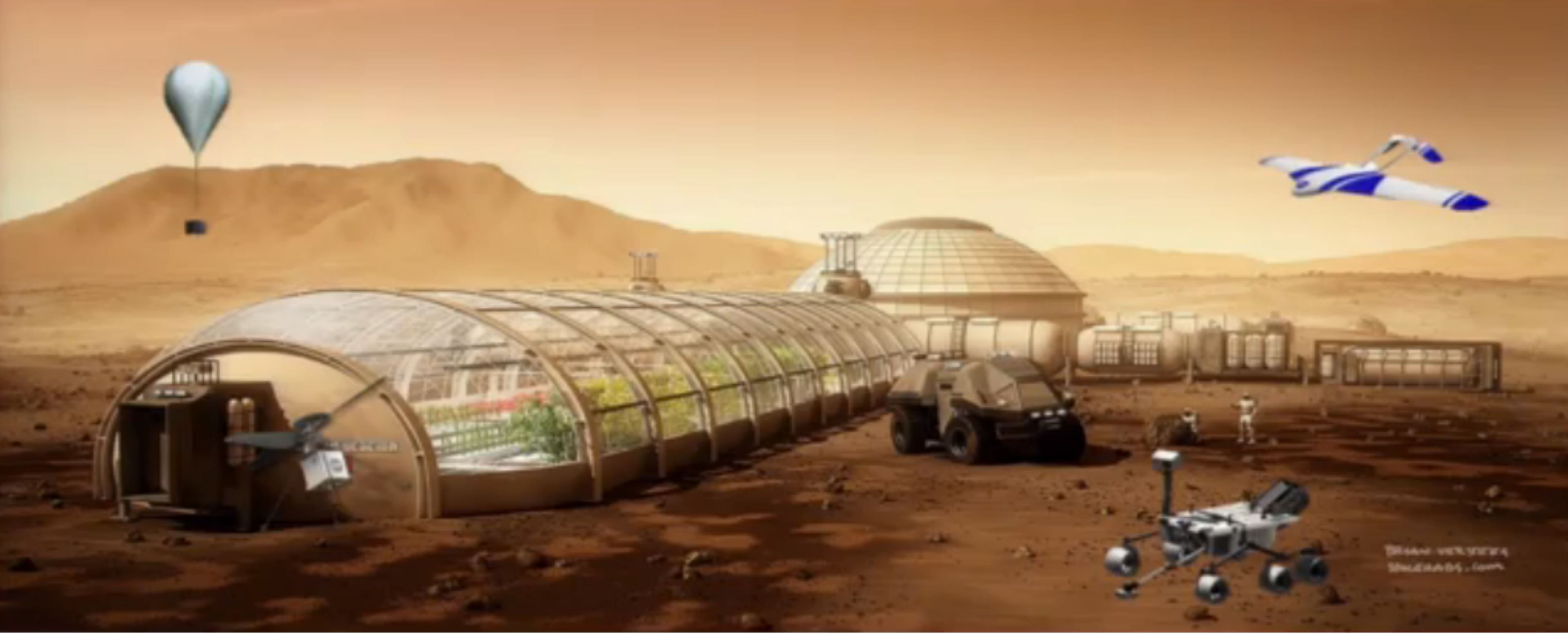


NASA/JPL Mission Design and Navigation(MD/Nav) Monte and MADCAP Software

Roby Wilson and Joseph Guinn
MD/Nav Section

January 2017

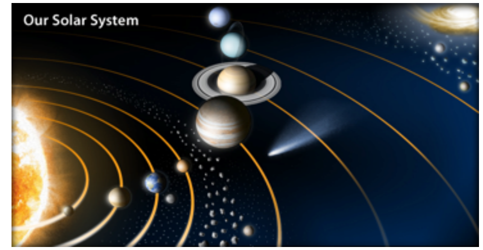
Jet Propulsion Laboratory
California Institute of Technology

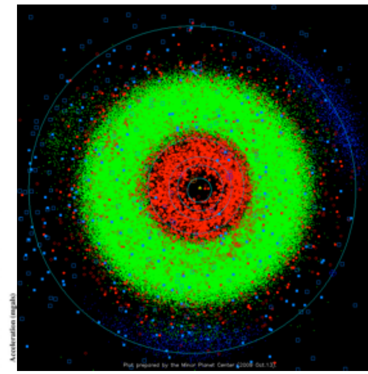
Outline

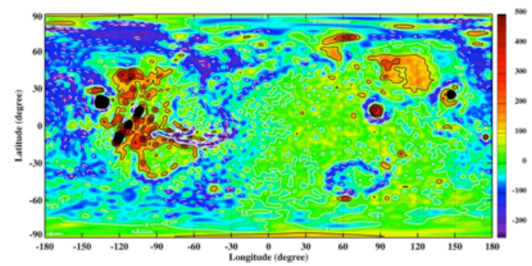
- Overview of JPL MD/Nav Section
  - 2 Mission Analysis (Trajectory) groups
  - 2 Orbit Determination groups
  - 1 Flight Path Control group
  - 1 Systems Engineering group
  - 1 Solar System Dynamics group
  - 2 Software groups (Monte + NAIF)
- Description of Monte Software
  - Discussion on Release and Licensing
- Description of MADCAP Service

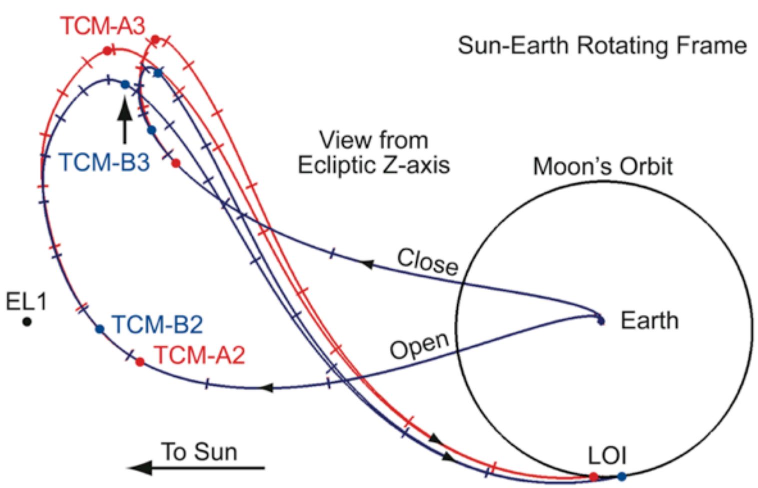
JPL Mission Design & Navigation Section

Build and maintain dynamical models and software tools for interplanetary navigation



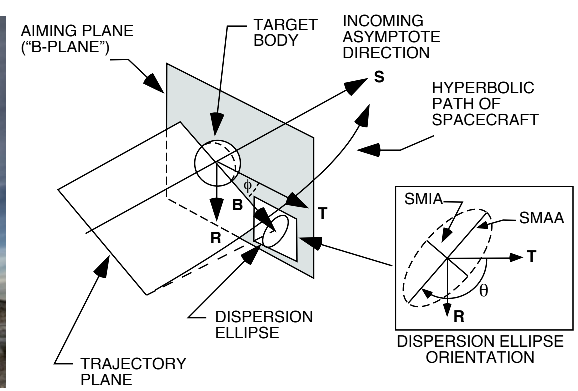






Design efficient routes for spacecraft to reach any remote Solar System location

Use deep space tracking measurements to safely pilot spacecraft to their ultimate destination

