# Automated Spacecraft Conjunction Assessment at Mars and the Moon


David Berry, Joseph Guinn, Zahi Tarzi, Stuart Demcak

*California Institute of Technology*
*Jet Propulsion Laboratory (JPL)*
*4800 Oak Grove Drive*
*Pasadena, California, USA, 91109*

# Introduction

- Conjunction assessment and collision avoidance are areas of current high interest in space operations
- Most current conjunction assessment activity focuses on the Earth orbital environment
- Several of the world's space agencies have satellites in orbit at Mars and the Moon, and avoiding collisions there is important too
- Smaller number of assets than Earth, and smaller number of organizations involved, but consequences similar to Earth scenarios
- This presentation will examine conjunction assessment processes implemented at JPL for spacecraft in orbit at Mars and the Moon

# Agenda

- Conjunction assessment requirements at Mars
- Rationale for automation
- "MADCAP" automated utility
- Conjunction assessment requirements at the Moon
- MADCAP Inputs / Features / Algorithms / Outputs
- Future Work

# Conjunction Assessment at Mars

- NASA and ESA have spacecraft in orbit/on approach
- NASA: Mars Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Science Laboratory (MSL) on approach
- ESA: Mars Express (MEX) spacecraft
- Also defunct spacecraft (Viking 1/2, Mars Global Surveyor) and natural satellites (Phobos, Deimos)
- Since mid-2002, ad hoc collision avoidance studies
- Ad hoc collision avoidance studies increased when MEX arrived in late 2003
- MRO aerobraking campaign in 2006 was major driver
- India, Russia, China interested in Mars missions

# Rationale for Automation

- Given planned longevity of Mars-orbiting spacecraft, ad hoc conjunction assessment was insufficient
- Spacecraft orbits relatively stable, but are modified periodically, e.g., for relay operations
- Spacecraft are also subject to standard perturbations (e.g., drag, gravity, solar radiation pressure)
- Due diligence: always be prepared to answer the question "how close are the orbits?”
- Result: “MADCAP” (MArs Deepspace Collision Avoidance Process) automation developed to study Mars spacecraft conjunctions

# Conjunction Assessment at the Moon

- NASA has several spacecraft in orbit at the Moon: the Lunar Reconnaissance Orbiter (LRO), GRAIL-A, GRAIL-B, ARTEMIS-P1, and ARTEMIS-P2
- India and Japan have spacecraft at the Moon that are no longer being tracked: Chandrayaan-1, Ouna (SELENE sub-satellite)
- MADCAP can also be used for Moon orbital environment

# MADCAP Methodology

- Each orbital environment has a unique parameter file
- Required:  A list of at least 2 objects per environment
- User specifies the desired conjunction attribute and threshold that will trigger user notification
- Other key parameters set ephemeris files to use, data items to analyze and print/plot, parameters used to calculate collision probability, email addresses
- Currently activated by a Linux cron job twice weekly for Mars, and daily in the case of the Moon

# Ephemeris Files

- Most recent ephemeris files for S/C in the MADCAP parameters are automatically downloaded from DSN
- MADCAP allows specification of one supplementary file per S/C in addition to the most recent trajectory
- Ephemeris files for non-operational S/C can be added by specifying an ephemeris file location
  - State uncertainty in such ephemerides is greater than that of current solutions, but better than nothing
- Natural body ephemerides may also be specified

# Orbit Conjunction Attribute Options

- Pairwise comparisons for all combinations of 2 spacecraft
- Comparisons occur over overlap of 2 ephemerides

