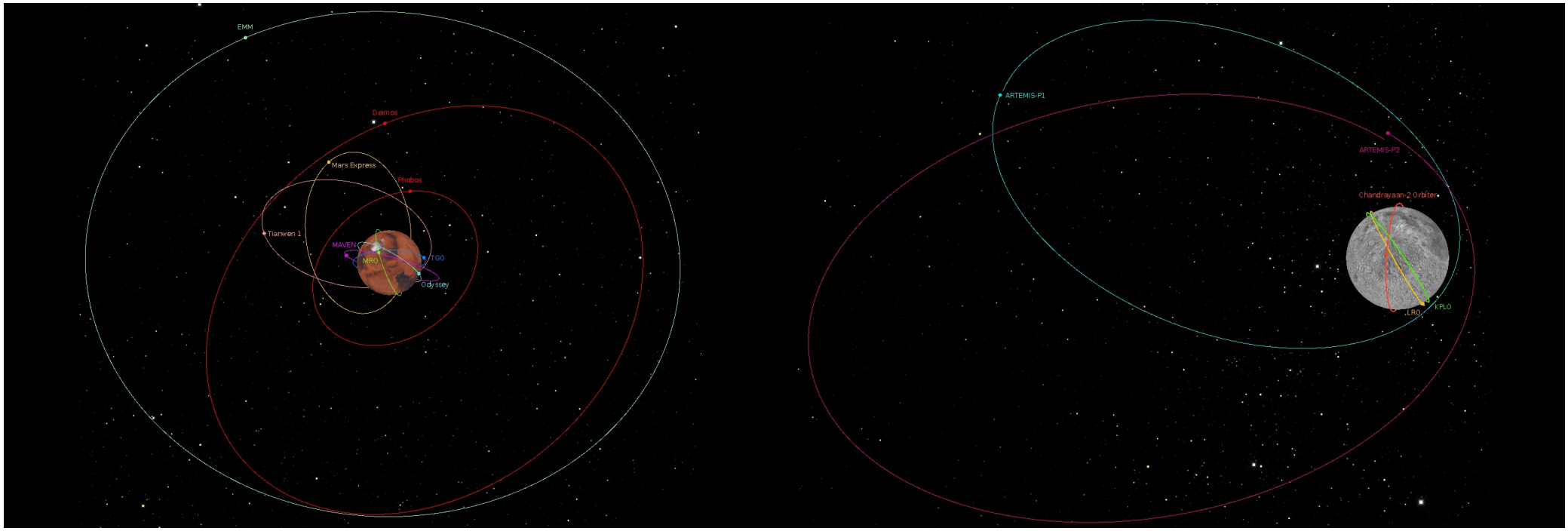


International Collaboration in Extraterrestrial Conjunction Assessment

Zahi B. Tarzi, David S. Berry

Jet Propulsion Laboratory
California Institute of Technology

5th International Conjunction Assessment Workshop
18-Jun-2025 – 20-Jun-2025, Toulouse, France

Introduction

- It is well known that conjunction assessment (CA) is necessary in the Earth orbiting environment to prevent spacecraft collisions and reduce debris in orbit.

- The Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) was developed at the NASA Jet Propulsion Laboratory for conjunction assessment use in shared deep space environments, for which ground-based radar tracking is a challenge.

- MADCAP is a component of NASA's conjunction assessment suite, used to screen objects in orbit at Mars (since 2011), the Moon (since 2011), Sun/Earth Libration points L1 (since 03/2020) and L2 (since 01/2022), and in Cislunar space (since 11/2024).

The Orbital Debris Problem

- NASA Orbital Debris Program Office cites more than 25,000 objects in Earth orbit > 10 cm officially cataloged by the Space Surveillance Network (SSN).
  (ODPO FAQ 05/2025)
- By contrast, there is currently no known orbital debris field at the Moon or Mars (other than a handful of inactive spacecraft) since there no reliable method to realistically track debris from Earth as is done with SSN. Therefore, it would be highly undesirable to create orbital debris fields at the Moon or Mars
- The creation of a debris field in these environments would complicate existing and future operations and could take many years to dissipate.
- Therefore, in several shared Non-Earth orbital environments, the growing number of orbiter missions makes the orbital debris management job **avoidance of creating a hazardous debris field in the first place**

The Importance of International Cooperation

- Due to the lack of passive tracking capability in deep space, keeping these environments safe is reliant on self-reported ephemeris and uncertainty data from mission teams.

- Many missions operating and planned in these areas are led by international space agencies and commercial companies.

- Thus international cooperation is crucial to ensuring the safety of shared deep space environments.

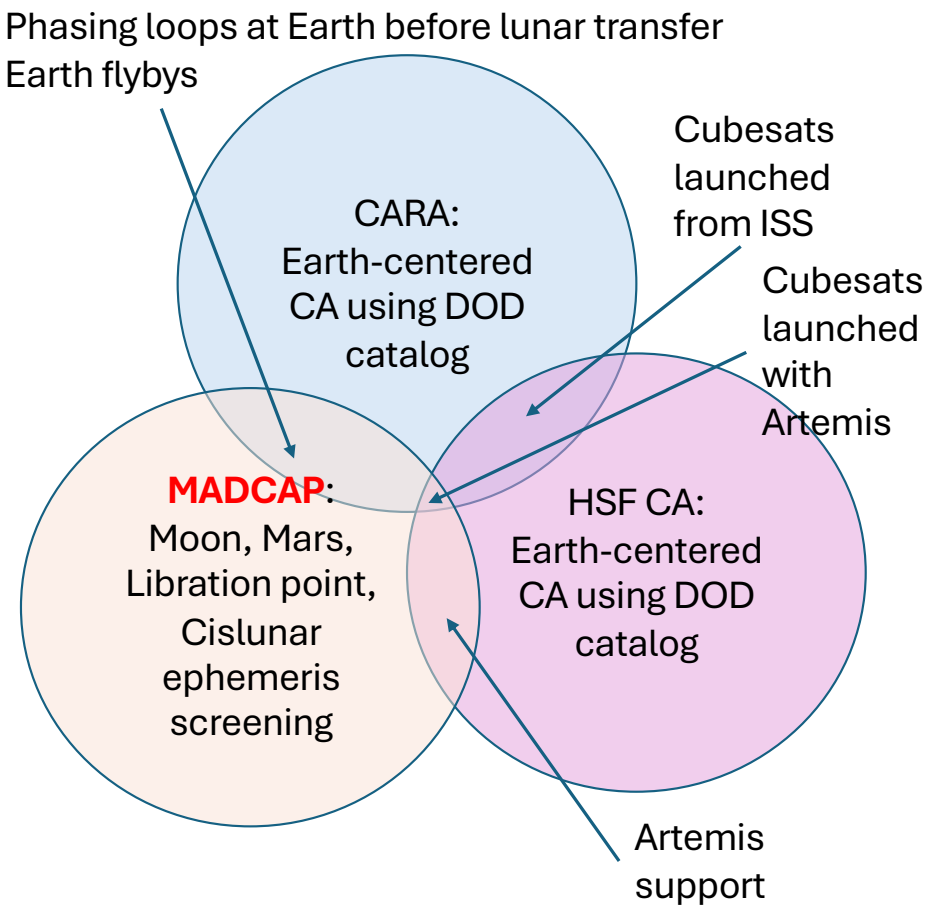
- The MADCAP Team strongly believes in the necessity of such international collaboration and cooperation