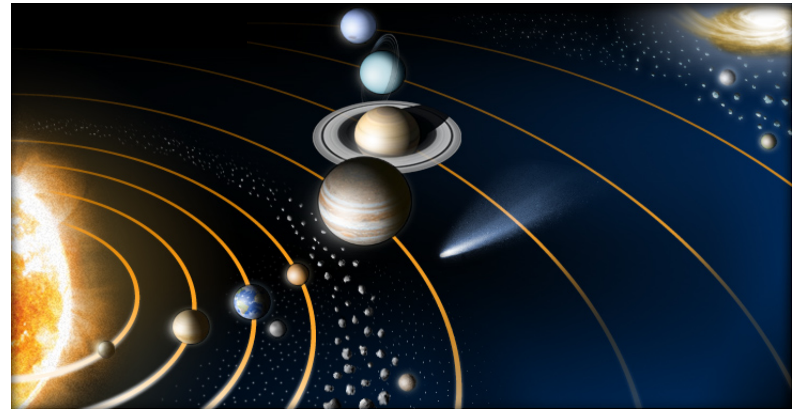


Deep Space Mission Design & Navigation

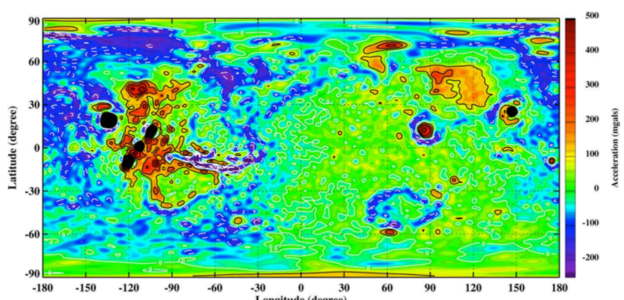
1. **Positions and Physical Models of Celestial Bodies**
2. **Optimal Trajectories**
   - Interplanetary and beyond
   - Orbiters (Earth, Moon, Planets, Asteroids, Comets, moons)
   - Complex Design Space (Low-energy, Low-thrust, Multi-spacecraft, etc.)
   - From Low to High fidelity (pre-Project through Operations)
3. **Deep Space Network Tracking**
   - Radiometric
   - Interferometric
   - Optical
4. **High precision dynamic and measurement models**
   - Relativity – intense gravity fields and high velocity tweak onboard clocks
   - Non-gravitational – spacecraft attitude control, venting, leaking and outgassing perturb trajectories
   - Maneuvers – chemical and/or low-thrust to setup EDL, Orbit Insertions, Flybys, etc.

Celestial Body Ephemeris and Physical Models

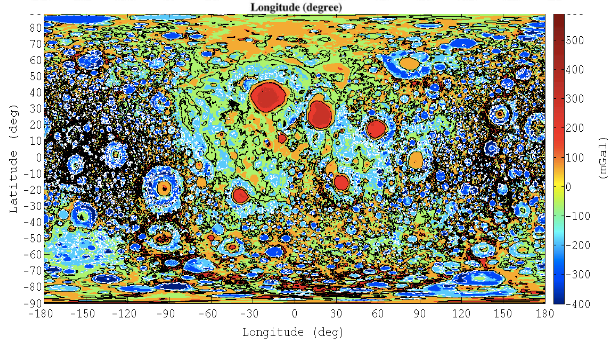
- *Locations & Uncertainties of*
  - *Planets & Natural Satellites*
  - *Small Bodies*
    - *NASA/JPL Maintains Horizons Database – Currently Contains ~700,000 Objects*
- *Pole Orientations*
- *Spin Rates*
- *Shape Models*
- *Gravity Fields*

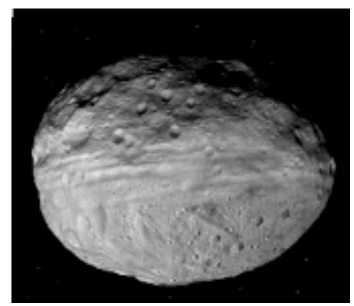


Mars Gravity Map

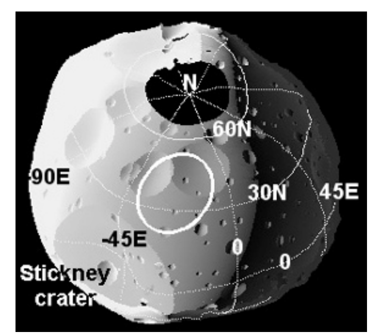


Lunar Gravity Map





Vesta Shape Model



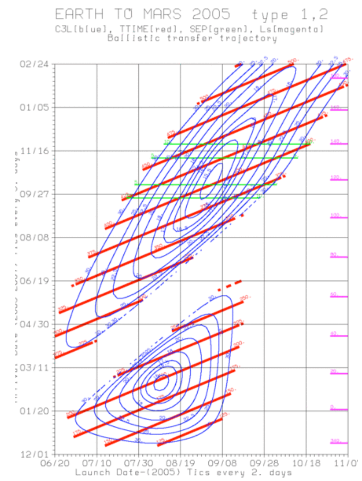
Phobos Orientation

Optimal Trajectory Design

Complex constraints complicate the initial search…

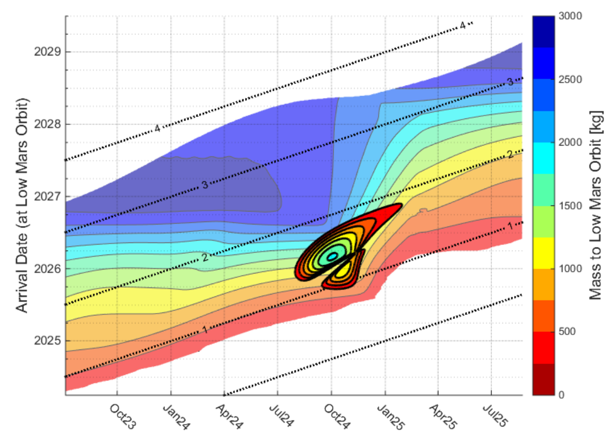
State of the art techniques are used to uncover exceptionally strong trajectory solutions…

Traditional Pork Chop Plot



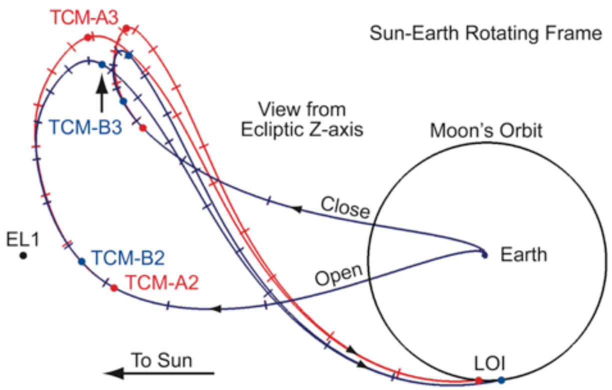
Arrival Date

Low-Thrust Bacon Plot



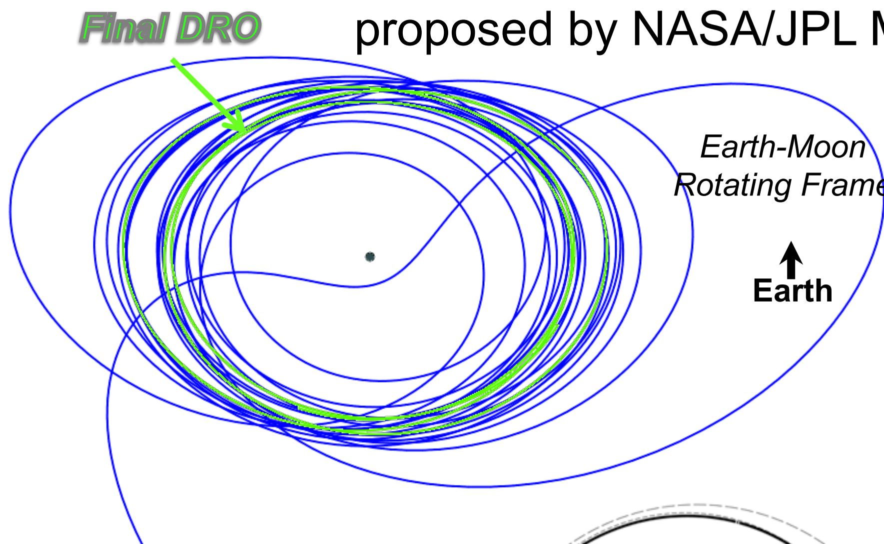
Launch Date

Low-Thrust & Low-Energy Trajectories

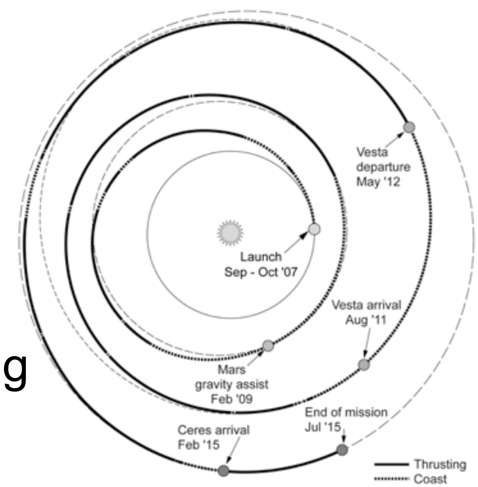


GRAIL low-energy trajectory enabled the mission to reduce fuel requirements and the lunar arrival velocity

Proposed
Asteroid Retrieval Mission
Distant Retrograde Orbit (DRO)
Stable storage orbit (>100yrs)
proposed by NASA/JPL MD/Nav



Dawn low-thrust trajectory has achieved a total delta-v over 10 km/s. Allows reaching both Vesta and Ceres.



