
$v_i$ = meteoroid speed without gravitational focusing
$v_0$ = minimum speed required to produce a crater
$v_1$ = speed at 100 km
$v_2$ = speed at 100,000 km
$v_\perp$ = normal velocity
$x$ = ratio of uncorrected crater diameter $d_0$ to meteoroid diameter $d$
$Y_t$ = yield strength of target
$y$ = unitless parameter that relates $t_t$, $f$, and $d$
$z$ = unitless parameter that relates $y$, $t_t$, and $d$
$\alpha_{i,j}$ = angle between surface normal vector $i$ and meteoroid radiant $j$
$\Delta$ = grain size parameter
$\bar{\eta}_g$ = average gravitational focusing factor
$\theta$ = azimuthal angle
$\mu$ = mean of a normal distribution
$\xi$ = depth-to-diameter ratio
$\rho$ = meteoroid density
$\rho_t$ = target density
$\sigma$ = standard deviation of a normal distribution
$\sigma_t$ = ultimate strength of target
$\phi$ = elevation angle
$\psi$ = angle between the velocity vector and the radius vector

### I. Introduction

METEOROID impacts threaten spacecraft and astronauts at all locations within the solar system. At certain altitudes in low Earth orbit, orbital debris is the primary driver of risk, but meteoroids dominate at altitudes below 250 km and above 4000 km [1]. In interplanetary space, orbital debris is nonexistent and meteoroids constitute the entire population of potentially dangerous impactors.

NASA's Meteoroid Environment Office (MEO) created the Meteoroid Engineering Model (MEM) [2] to assist spacecraft engineers in assessing the risk posed by meteoroids. MEM models the meteoroid background component, which meteor astronomers term the "sporadic complex." The sporadic component comprises the vast majority of the meteoroid environment at sizes that are potentially threatening to spacecraft (i.e., those between 100 to 200 $\mu$m and 1 cm in diameter); meteor showers contribute somewhere between 1 and

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Received 4 June 2019; revision received 11 September 2019; accepted for publication 12 September 2019; published online 18 November 2019.

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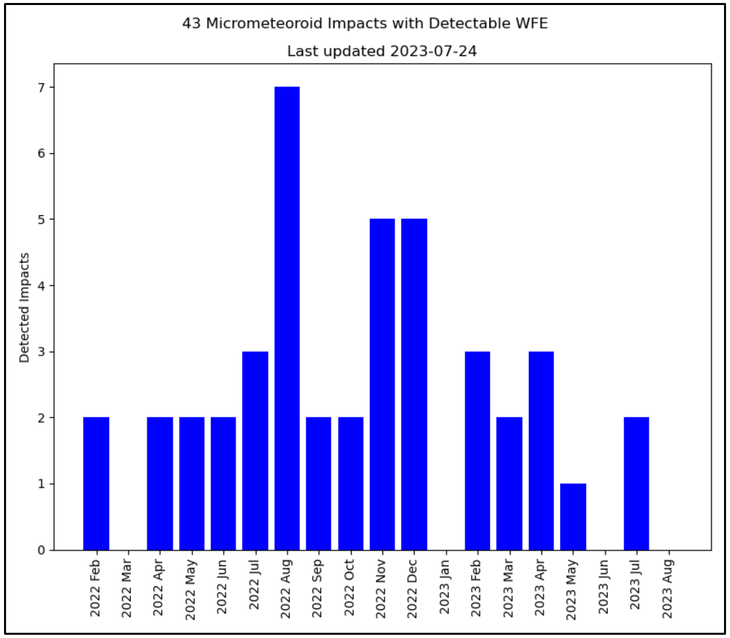
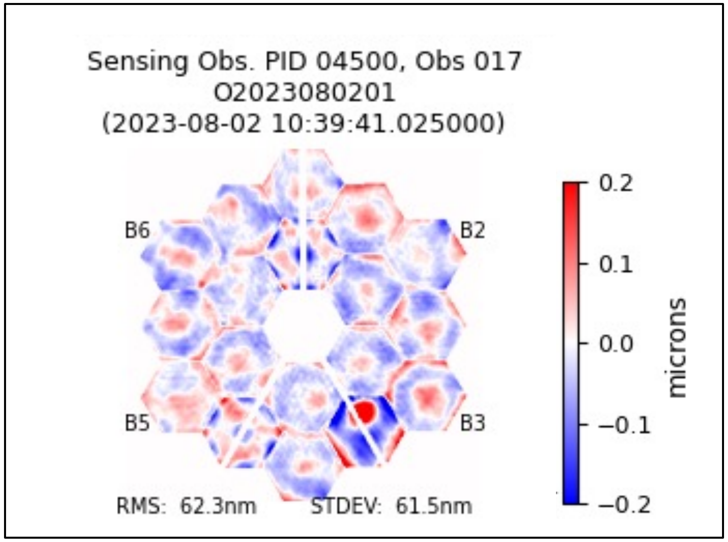
# JWST On-Orbit Micro-Meteoroid Events and Analyses To-Date