| Conjunction Attribute | Description |
|---|---|
| closap_times | Times of closest approaches of the two bodies |
| closap_distance | Relative distance and speed at closest approach |
| closap_angles | Angles between velocity vectors and orbit planes with respect to central body |
| closap_state_diff | State of spacecraft 2 relative to spacecraft 1 |
| closap_states | States of both spacecraft with respect to central body and coordinate system |
| xing_distance | Distance between orbits at orbit crossings |
| xing_distance_min | Smaller of orbit crossing distances |
| xing_times | Times of orbit crossings |
| xing_times_min | Times of minimum orbit crossing |
| xing_traj | Radius and true anomaly at orbit crossings |
| xing_traj_min | Radius and true anomaly at minimum orbit crossing |
| mod_distance | Minimum orbit distances (useful for nearly coplanar orbits) |
| mod_distance_min | Smaller of two minimum orbit distances |
| mod_times | Times of minimum orbit distances |
| mod_times_min | Times of smaller of two minimum orbit distances |
| mod_traj | Radial distance and true anomaly at minimum orbit distances |
| mod_traj_min | Radial distance and true anomaly at smaller of two minimum orbit distances |
| col_prob | Collision probability for specified covariance |

# Collision Probability

- Intuitive collision probability at Mars/Moon is zero
- Collision consequences catastrophically high: lost tax investment, loss of science data, debris environment, repercussions if spacecraft from two nations collide
- Other faults with intuitive notions: science orbits with similar characteristics, surface S/C using relay services
- Analytic approaches yield better collision probability
- After considering several approaches, an advisory group selected a technique based upon a paper by Sal Alfano of Center for Space Standards & Innovation:

$$P = \frac{1}{2 \cdot \pi \cdot \sigma_x \cdot \sigma_y} \cdot \int_{-OBJ}^{OBJ} \int_{-\sqrt{OBJ^2 - y^2}}^{\sqrt{OBJ^2 - y^2}} \exp\left\{ \left( \frac{-1}{2} \right) \cdot \left[ \left( \frac{x + x_m}{\sigma_x} \right)^2 + \left( \frac{y + y_m}{\sigma_y} \right)^2 \right] \right\} dx\,dy$$

# Output Reports

- MADCAP prepares three types of reports: detail, summary, and plots
- Detail reports contain the results of analysis of the conjunction attributes for each pair of spacecraft, sorted by the conjunction attribute desired by user
- Summary report focuses on the "close approach distance" attribute, and categorizes the close approaches as green, yellow, or red
- Thresholds for green, yellow, red categorizations are established by the user
- MADCAP will also generate plots of several of the conjunction attributes if requested by the user

# Sample MADCAP Detail Report

```
# Table of closest approach events for 'SC01' and 'SC02'
# Begin Time:  27-APR-2012 00:55:27.0000 TAI
# End   Time:  10-MAY-2012 00:01:06.1840 ET
# Central Body:  Moon
# Coordinate System:  IAU Moon Pole
# Output Time System:  UTC    (UTC-ET =   -66.1855 sec [at begin time])
# Ephemeris files supplied by user:
#   /home/common/scripts/inputs/ephemerides/de421.boa
#   /home/moon/scripts/inputs/ephemerides/de421_Lunar.boa
#
ome/moon/scripts/inputs/ephemerides/spk_sc1_120424_120510_120425_od123v1.bsp
#
ome/moon/scripts/inputs/ephemerides/spk_sc2_120423_120510_120425_od234v1.bsp
#   /home/moon/scripts/inputs/ephemerides/spk_sc2_14day_20120426_01.bsp
#
```

| # Calendar Date | Julian Date (days) | RELATIVE Distance (km) | RELATIVE Speed (km/s) | Collision Probability |
|---|---|---|---|---|
| 06-MAY-2012 11:31:03.547 | 2456053.97990 | 14.05064 | 2.89753 | 0.00587 |
| 01-MAY-2012 10:23:40.970 | 2456048.93311 | 28.22475 | 2.90483 | 0.00229 |
| 03-MAY-2012 02:07:21.064 | 2456050.58844 | 55.77511 | 2.89525 | 0.00007 |
| 08-MAY-2012 03:14:48.459 | 2456055.63528 | 98.52263 | 2.89337 | 0.00000 |
| 04-MAY-2012 19:47:24.982 | 2456052.32459 | 101.18978 | 2.89296 | 0.00000 |
| 09-MAY-2012 20:54:47.876 | 2456057.37139 | 106.70121 | 2.89202 | 0.00000 |
| 04-MAY-2012 18:48:55.329 | 2456052.28397 | 117.16007 | 2.78184 | 0.00000 |
| 09-MAY-2012 19:55:59.805 | 2456057.33055 | 123.63937 | 2.77510 | 0.00000 |