Europa Multiple Flyby Mission Concept

- Dip into the harsh radiation environment to collect data
- Get out of intense radiation environment and downlink high volume of data

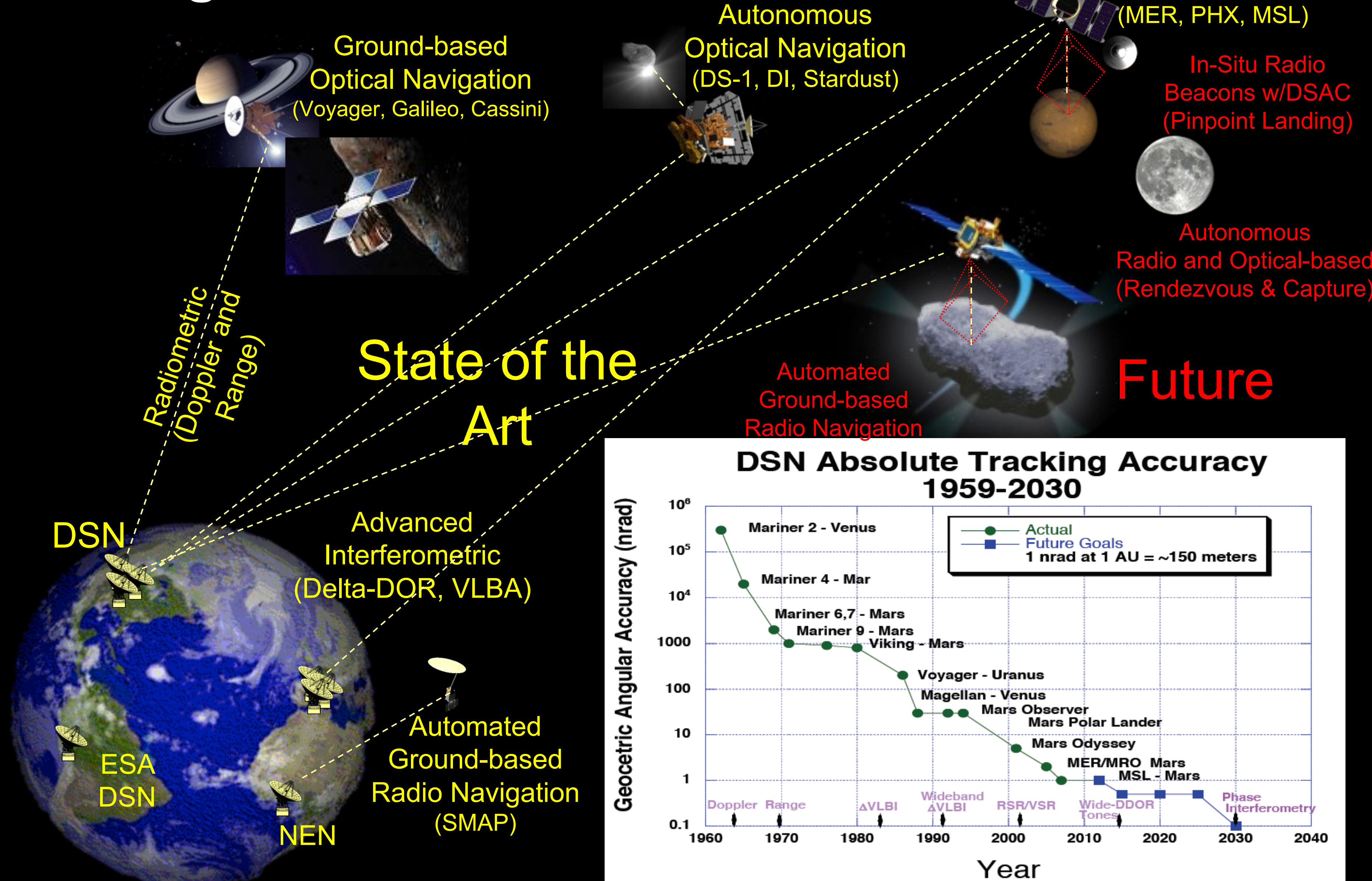
Key Statistics	13F7-A21
Tour Duration	3.5 years
Number of Flybys: Europa Ganymede Callisto	 45 5 9
Time between Flybys: Maximum* Minimum Mean*	 57.2 days 5.5 days 18.9 days
Maximum Inclination	20.1°
Maximum Eclipse Duration	4.5 hours
Total Ionizing Dose** (TID)	2.8 Mrad
Deterministic ΔV (post-PRM)	164 m/s
Statistical ΔV (99%)	223 m/s
Total Mission ΔV	1596 m/s

*Not including the 202-day capture orbit

**Si behind 100 mil Al, spherical shell (GIRE2)

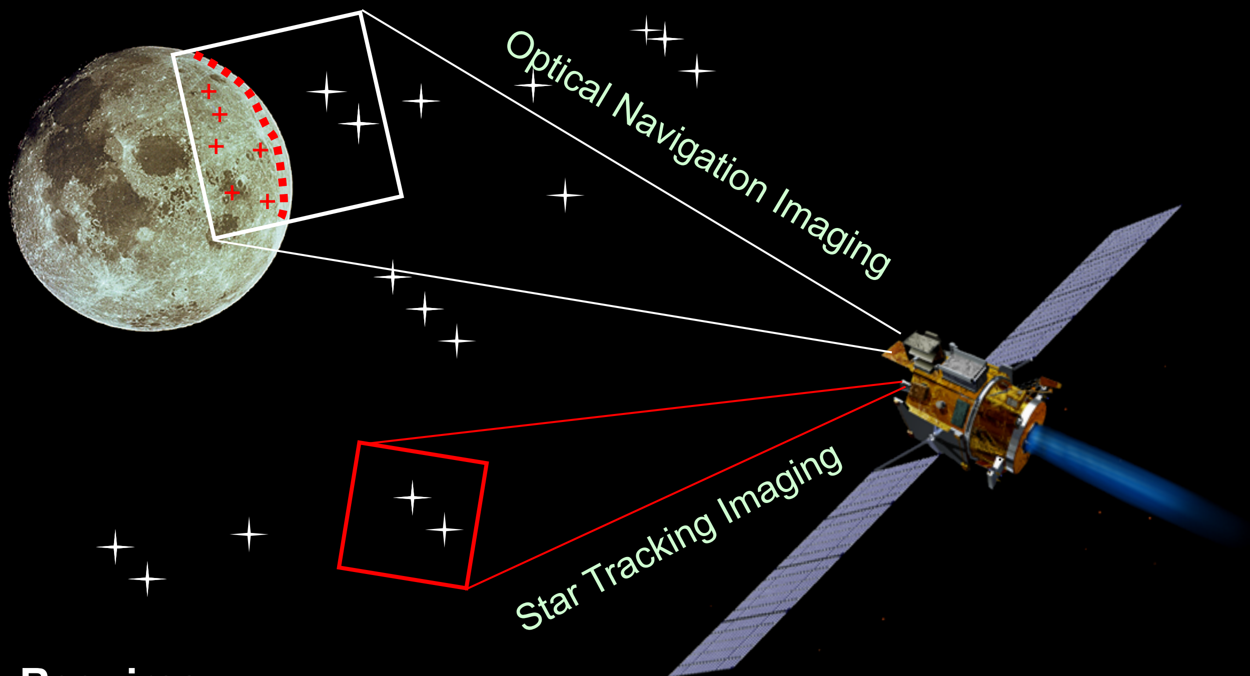
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Navigation Measurements



What is Optical Navigation?

Vital for objects with uncertain positions or autonomous operations.