# Primary Mirror Micro-Meteoroid Events to Date

- **As of 8-3-23 there have been 43 micro-meteoroid events that resulted in a measurable WFE on the Primary Mirror.**
    - The average rate of events is 2.2 events per month.
    - The histogram on the upper right shows the events counts.
- **With exception of an event that occurred in May 2022, all events have produced minor WFE,**
    - Total WFE contribution at the system level has been ~1 nm for these MM events.
    - Many of the resulting WFE have been correctable.
    - Pre-launch allocation for MM induced WFE was 31 nm for a 5.5 year life.
- **At the present time the overall observatory WFE of the NIRCam channel is 70 nm and the OTE is 62 nm.**
    - This includes the contributions from the anomalous May event described on the following chart
    - See OTE WFE map on the lower right.





# Analyses of Normal Activity

- **The MSFC MEO performed analyses to compute the impact rates on the PM as a function of observatory pointing for MM energies of 1 J or greater.**
    - The analysis was performed with and without shielding of the PM by the sunshield.
    - The analysis results on the right show the dominant flux levels are in the direction “RAM” direction.

- **The MEO conducted analysis to estimate the most likely Low Energy MM Threshold to correlate with the observed impact rate.**
    - The analysis estimated that the measurable impacts correlate with MM lower threshold energies between 0.88J and 1.03J