NASA Conjunction Assessment Entities

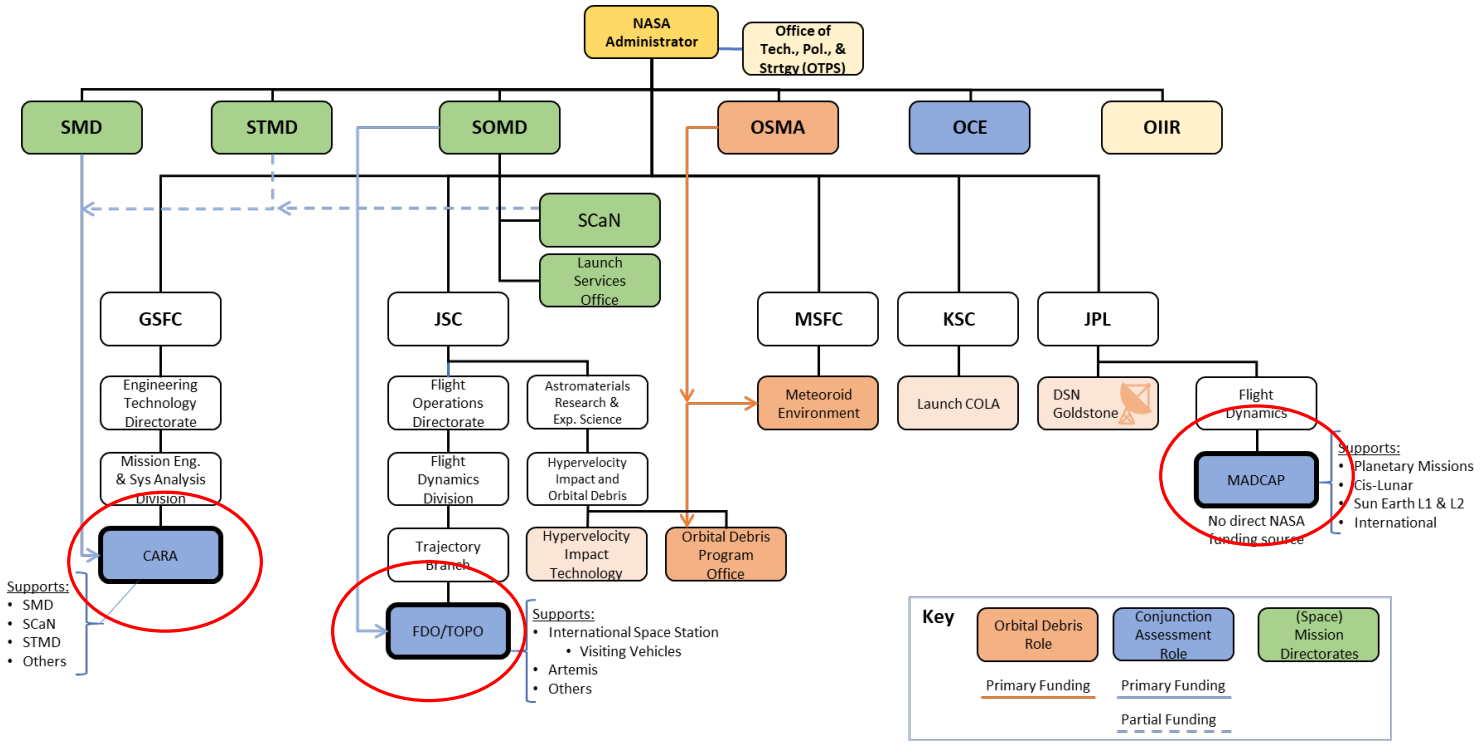
- **Human Spaceflight (HSF)**
  - **ISS and visiting vehicles**
  - **Commercial Crew**
  - **JSC-based**

CAPO Managed since 8/2022

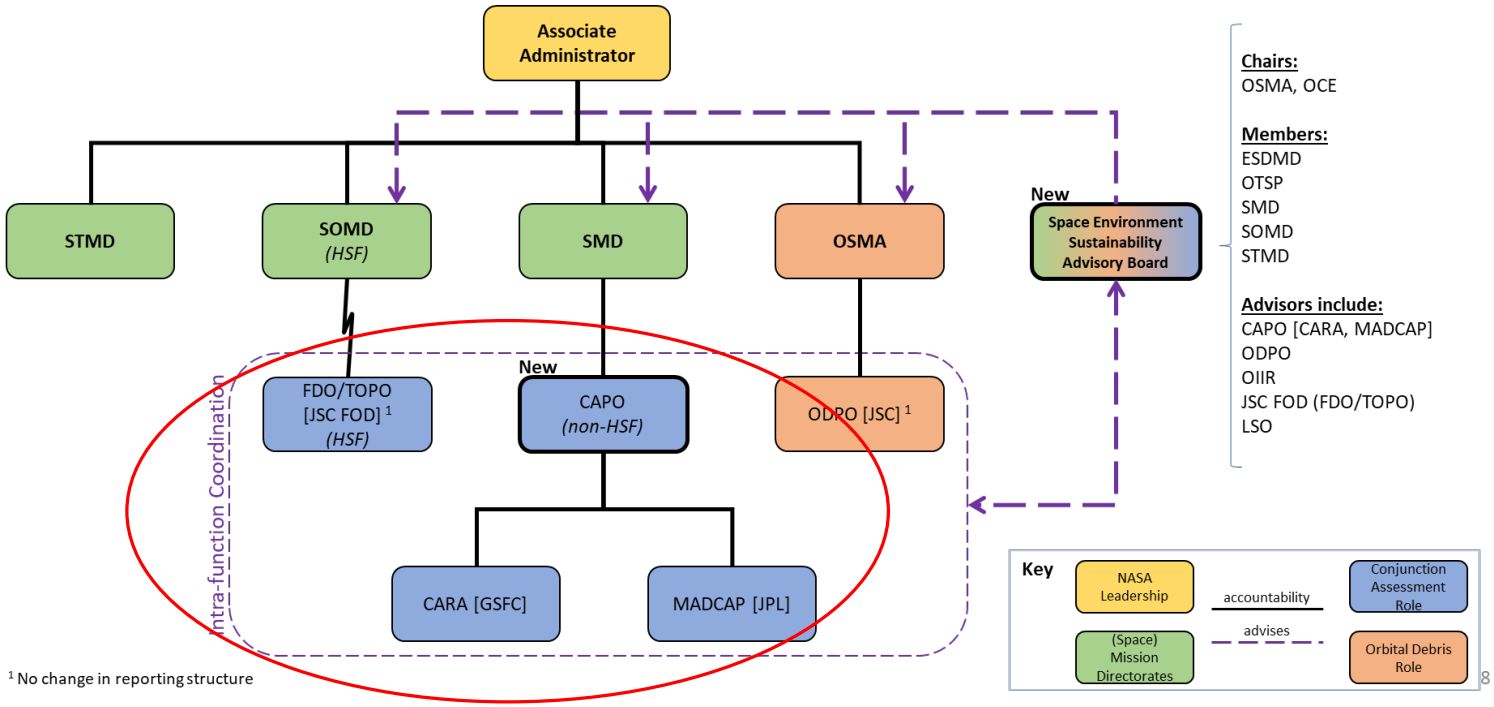
- **CARA**
  - **Non-HSF, Earth-orbiting missions (~100 assets)**
  - **GSFC-based**
- **Multimission Automated Deepspace Conjunction Assessment Process (MADCAP)**
  - **Cislunar and beyond**
  - **JPL-based**