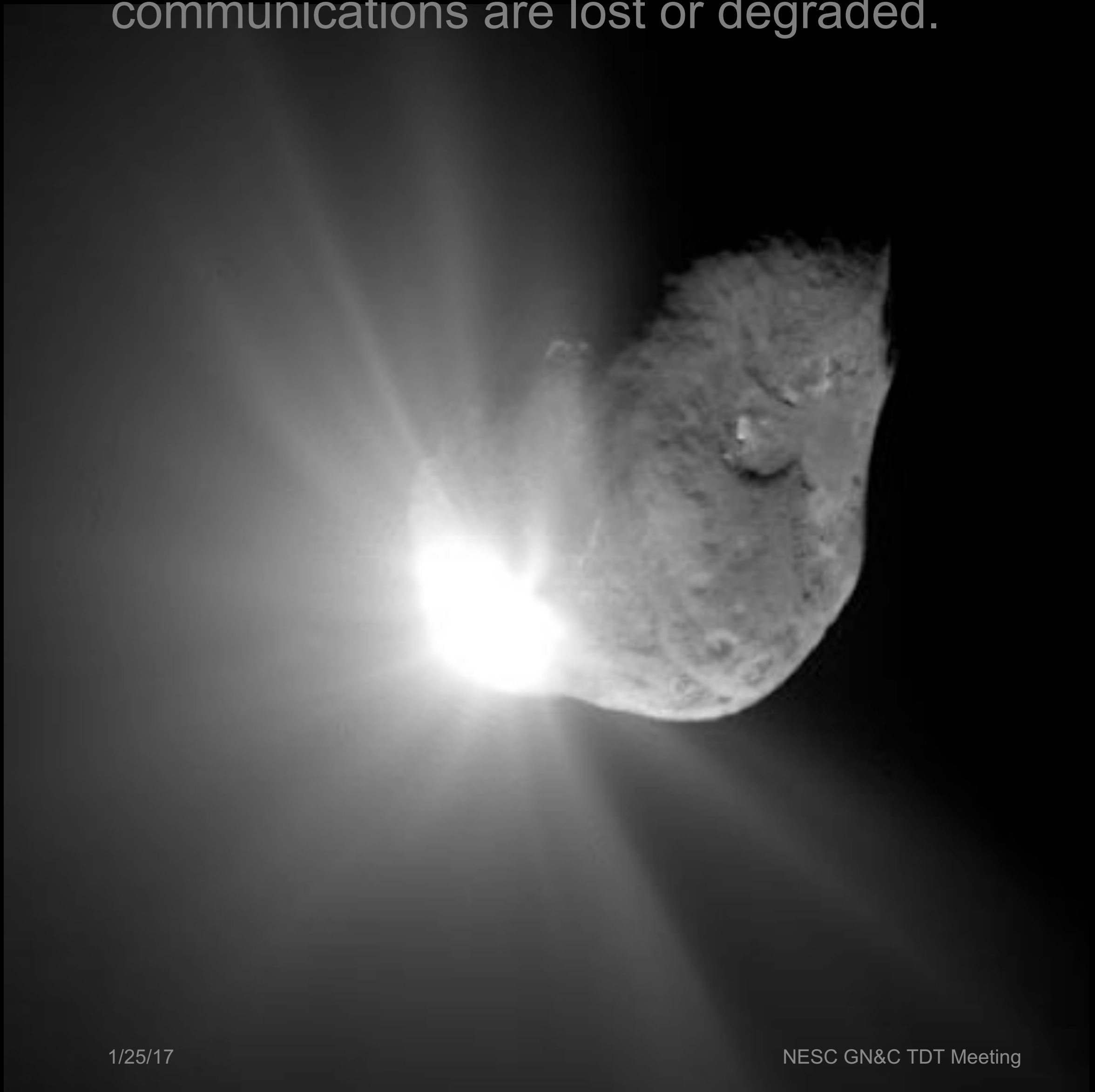
Determining the location of a near-field object (e.g. the Moon) relative to a well-known far-field object (e.g. the background starfield) or relative to well known camera attitude.

Requires:

- Accurate star catalogs, and physical body models, including landmarks.
- Accurate camera calibrations including geometric distortions and photometric modeling.
- Astrometric-quality imaging systems (often) with high-dynamic range.
- Filtering and estimation of optical-relevant parameters with s/c position and attitude.
- Ground-based Optical Navigation processing is very similar to radiometric ground processing - with the addition of (sometimes difficult and labor-intensive) image processing.

AutoNav

Enabling for high speed encounters or for contingencies where radio communications are lost or degraded.



On July 4, 2005, AutoNav enabled the third of NASA's first three comet nuclei missions DeepImpact at Templ1 (left); the other two being:

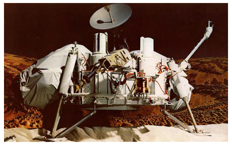
Borrelly, Sept 2001, and Wild 2, Nov. 2002, both also captured with AutoNav. These were followed by Hartley2 in 2010, and a Tempel 1 revisit in 2011.

AutoNav placed optical navigation elements onboard for otherwise impossible speedy turn-around of navigation operations.