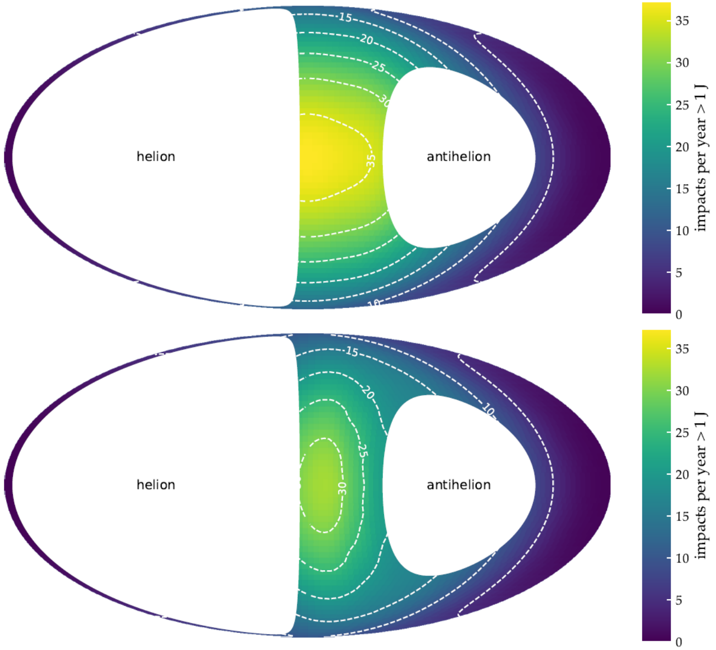


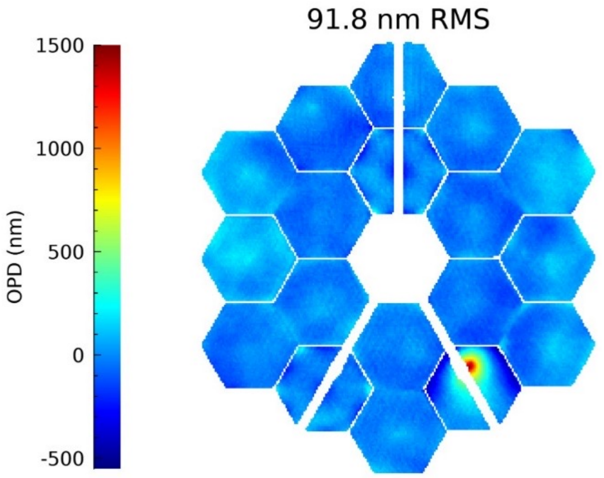
Figure 4: The impact rate of meteoroids carrying a kinetic energy of at least 1 J as a function of pointing angle over the mission lifetime. The top panel shows the impact rate with no shielding, and the bottom panel includes 155 $m^2$ of shielding area.

**Figure taken from Memo OSMA/MEO/JWST-001, 24 August 2022**

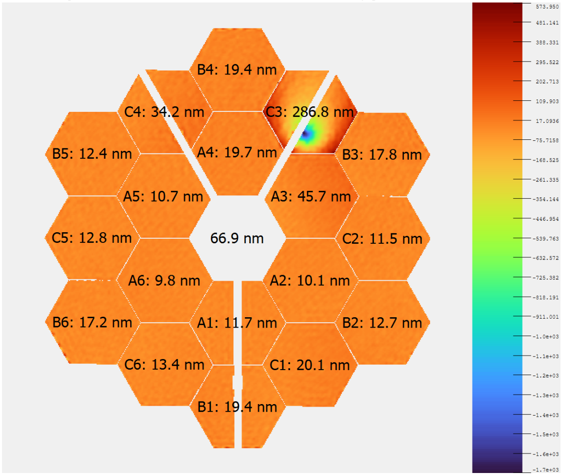
# Anomalous MM Event of May 2022

- **An impact was recorded on Segment C3 in the period between 5-22-22 and 5-24-22 that was significant.**
    - WFE maps are shown on the right.
    - This latest hit was in close proximity to a previous hit on C3.
- **Change in Static WFE of the NIRCam-OTE was ~ 20 nm before correction.**
- **A good portion of the residual WFE from this event was correctable, but because of location on the C3 segment, a fair portion of the WFE was uncorrectable.**
    - After the full corrections, the system level WFE was reduced to ~ 9 nm.
- **The unexpected magnitude of this event triggered an investigation and the formation of a Micro-Meteoroid Working Group (MMWG).**

**Computations According to Telfer**



**Computations According to Jurling**
*(OPD is flipped vertically)*



# Investigation of the C3 Event

- **The MMWG performed modeling of various hypothetical impacts on the C3 segment structure model to find likely scenarios that could explain not only the rms WFE but also observed surface error profile, which was rather large in extent.**
  - Leveraged hydrocode capabilities to model and simulate impacts.
  - Compliment hydrocode results with finite element analyses.
- **The studies concluded that a likely scenario consisted of:**
  - A high energy meteoroid with energy between 7 and 26 J.
  - An impact which penetrated the front of C3 segment and impacted the "Whiffle Tree" mount on the backside of the segment.
  - The resulting stress in the Whiffle Tree mount produced the larger distortion field.
- **Given the estimate of the energy of the MM, and the smaller total area of the Whiffle Trees, this scenario was deemed relatively unlikely. However limiting celestial pointing where higher energy MM are more likely was considered and ultimately adopted as a mitigation.**

# Micro-Meteoroid  Mitigations and Future Efforts

# Meteoroid Avoidance Zone (MAZ)

- **Given the risk of damage from higher energy MM's, the MMWG investigated the benefits of limiting observing time in the RAM direction.**
  - This limitation would not limit total observations, but would impose challenges on the scheduling and flexibility for rescheduling
- **The MEO investigated three such MAZ geometries as illustrated in the upper right:**
  - A 35° half angle about the RAM direction
  - A 75° half angle about the RAM direction
  - A 35° "band about the RAM direction
- **The MEO analyzed the reduction in MM fluxes for various threshold energies that would result from these, as shown on the lower right.**
- **The MMWG recommended that Project adopt a 75° half angle MAZ for the Cycle 2 science, with the goal restricting science in this region to under 15%.**
  - The Project accepted this recommendation
  - High value science of opportunity and or transient phenomenon would be allowed in this region
- **During or after Cycle 2, the MMWG will reconsider the benefits of this MAZ and any potentially modifications.**