Previous NASA Conjunction Assessment Structure (Distributed)



Current NASA Conjunction Assessment Structure - Consolidated



MADCAP Software Overview

- Built upon NASA/AMMOS multi-mission navigation software Monte
- Processing on a JPL flight operations computer is automated; use and performance are monitored and managed by a team of JPL Mission Design & Navigation personnel
- Uses ephemerides for flight projects provided to the DSN/SPS or one of a pair of AWS S3 systems to perform CA processing by searching spacecraft trajectories for future orbit crossings/close approaches
- Notifies mission teams of upcoming conjunctions which may be of concern (Red Events) via output reports sent to stakeholders by email
- New software updates are prepared and delivered approximately every 12 to 18 months

Trajectory & Uncertainty Inputs

- In order to perform conjunction assessment, MADCAP requires the following information for each body in the orbital environment:
  - Trajectory information to find close conjunctions
  - Trajectory uncertainty information (normally computed by the spacecraft's navigation team as part of the orbit determination (OD) process) to evaluate the risk of collision
- At lunar distances and beyond, this must be obtained from the project's navigation teams.

MADCAP Trajectory Formats

- MADCAP can process trajectory data that is stored in two formats:
    - SPICE (Spacecraft Planet Instrument C-matrix Event) SPK (Spacecraft and Planet Kernel)
    - CCSDS (Consultative Committee for Space Data Systems) OEM (Orbit Ephemeris Message)
- Many spacecraft in deep space environments regularly upload trajectory files to the Deep Space Network (DSN) Service Preparation Subsystem (SPS) portal for tracking purposes.
    - DSN/SPS supports trajectories in both SPK and OEM formats, which makes it a convenient source for ephemerides used by MADCAP
- Spacecraft not using DSN can submit files to MADCAP via the “MADCAP Deepspace Ephemeris eXchange” (MDEX), a secure Amazon Web Services (AWS) S3 system

MADCAP Conjunction Risk Categorization

- Probability of Collision (Pc) is used as the main conjunction risk assessment metric in the Earth Environment

- MADCAP will calculate and report Pc when there is uncertainty covariance data available for both objects involved in a close conjunction.

- If covariance data is only available for one object, then a worst-case Pc is calculated and reported.

- No Pc can be calculated if uncertainty covariance information is not available for either body.

MADCAP Conjunction Risk Categorization

- **Problem:** Covariance data has historically not been provided for most spacecraft operating in deep space environments, and MADCAP cannot compute Pc without this data.

- **Resolution:** MADCAP calculates thresholds used to categorize conjunctions as High Risk or “Red” based on three conjunction attributes intended to reflect the typical 3-sigma orbit position uncertainties.

MADCAP Process – Analysis: Close Approach Event Attributes

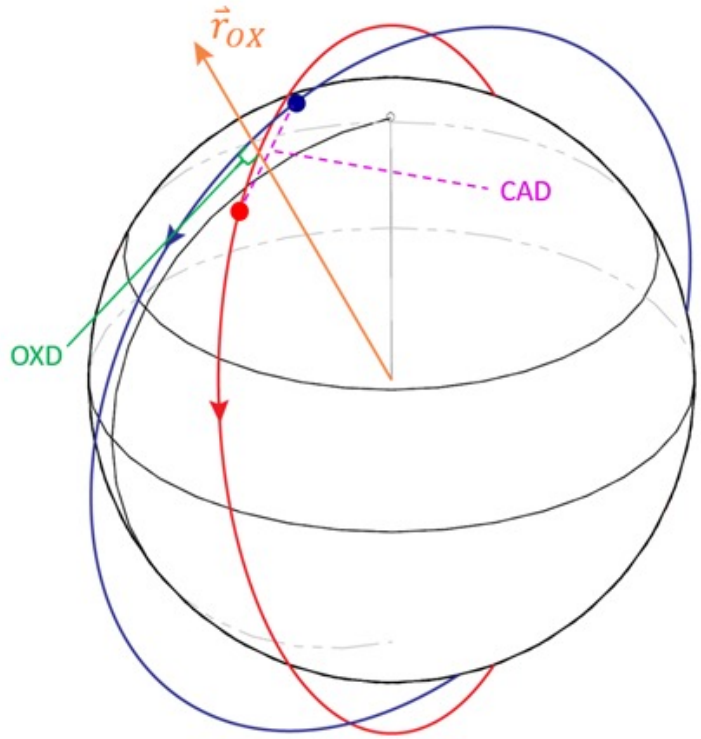
Close Approach Distance (CAD): The relative distance between the spacecraft pair at the time of the Close Approach Event. Reported as an absolute magnitude.

Orbit Crossing Distance (OXD): The minimum distance between the orbits of the two spacecraft as they exist at the time of the Close Approach Event.

$$OXD = r_1(t_{OX1}) - r_2(t_{OX2})$$

Orbit Crossing Timing (OXT): The difference between the time that each spacecraft is at the OXD location.

$$OXT = t_{OX1} - t_{OX2}$$



$\vec{r}_{OX}$ represents the body's orbit radial direction at the time of the crossing.

"1" and "2" represent primary and secondary bodies, defined by order listed in summary report.

Conjunction Screening – "Red Thresholds"

- Events are flagged “Red” if their Orbit Crossing Distance (OXD) and Orbit Crossing Timing (OXT) values are below calculated thresholds
- Unique thresholds are specified by the Navigation team for each spacecraft based on their risk tolerance.
  - Thresholds are based on the body’s covariance data if available in ephemeris file
  - Otherwise based on a quadratic fit of the body’s typical 3σ uncertainty values as a function of time to the event, measured from the last data point
    - Last data point assumed to be the ephemeris file submit time to SPS/MDEX, or the MADCAP process start time if that is not available
  - Red events are only considered in next 14 days from process start time.
- For missions with varying orbital environment characteristics or spacecraft operations processes, thresholds are usually set to reflect the worst-case uncertainty regime.

Conjunction Risk Mitigation

- When a High Risk or “Red” conjunction is reported, the MADCAP team will reach out within 24 hours to the missions involved to ensure they are aware of the situation, and gain further knowledge to assess conjunction risk.
- Such information would include estimates of uncertainty (if not provided via covariance data), known upcoming trajectory altering events (maneuver, momentum wheel unload, landing plan), and other operational considerations.
- This data, along with the Pc (if available), will be used by the teams to come to a decision on any action that may be required to mitigate conjunction risk.
- If teams cannot come to a conclusion as to necessary action, a "Maneuver Coordination Meeting" will be convened by the MADCAP Team.