MONTE

THE NEXT GENERATION OF MISSION DESIGN & NAVIGATION SOFTWARE

William Taber
Scott Evans



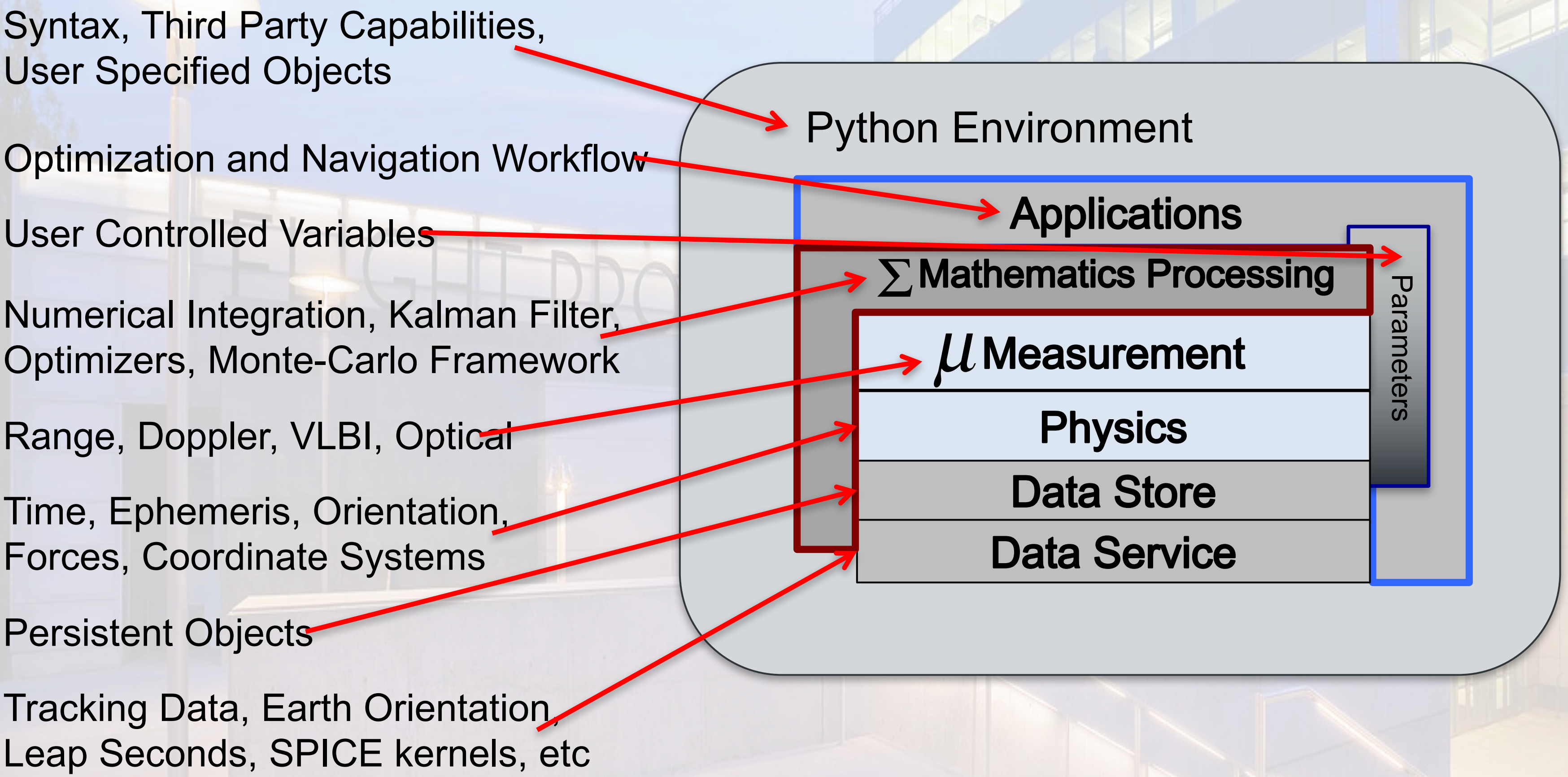
Replacing a Legacy


- MONTE
  - Mission Analysis, Operations and Navigation Toolkit Environment
  - Developed to modernize, upgrade, unify JPL's navigation, maneuver, and mission design software (DPTRAJ/ODP/MASL)
    - Software developed beginning in the '60s with over 30 years of proven track record
  - Goals
    - Exploit advances in computational technology
    - Retire risk associated with old technology
    - Free ourselves from the constraints of the old technology
      - Use OO, modern development processes, modern development tools.
  - MONTE has achieved these goals and today is JPL's premier navigation and mission design software.

Development Considerations

- Modern open standard OO language
  - C++ provides compiled OO with benefits of C
- Exploit Open Source
- A scriptable toolbox OO interface
  - Python to present user connection to C++
    - Extensible, worldwide open source community, platform independent
- Strong balance development process
  - CMMI maturity level 3
  - Development team was JPL’s pathfinder in CMMI

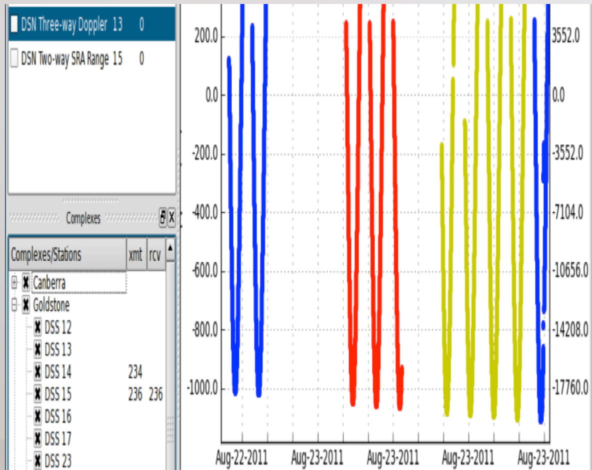
MONTE Architecture



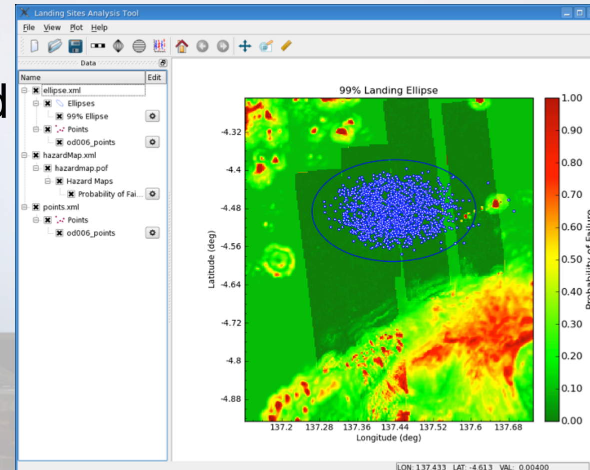
Applications

- Users need high level capabilities for graphical manipulation and to provide common scriptable workflows.
  - UI system (User Interface)
  - Multi-leg Trajectory Optimization
  - Trajectory Differential Corrector
  - Access to the Horizons Small Body Ephemeris System

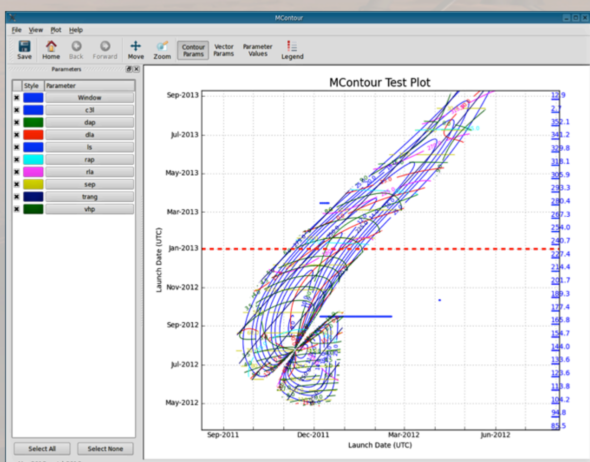
Applications



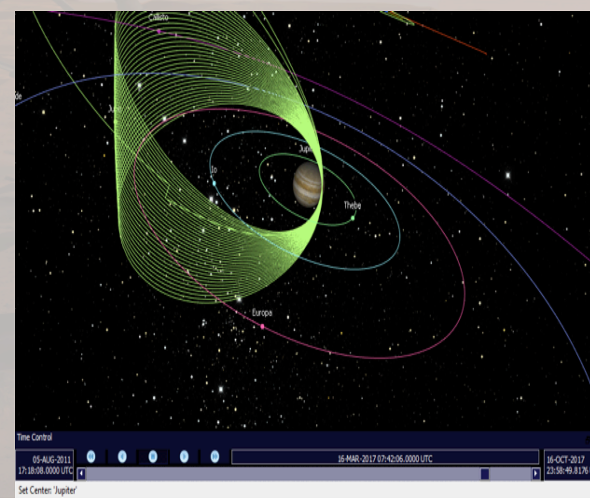
Residual viewing and editing



Landing site statistical hazard avoidance



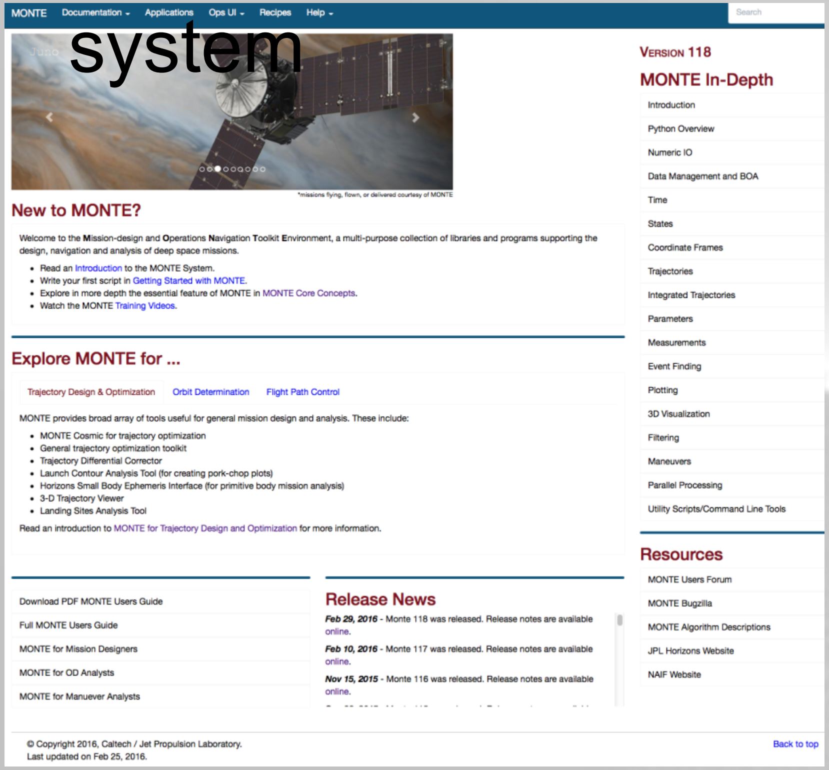
Launch contour analysis



3-D rendering and analysis

MONTE Ecosystem

- Documentation
  - Documentation cross-linked, web-based system



MONTE Ecosystem

- Documentation
  - Tutorials
  - User Guides
  - Tested Examples
  - Videos

```
( inside the DivaPropagator definition )

# First create the integration state, and set parameters to user-defined
# or default values. The actual state to be propagated will be added at
# a later time.
istate = M.IntegSetup( boa )
istate.setStateTol( StateTol )
istate.setMassTol( MassTol )
istate.setFrameTol( FrameTol )
istate.setTimeTol( TimeTol )
istate.setUserTol( UserTol )
istate.setPartialTolScale( PartialTolScale )
istate.setTimeFrame( IntegTimeFrame )
istate.setResetStm( ResetStm )
istate.setStateForces( Forces )

# Create the propagator with the empty state, and set tolerances.
obj = M.DivaPropagator( boa, Name, istate )
obj.setMinStep( MinStep )
obj.setMaxStep( MaxStep )
obj.setRelativeParTol( RelativeParTol )
obj.setCacheSize( CacheSize )
obj.setDiffLinesPerLeg( DiffLinesPerLeg )
```

– Most text/equations are embedded in the source code where the capability is implemented
– Complete doc strings in Python interface.