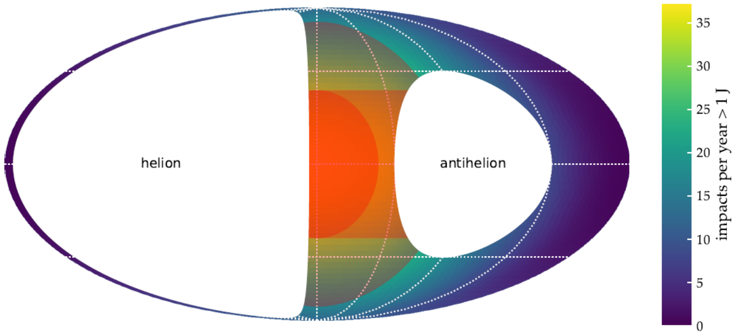
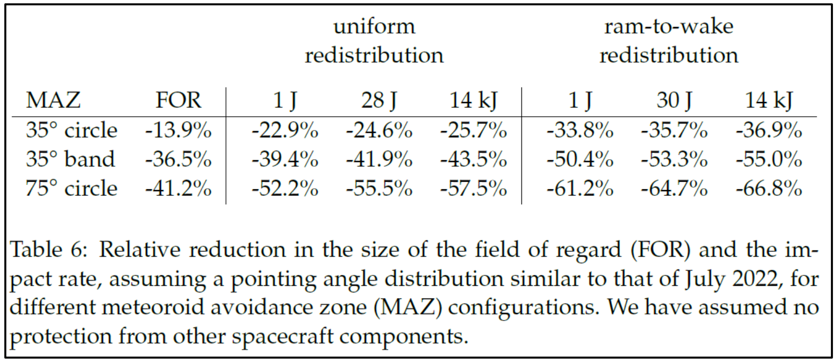


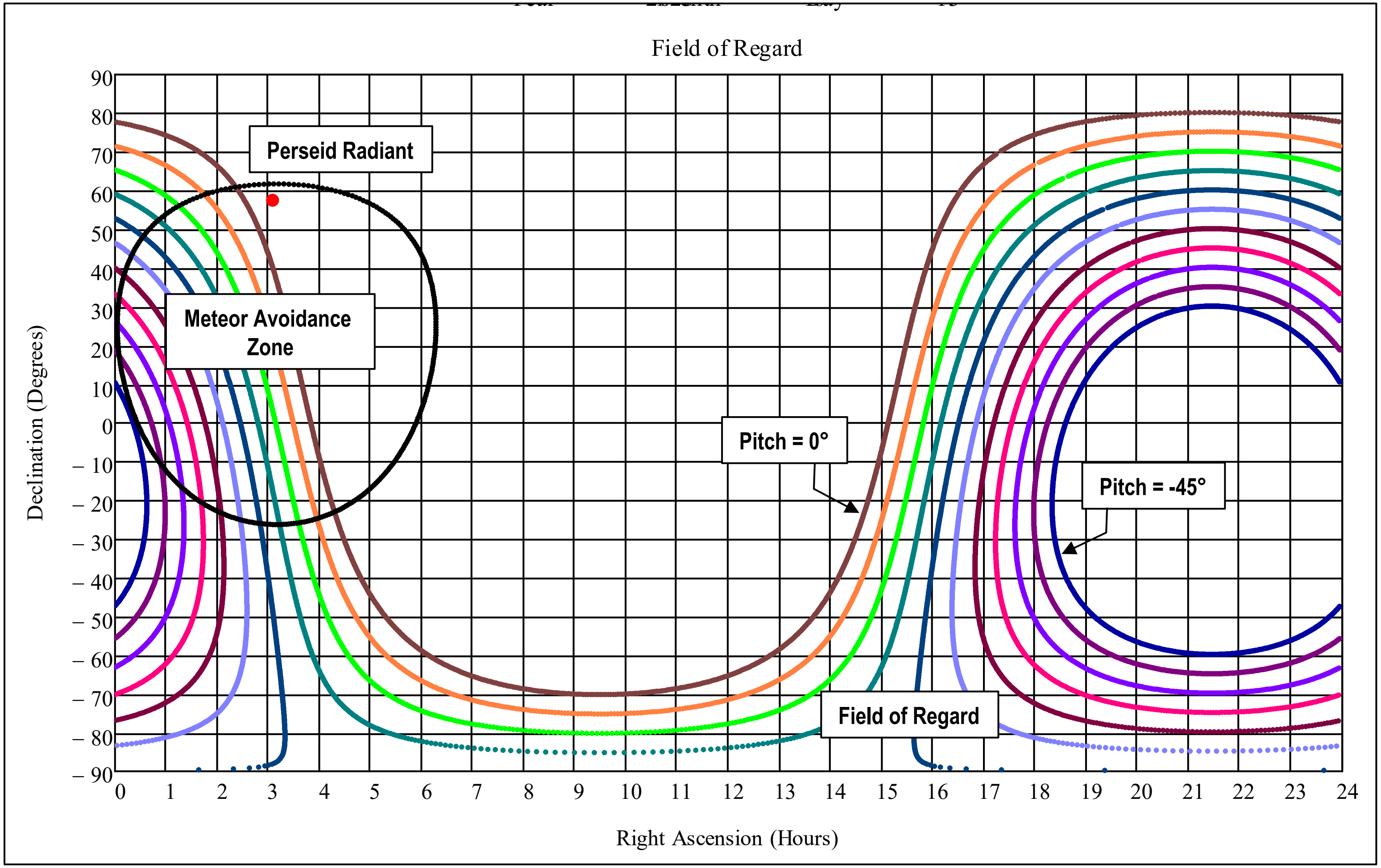
Figure 7: Three possible meteoroid avoidance zones (MAZs), depicted as semi-transparent red areas laid on top of figure 3. The largest is a 75° circle around the ram direction, the next largest is a band 35° in height and 90° in width, and the smallest is a 35° circle.