Current MADCAP Environment

Mars (daily runs)

- Active Spacecraft: Odyssey, Mars Express, MRO, MAVEN, TGO, EMM, Tianwen-1 (7)
  - Passed through Martian Environment briefly in 2025: Europa Clipper, HERA (2)
- Natural Bodies: Phobos, Deimos (2)
- Inactive Spacecraft: Mariner 9, Viking 1, Viking 2, MGS, MOM (5)

Moon (daily runs)

- Active Spacecraft: LRO, ARTEMIS-P1, ARTEMIS-P2, CH2O, CAPSTONE, KPLO, HAK2 (7)
  - Passed through Lunar Environment briefly in 2025: BGM1, IM2, LTB, Odin, Chimera (5)
- Inactive Spacecraft: CH1 (1)

Sun/Earth Lagrange Points (weekly runs)

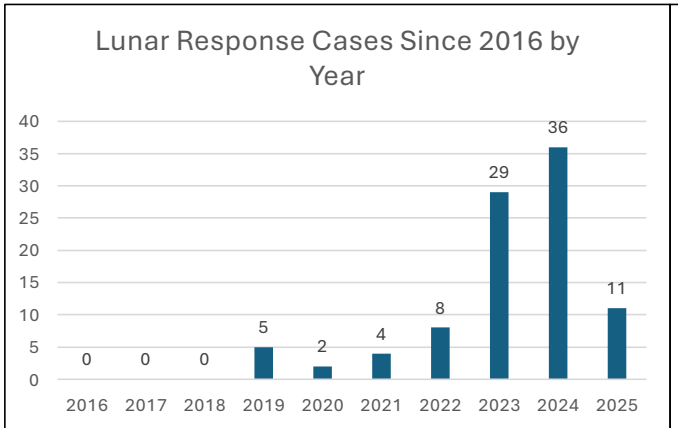
- **L1**
  - Active Spacecraft: ACE, SOHO, WIND, DSCOVR, ADIT (5)
- **L2**
  - Active Spacecraft: JWST, EUCLID (2)

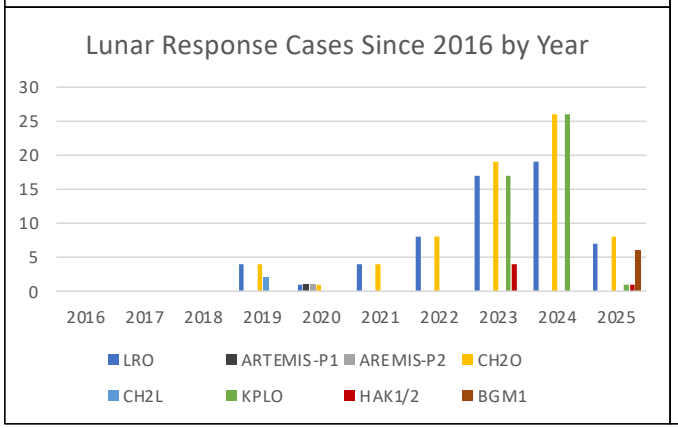
Cislunar (weekly runs)

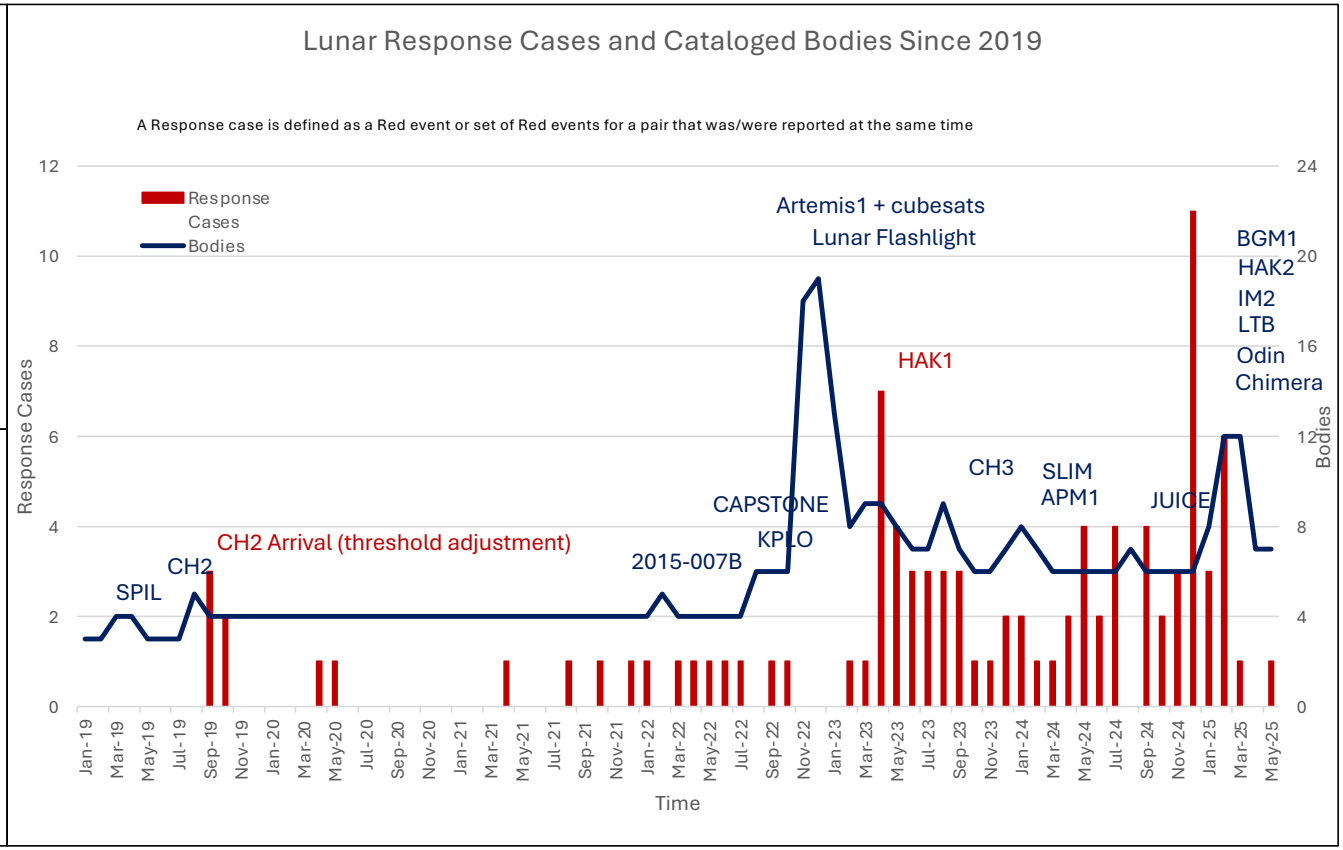
- Active Spacecraft: CHANDRA, TESS, MMS1, MMS2, MMS3, MMS4, CH3P (7)
  - Passed through Cislunar Environment briefly in 2025: BGM1, IM2, LTB, Odin, Chimera, HAK2 (6)

MADCAP Lunar Response Cases

A Response case is defined as a Red event or set of Red events for a pair that was/were reported at the same time