MONTE Ecosystem

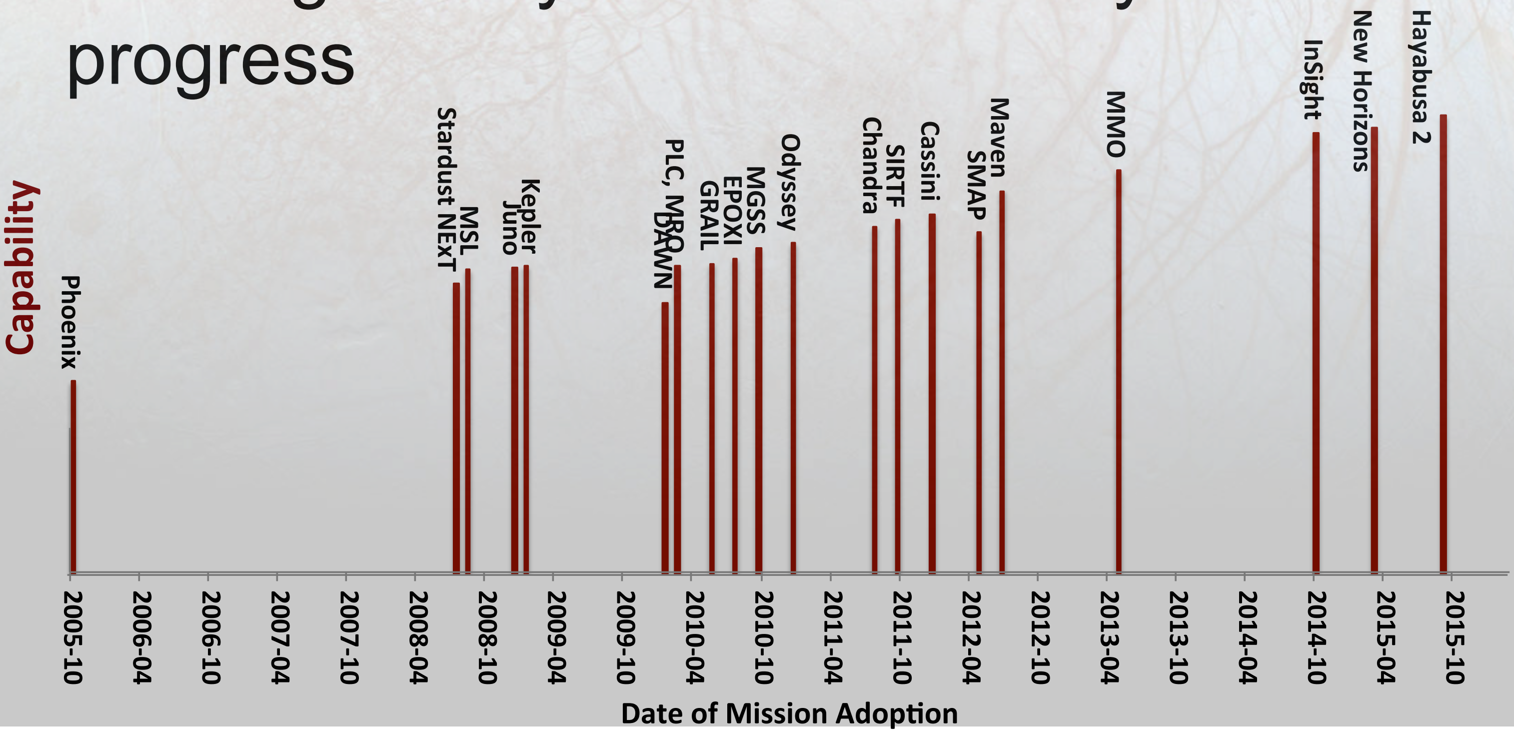
- Process
  - Unit Test Requirements
    - All functions require testing
    - Code coverage
    - All tests configuration managed
  - Style Requirements
  - Defect Tracking
    - Bugzilla
  - Software Metrics
  - Daily Clean Night Build and Test
  - Defined Release Process
  - Defined Scope Management Process
  - Stakeholder Communications
    - Bulletin Boards
    - Participation in bi-weekly Mission Designer and Navigator Meetings

Getting It Right

- Test System
  - Testing is extensive
    - 700 ksloc deliverable
    - 1400 ksloc of test code
  - User design/developer implemented system tests
- Where capabilities overlap round-off agreement with legacy software
- User testing of new features that are then incorporated into the system tests
- Defect response
  - Write a test that demonstrates the problem
  - Fix the code, see that that test passes
  - Run all regression tests

Operations and Adoption

- Adoption by mission required a push by management
  - Meetings every 2 weeks to analyze progress



New MONTE Sharing Model

- **While the JPL MD/Nav section continues to provide Navigation operations services for external collaborations, the MONTE software has matured to a point that it is now available externally to other US Government entities.**
- **An executable version is recommended to ensure proper build and installation; however, source code is available if necessary.**
- **Release to universities and commercial users will be evaluated on a case-by-case basis in close coordination with Caltech's commercialization and Intellectual Property (IP) protection offices.**
- **It is expected that AMMOS/MGSS will continue to provide software repair and sustaining support. Future year MGSS funding requests will be augmented by the amount of external support realized.**
- **Flight project specific enhancements will, in general, be the responsibility of the requesting flight project. Coordination with MGSS will be considered along with schedule needs to address these enhancements.**

MONTE Export Restrictions

- **Since September 2015, MONTE is no longer restricted under ITAR.**
- **The Department of Commerce has designated MONTE as EAR-9D515. To allow for unrestricted use, a "Design" version of MONTE is available that carries the EAR-99 classification.**
- **The "Design" version eliminates operational measurement processing. However, simulated measurement capabilities are retained.**
- **The "Design" version is targeted for classroom use and other situations that pose difficult access management.**
- **US Government entities can obtain the complete MONTE**
  - **To obtain contact Bill Taber William.Taber@jpl.nasa.gov or Joe Guinn Joseph.Guinn@jpl.nasa.gov**