# Sample MADCAP Summary Report

Collision Analysis was performed between SC04, SC05, and SC06 using the following ephemerides:

| | |
|---|---|
| spk_SC04_noburn.bsp | 21-FEB-2012 08:00:00 UTC - 29-FEB-2012 23:59:59 UTC |
| spk_SC05_od108v1.bsp | 26-FEB-2012 13:00:00 UTC - 07-MAR-2012 23:59:59 UTC |
| spk_SC05_reference_traj.bsp (Ref) | 24-FEB-2012 17:15:00 UTC - 05-JUN-2012 07:11:50 UTC |
| SC06-short_01.bsp | 28-FEB-2012 00:00:00 UTC - 13-MAR-2012 00:00:00 UTC |

The following body pairs have a status RED close approach event in less than 14 days:

| | | |
|---|---|---|
| SC04-SC05 | 19.76 km | 01-MAR-2012 00:49:18 UTC |
| SC04-SC05 | 10.26 km | 01-MAR-2012 02:43:52 UTC |
| SC04-SC05 | 0.80 km | 01-MAR-2012 04:40:43 UTC |
| SC04-SC06 | 11.63 km | 03-MAR-2012 14:37:48 UTC |
| SC05-SC06 (SC05 Ref) | 11.83 km | 10-MAR-2012 07:27:40 UTC |

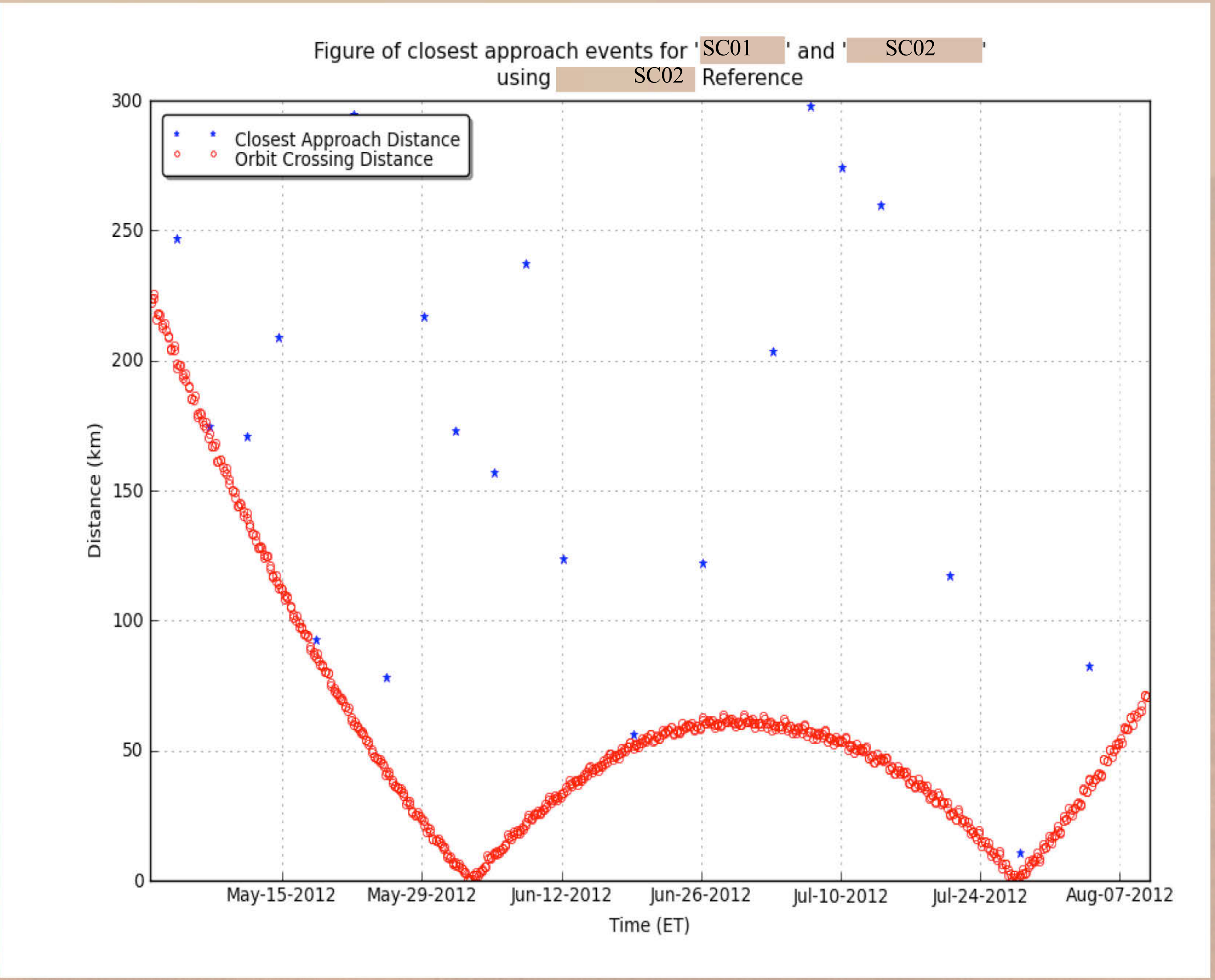
The following body pairs are status RED (closap_distance <= 20 km):