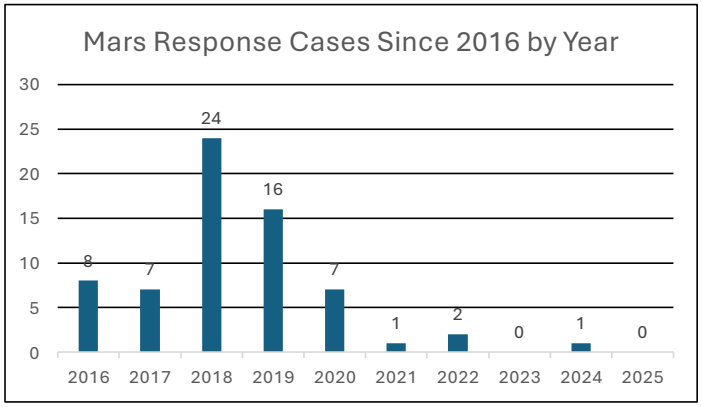


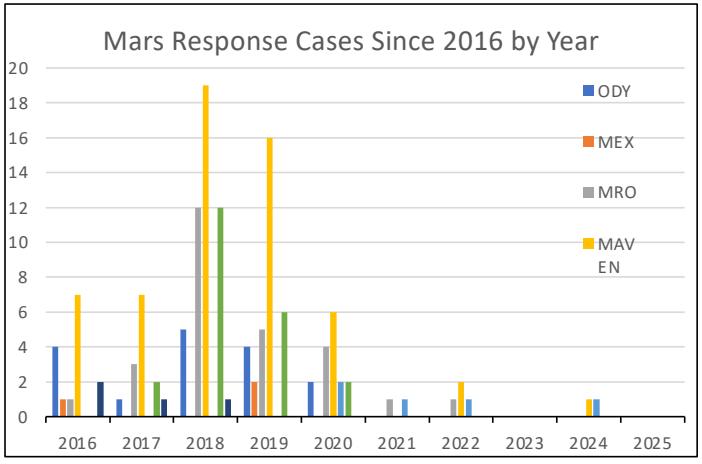


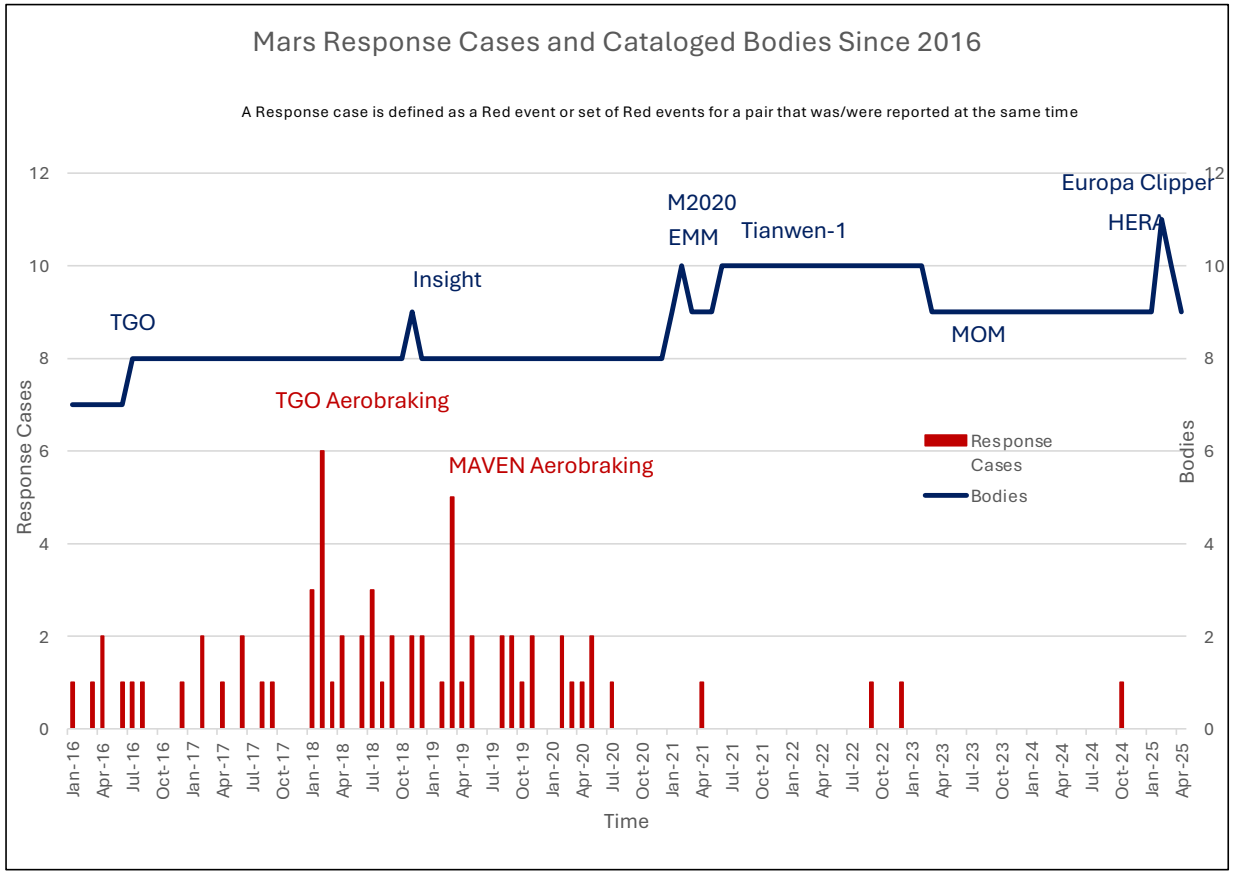
MADCAP Mars Response Cases

A Response case is defined as a Red event or set of Red events for a pair that was/were reported at the same time

2025 Response Cases: 0

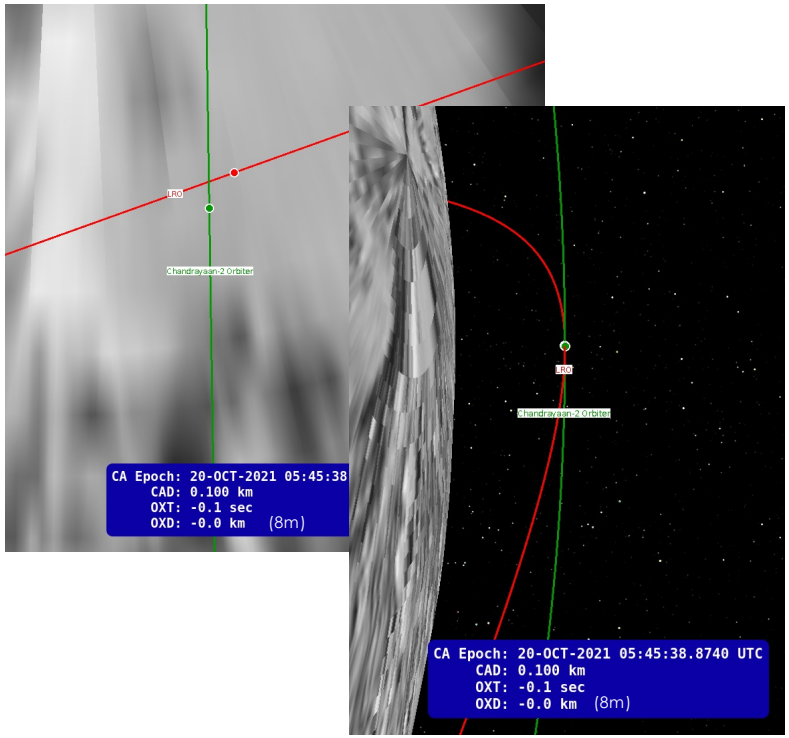






Recent Response Case Example: LRO/CH2O (No Covariance)