| | | uniform redistribution | | | ram-to-wake redistribution | | |
|---|---|---|---|---|---|---|---|
| MAZ | FOR | 1 J | 28 J | 14 kJ | 1 J | 30 J | 14 kJ |
| 35° circle | -13.9% | -22.9% | -24.6% | -25.7% | -33.8% | -35.7% | -36.9% |
| 35° band | -36.5% | -39.4% | -41.9% | -43.5% | -50.4% | -53.3% | -55.0% |
| 75° circle | -41.2% | -52.2% | -55.5% | -57.5% | -61.2% | -64.7% | -66.8% |

Table 6: Relative reduction in the size of the field of regard (FOR) and the impact rate, assuming a pointing angle distribution similar to that of July 2022, for different meteoroid avoidance zone (MAZ) configurations. We have assumed no protection from other spacecraft components.

# The MAZ and JWST FOR for August 2023



- **Perseid Radiant Point ($\alpha = 3^h\ 5^m$, $\delta = 57°$ ) is Outside the JWST FOR for the peak period on August 13, 2023.**

# Hypervelocity Testing at White Sands

- **Because of the larger-than-expected micrometeoroid strike in May of 2022 on the primary mirror of the JWST, the project has commissioned the White Sands Test Facility  Remote Hypervelocity Test Laboratory (RHTL) to perform hypervelocity impact testing on beryllium mirror materials.**
  - The purpose is to characterize the damage to the test articles by launching polymethyl methacrylate (PMMA) and Aluminum Oxide projectiles at 8 km/s, (Kinetic energy of approximately 8 J)
- **The testing exposed the following sunshield and mirror materials to hypervelocity impacts**
  - Kapton at room temperature
  - ULE Glass at room temperature
  - Beryllium at 100K
- **The tests have been recently completed and the results are being examined**
  - Preliminary inspections show good correlation with model predictions

# Conclusion

- Despite the one anomalous micro-meteoroid impact, the JWST optical system continues to perform over 2 times better than required.
- The overall average flux rates seen on the PM are in family with pre-launch predicts and allocations.
- Given the importance of JWST to astrophysics, the Project is implementing a MAZ to reduce the probability of higher energy impacts, and is conducting tests to help develop better models for WFE vs MM properties, including cryogenic tests.
- The JWST Team is transferring lessons learned to the planning of future telescope missions, including the incorporation of more traditional telescope barrels which can reduce PM exposure to MM by over 90% depending on the barrel length.