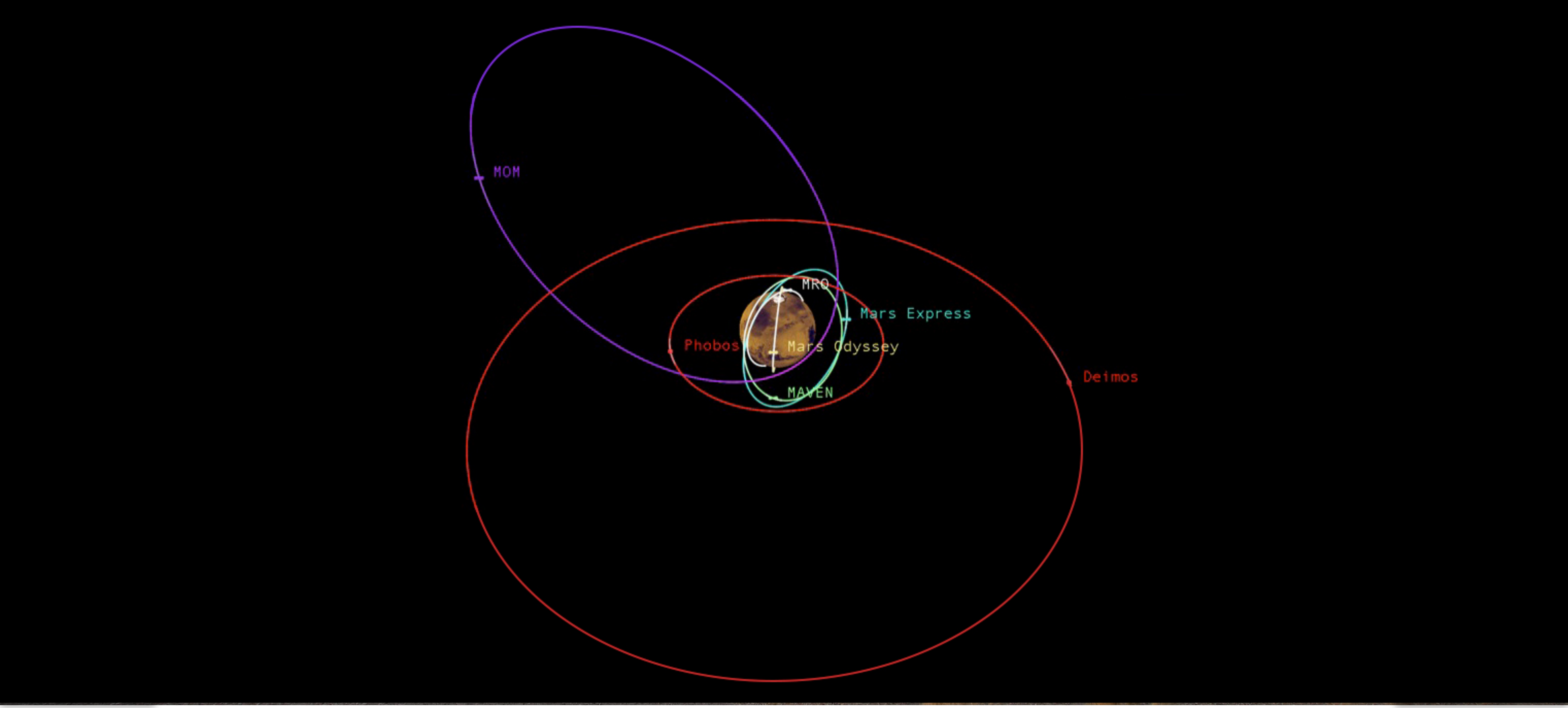
Summary

- Since 2001, the Mission Design and Navigation (MD/Nav) section at JPL has developed the MONTE (Mission-analysis, Operations and Navigation Toolkit Environment) ground software.

- Since 2012, all JPL supported flight projects have transitioned to using MONTE. Currently, this includes more than a dozen active deep space and Earth orbiter missions and many flight projects in pre-launch development.

- MONTE was jointly funded by NASA's Science Mission Directorate under the Multi-mission Ground System and Services (MGSS) Program Office and by JPL flight projects.

- At the end of fiscal year 2016, a five-year enhancement effort funded by MGSS concluded. At that time MONTE achieved a sufficient level of maturity in test validation and verification, documentation and flight performance to safely offer externally.



An Updated Process for Automated Deepspace Conjunction Assessment

Zahi Tarzi, David Berry, Ralph Roncoli

Jet Propulsion Laboratory
California Institute of Technology

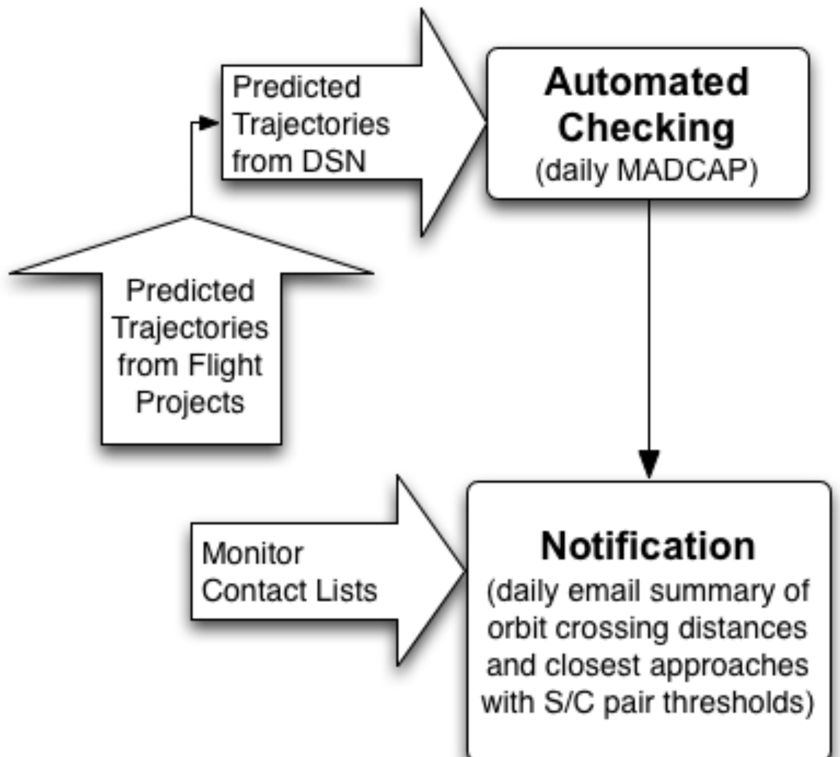
25th International Symposium on Space Flight Dynamics
October 19-23, 2015 Munich, Germany

Introduction

- There is currently a high level of interest in conjunction assessment in the Earth orbital environment.
- Several of the world's space agencies have satellites in orbit around Mars and the Moon with additional future missions planned.
- Although the number of spacecraft in these environments is small:
  - Missions designed for scientific sensing or communication relay purposes tend to have similar orbital characteristics.
  - The small number of assets makes the costs of collisions extremely high with respect to lost science capability.
- The Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) is currently used at the Jet Propulsion Laboratory for NASA to perform conjunction assessment at Mars and the Moon.
- This process will be described and the generated reports will be explained.
- Special cases and events are described which have driven the improvement of the software and continue to spur future enhancements.

Conjunction Assessment Process

Overview



Conjunction Assessment Process

Input Parameters

Environment: Central Body, Coordinate System

Bodies and Ephemerides: List of the Bodies to be analyzed and ephemeris files to be used

↓

- Primary file can be local file or the latest predicts grade file available on the Deep Space Network's (DSN) Service Preparation System (SPS) Portal.
- Secondary file can be specified to be used in addition to primary. Can be a local file or the latest scheduling grade file available on the DSN SPS

Conjunction Assessment Process

Input Parameters

Environment: Central Body, Coordinate System

Bodies and Ephemerides: List of the Bodies to be analyzed and ephemeris files to be used

Thresholds List of thresholds to be used to create the Summary Report and decide whether to send out ancillary data reports.

- "Red Event" Thresholds - significant, near-term conjunction events
  - Based on covariance data if available in ephemeris file.
  - Otherwise based on quadratic fit of 3σ values as a function of time to the event.
- "All Event" Thresholds - all notable events in the interval analyzed.
- Ancillary Data thresholds - establish when to send out ancillary data reports.
- Unique thresholds are specified for each spacecraft, the larger of the pair analyzed is used.

Conjunction Assessment Process

Input Parameters

Environment: Central Body, Coordinate System.

Bodies and Ephemerides: List of the Bodies to be analyzed and ephemeris files to be used.

Thresholds List of thresholds to be used to create the Summary Report and decide whether to send out ancillary data reports.

Data Analysis Options: Specifications of what data will be printed in tables and plots and how they will be formatted.

Directories: Locations of input files and output files.

Email Lists: Various email lists specifying who will receive Summary Reports, and Ancillary Data Reports.