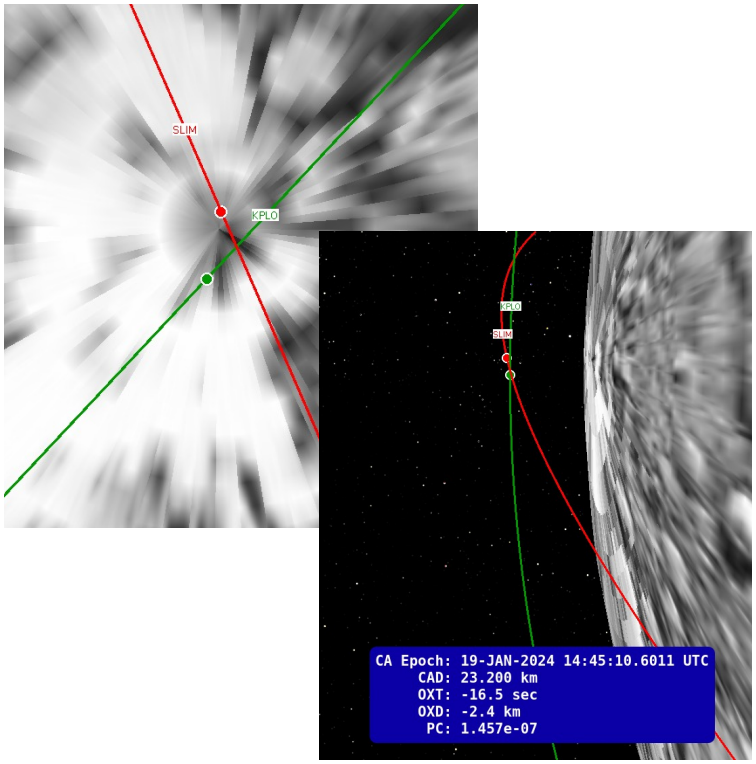
A Red event was flagged by MADCAP on 10/13/2021 between the NASA LRO Lunar orbiter and the ISRO orbiter CH2O



- Two collision avoidance maneuver meetings were facilitated by the MADCAP Team with both SC teams: 2021-10-14 (initial planning) & 2021-10-16 (go/nogo)
- ISRO planned and executed a maneuver for CH20 at 2021-10-18 14:52 UTC which resolved the immediate conjunction and did not result in downstream events of concern.
- No Pc calculated due to lack of covariance data from either spacecraft.

Recent Response Case Example: KPLO/SLIM (2 Covariance)

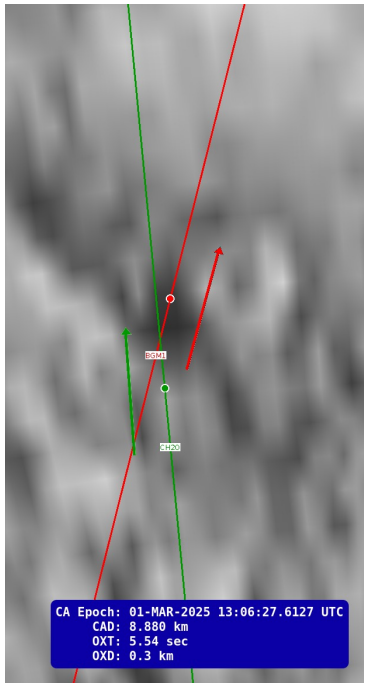
A Red event was flagged by MADCAP on 1/10/2024 between the JAXA SLIM Lunar Lander and the KARI orbiter KPLO

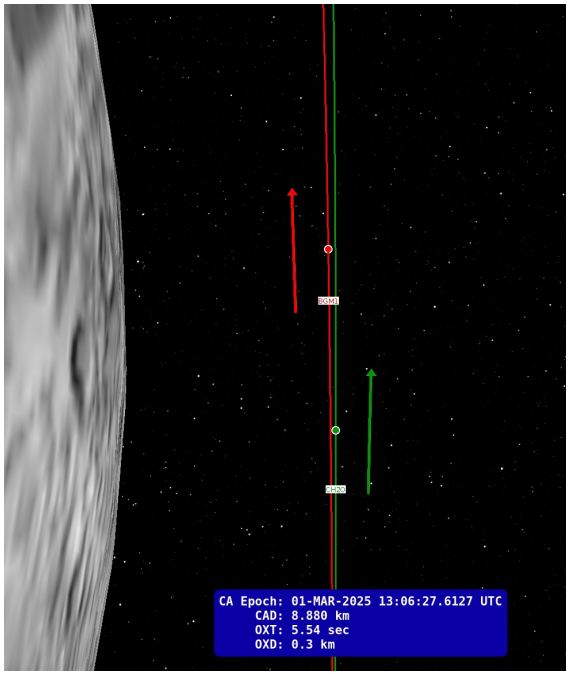


- Meetings were facilitated by MADCAP Team with both spacecraft teams. Covariance data was provided for both SC enabling MADCAP to report a Pc of 1.5e-07
- Although this Pc is low, the KPLO team decided to perform a Collision Avoidance maneuver to increase OXT since SLIM had a maneuver planned just before the conjunction, resulting in a large uncertainty at conjunction time.
- The maneuver was successful, adding minutes of separation time between the two spacecraft and decreasing the Pc to zero.

Recent Response Case Example: CH2O/BGM1 (1 Covariance)

A Red event was flagged by MADCAP on 2/25/2025 between the ISRO Lunar Orbiter CH2O and the Blue Ghost Lunar Lander BGM1





- Special MADCAP runs were setup to monitor the situation as BGM1 was performing maneuvers prior to landing.
- Meetings were facilitated by MADCAP Team with both spacecraft teams. Covariance data was provided by the BGM1 team enabling MADCAP to report a worst-case Pc of 7.8e-06
- The teams exchanged ephemeris data, and BGM1 delivered updated more accurate uncertainty covariance data. The decision was made that this conjunction was below the risk threshold for maneuver.

Some Challenges

- One of the more pressing challenges the MADCAP Team faces is that not all space actors who fly spacecraft in shared non-Earth environments share their ephemerides with MADCAP, posing safety risks for themselves and nearby assets
- Debris clouds created in these environments cannot be tracked, adding significant risk if a collision were to occur
- One obstacle to sharing is an inability to effectively communicate among some members of the community, as multilateral international organizations do not have conjunction assessment as part of their scope of work, e.g.:
  - Inter-Agency Space Debris Coordination Committee (IADC)
  - International Committee on Global Navigation Satellite Systems (ICG)
  - United Nations Committee on Peaceful Uses of Outer Space (UNCOPUOS)
- This International CA Workshop, however, is completely focused on CA issues, and is better suited for multilateral discussion of deep space CA

More Challenges

- The MADCAP team has been interested in the best way to include non-operational spacecraft in its analyses... there are several at Mars
- Long-term orbital predictions can be produced by propagating previously known states
- These predicts are better than nothing, but uncertainties are greater for inactive satellites
- Because of these uncertainties, conjunctions identified with inactive spacecraft are suspect
- Even at Lunar distances, Earth-based radar detection of dead lunar satellites was challenging and required a reasonably good a priori trajectory

Conclusions

- A general overview of the MADCAP automated conjunction assessment process for shared non-Earth environments was provided
- Keeping these environments safe is reliant on self-reported ephemeris and uncertainty data from mission teams
- With accurate trajectories for orbiters regularly available, MADCAP can help avoid creation of hazardous debris fields, thus benefiting all spacefaring nations wishing to explore in these shared orbital environments
- The MADCAP Team strongly believes in the necessity of international cooperation and collaboration in extraterrestrial conjunction assessment, to keep shared orbital environments safe for all space operators
- Due diligence: The MADCAP Team always wants to be prepared to answer the question "how close are the orbits?”