| | | |
|---|---|---|
| SC04-SC05 | 0.80 km | 01-MAR-2012 04:40:43 UTC |
| SC04-SC06 | 11.63 km | 03-MAR-2012 14:37:48 UTC |
| SC05-SC06 (SC05 Ref) | 11.83 km | 10-MAR-2012 07:27:40 UTC |

The following body pairs are status YELLOW (20 km < closap_distance <= 200 km):

| | | |
|---|---|---|
| SC04-SC06 | 137.29 km | 29-FEB-2012 07:10:33 UTC |
| SC04-SC06 | 136.78 km | 29-FEB-2012 07:10:33 UTC |
| SC04-SC05 | 28.57 km | 29-FEB-2012 22:55:07 UTC |
| SC05-SC06 | 23.99 km | 01-MAR-2012 22:54:45 UTC |
| SC04-SC05 (SC05 Ref) | 45.17 km | 05-JUN-2012 06:18:10 UTC |

# Sample MADCAP Plot



# Communicating Results

- The MADCAP parameter file contains a list of email addresses to which the output reports will be sent
- Accommodations are made for normal engineering reporting and for management escalation reporting
- Current spacecraft in the Mars and Moon environments normally maintain a safe separation
- Occasional close approaches with low miss distance have warranted some discussion as to whether any action was necessary
- At present no official decision-making process has been established for handling these events

# Future Work

- Formalize process when approaches are “too close”
- Refine uncertainty modeling to improve collision probability calculation
- Collaboration with NASA/GSFC and ESA's Space Situational Awareness program will be explored
- Incorporate more sophisticated automation than Linux “cron”
- Include other shared orbital environments of potential interest (Earth-Sun L1/L2, Earth-Moon L1/L2)
- Provide option to output a CCSDS Conjunction Data Message (CDM), an emerging international standard

# Conclusion

- The techniques used at JPL for automated conjunction assessment at Mars and the Moon have been presented
- Processes not unique to any specific orbit environment
- Potential future work to enhance the current baseline operation has been outlined
- Future spacecraft at Mars, the Moon, Earth-Sun L1/L2, and Earth-Moon L1/L2 are likely
- MADCAP techniques can be used in all of these multi-spacecraft environments to ensure a safer orbital environment for all