Email: madcap_team@jpl.nasa.gov Website: https://www.nasa.gov/cara/madcap

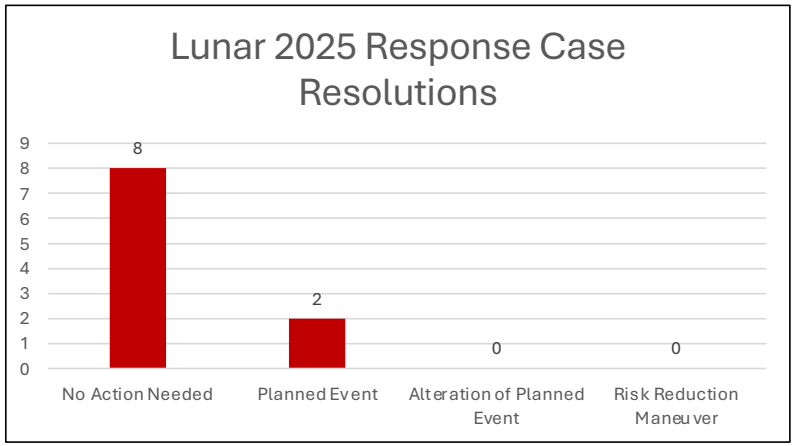
Backup Material

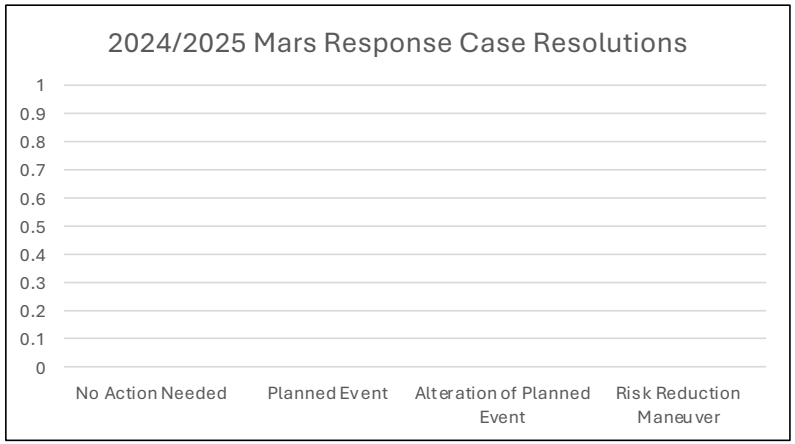
MADCAP 2025 Stats

1/1/2025-4/02/2025

Response Case Resolutions

A Response case is defined as a Red event or set of Red events for a pair that was/were reported at the same time

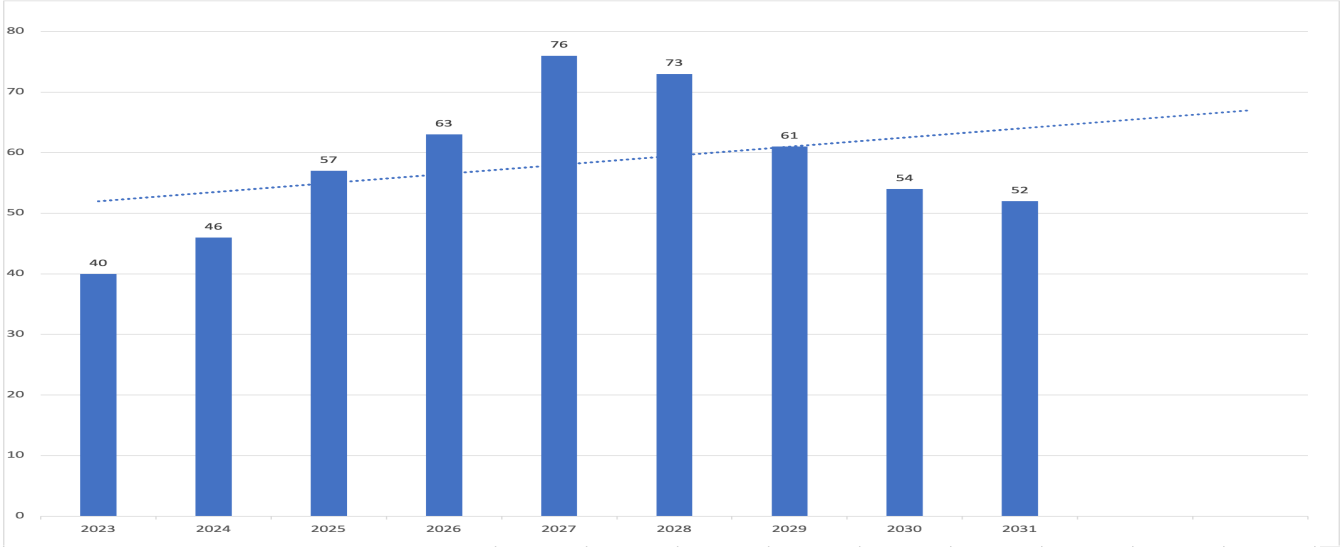




- No Action Needed: Event was no longer deemed high risk after uncertainties reduced due to updated OD
- Planned Event: One or more of the SC had a trajectory impacting event (maneuver, momentum wheel unload, etc) planned before the conjunction time and execution of this event resolved the conjunction.
- Alteration of Planned Event: SC changed the timing or design of a trajectory impacting event (maneuver, momentum wheel unload, etc) to resolve the conjunction
- Risk Reduction Maneuver: SC performed a previously unplanned maneuver designed and executed specifically to reduce conjunction risk.

- NOTE: No response cases yet for Sun/Earth Lagrange Point environments. No response cases in 2024 or 2025 to date at Mars.

Predicted Future MADCAP Supported Missions (By Year & Environment, as of 04/14/2025)

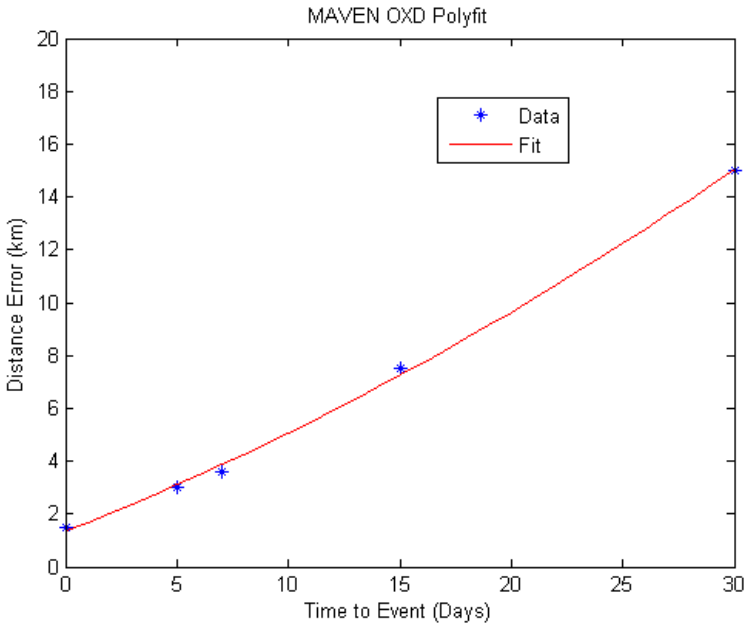


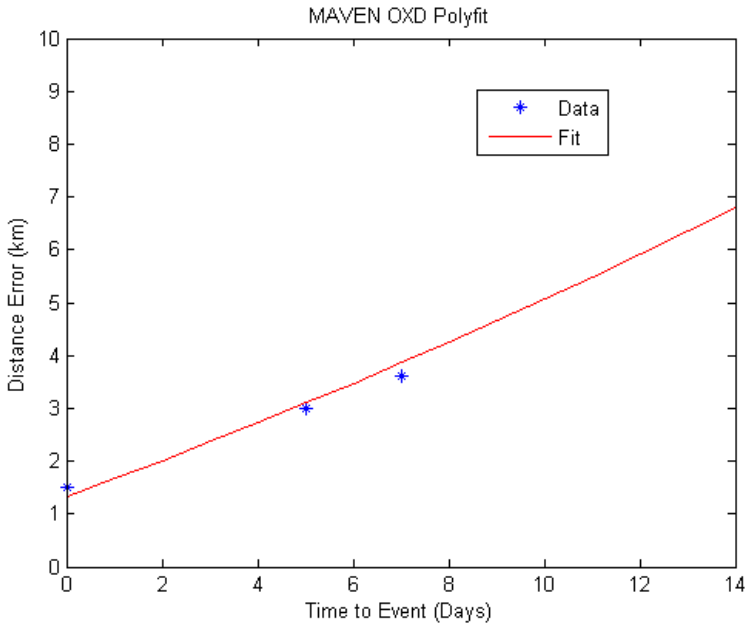
Mission Count as of 4/14/2025	40	46	57	63	76	73	61	54	52
Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
Venus	1	1	1	1	1	3	1	3	4
Moon	16	21	27	32	41	38	22	23	17
S/E L1	4	5	7	7	7	5	4	4	4
S/E L2	4	4	4	5	6	5	6	5	4
S/E L5	0	0	0	0	0	0	0	0	0
Mars	7	7	10	10	13	10	15	9	12
Comet/Asteroid	0	0	0	0	0	0	0	0	0
Jupiter	1	1	1	1	1	0	0	1	2
Cislunar	7	7	7	7	7	11	9	9	9

Backup: Example Polynomial Fits for Thresholds

- In order to specify polynomial thresholds, Nav Teams are asked to provide data for typical 3-sigma uncertainties based on elapsed time from the last data point.
- The orbit radial uncertainties are used to inform the OXD thresholds, while the orbit timing uncertainties are used to inform OXT thresholds.
- A polynomial is fitted to the data and the coefficients used in the MADCAP Mars runs.
- Examples are shown in the following slides for the MAVEN Mars mission.
- In some cases, certain data is left out to get a better fit of the first 14 days out or to move the fit out of negative values.

MAVEN OXD

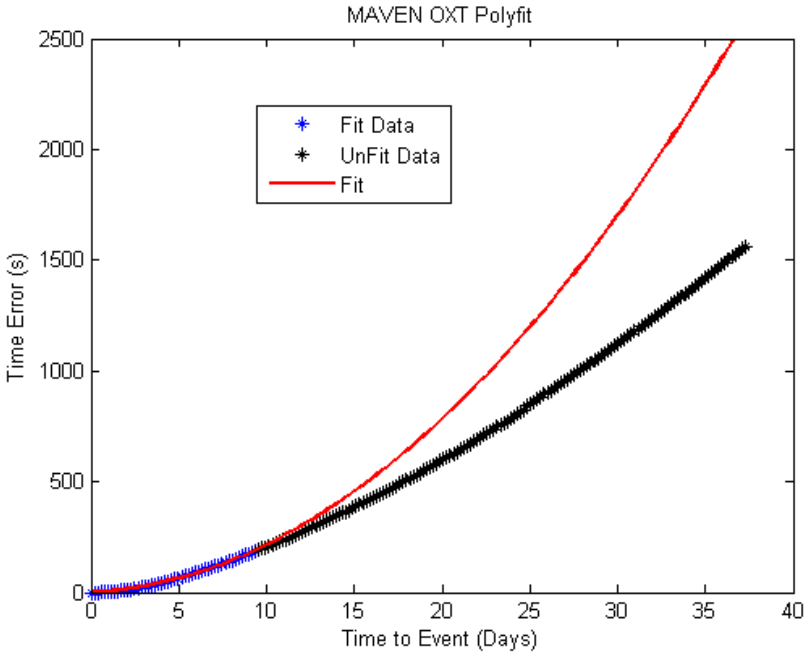


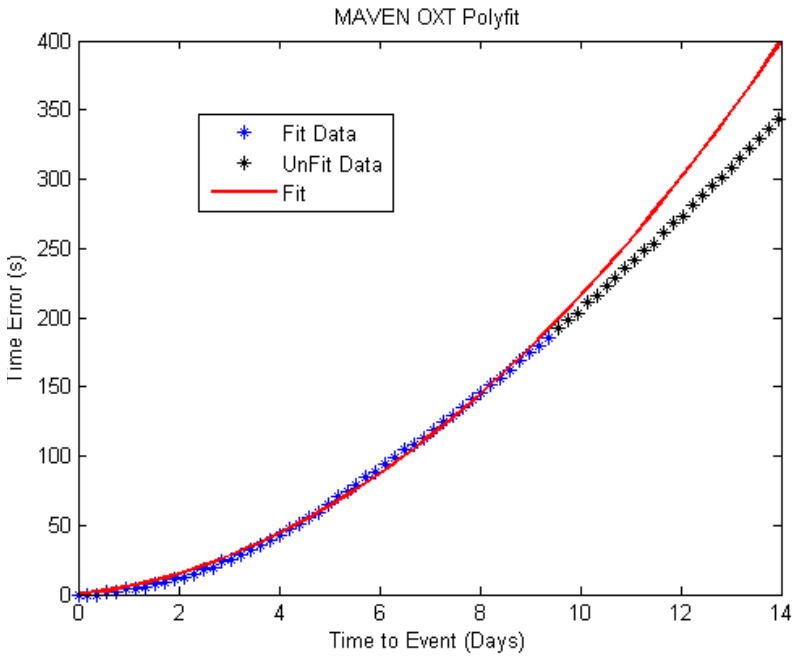


OXD threshold = OXD2 t^2 +OXD1 t +OXD0 (km)

OXD0 = 1.3357 OXD1 = 0.3322 OXD2 = 0.0042

MAVEN OXT





Note: Only first 9.5 days of data fit in order to get better fit for first 14 days without dipping too far below data for first few days.

OXT threshold = OXT2 t^2 +OXT1 t +OXT0 (s)

OXT0 = 0.01 OXT1 = 3.9752 OXT2 = 1.756