Conjunction Assessment Process

Analysis

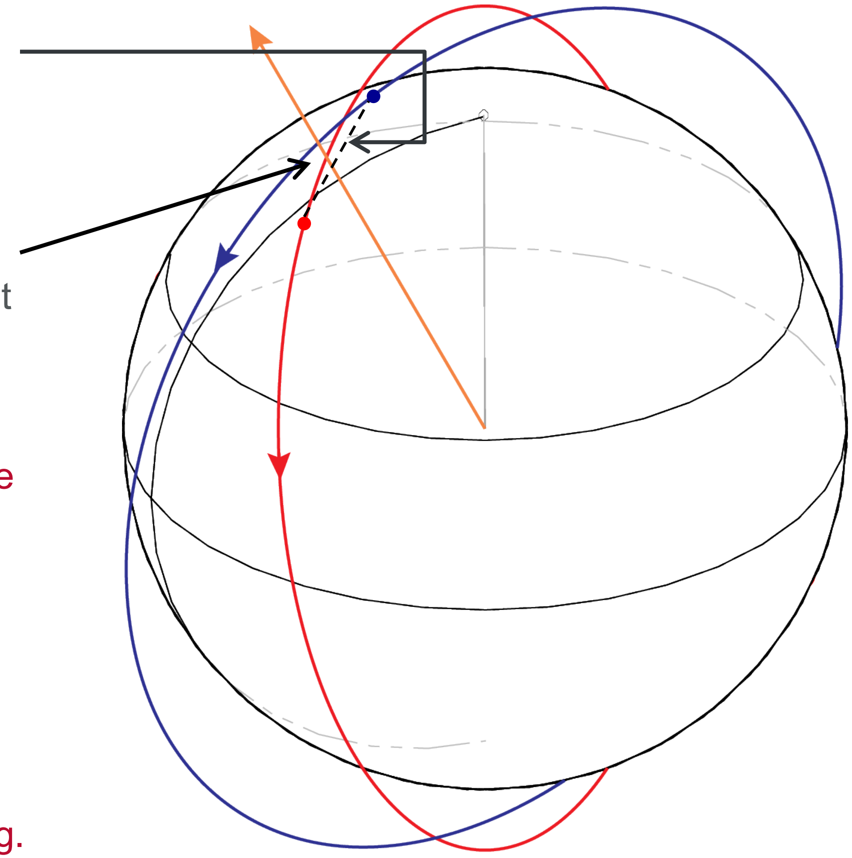
MADCAP performs pairwise comparisons of the ephemerides of the spacecraft listed in the parameter file.

A search is conducted for local minimum relative distances between the two spacecraft analyzed; each relative minimum is considered a “Close Approach Event”.

Times of the events and various orbit attributes are printed to tables. A few of the most used attributes are explained on the next slide.

Conjunction Assessment Process

Analysis



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.

- Convention: Positive if the orbit crossing altitude of the first spacecraft is larger than the orbit crossing altitude of the second spacecraft.

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

- Convention: Time first body is at the crossing minus the time second body is at the crossing.

"First" and "second" refer to the order they are listed in their pairings in the summary report.

Conjunction Assessment Process

Outputs

Summary Report: Sent out in the body of an email to a wide distribution to inform recipients of any noteworthy upcoming conjunction events at the body analyzed.

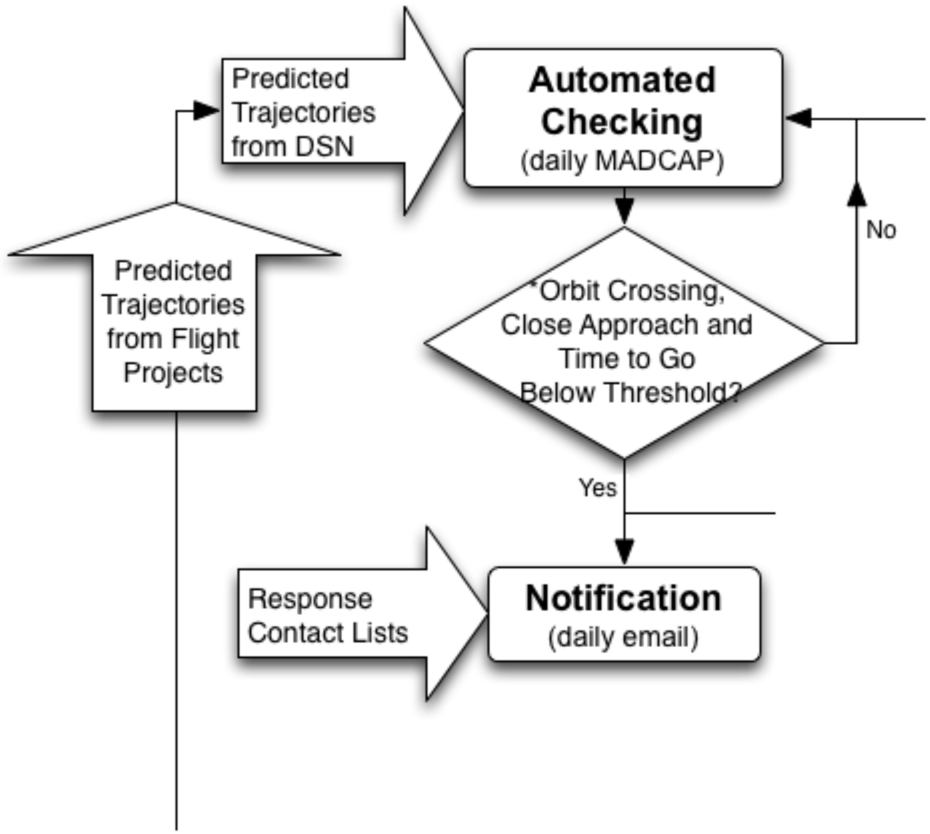
Ancillary Data Table: Sent out as an attachment in the Ancillary Data Email if specified thresholds are met. Lists requested conjunction attributes for the time analyzed.

Ancillary Data Plot Sent out as an attachment in the Ancillary Data Email if specified thresholds are met. Displays CAD and OXD over the time analyzed.

Examples of these output products are presented in later slides.

Conjunction Assessment Process

Response Flow



Summary Report Example - Mars

Time and Bodies

```
Analysis Time: 2015-09-01 17:52:47 UTC
```

→ Time the analysis was performed

Conjunction Assessment Bodies and Types

Body	Name	Type
1	Odyssey	Active
1r	Odyssey	Active/Reference
2	Mars_Express	Active
2r	Mars_Express	Active/Reference
3	MRO	Active
4	MAVEN	Active
5	MOM	Active
6	Phobos	Natural
7	Deimos	Natural
8	MGS	Inactive

Each body "type" is listed:

- Active: operational spacecraft
- Natural: natural space bodies
- Inactive: non-operational spacecraft

Each body is uniquely identified by a body ID number

- "r" stands for reference file
- "a" stands for additional file

Summary Report Example - Mars

Red and All Tables

Red (Conjunction Data < 'Red' Thresholds and Event < 14 days from Analysis Time)

Bodies	OXD value/limit (km)	OXT value/limit (sec)	CAD value/limit (km)	CA Epoch (UTC-SCET)
3-4	4.7 7.6 4P	1676.0 1764.7 4P	897.3 ----- --	2015-09-02 04:09:43

Value Threshold Source
C-Covariance
P-Polynomial

Value No Threshold

Time at Closest Approach

All (Conjunction Data < 'All' Thresholds for all time considered)

Bodies	OXD (km)	OXT (sec)	CAD (km)	CA Epoch (UTC-SCET)
3-4	4.7	1676.0	897.3	2015-09-02 04:09:43
1-5	17.8	30.4	86.3	2015-09-23 01:15:31
1r-5	17.8	30.4	86.3	2015-09-23 01:15:31
3-4	9.6	-2754.4	2821.9	2015-09-26 19:39:01
3-4	6.4	1083.7	1486.8	2015-09-27 00:40:44

Value (constant threshold not listed here)

Value (no threshold)

Value (constant threshold not listed here)

Summary Report Example - Mars

Red Thresholds

Red Thresholds -- Polynomial Coefficients

Body	Name	OXD0 (km)	OXD1 (km/t)	OXD2 (km/t^2)	OXT0 (sec)	OXT1 (sec/t)	OXT2 (sec/t^2)
1	Odyssey	0.0009	0.0013	0.0000	0.0705	-0.0411	0.0096
2	Mars_Express	1.0000	0.0000	0.0000	3000.0000	0.0000	0.0000
3	MRO	0.0877	-0.0315	0.0040	0.0100	0.4939	0.0765
4	MAVEN	6.0000	1.5000	0.0326	1.0000	600.0000	1000.0000
5	MOM	0.2498	0.0014	0.0012	0.0100	33.0089	0.3246
6	Phobos	30.0000	0.0000	0.0000	15.0000	0.0000	0.0000
7	Deimos	40.0000	0.0000	0.0000	20.0000	0.0000	0.0000

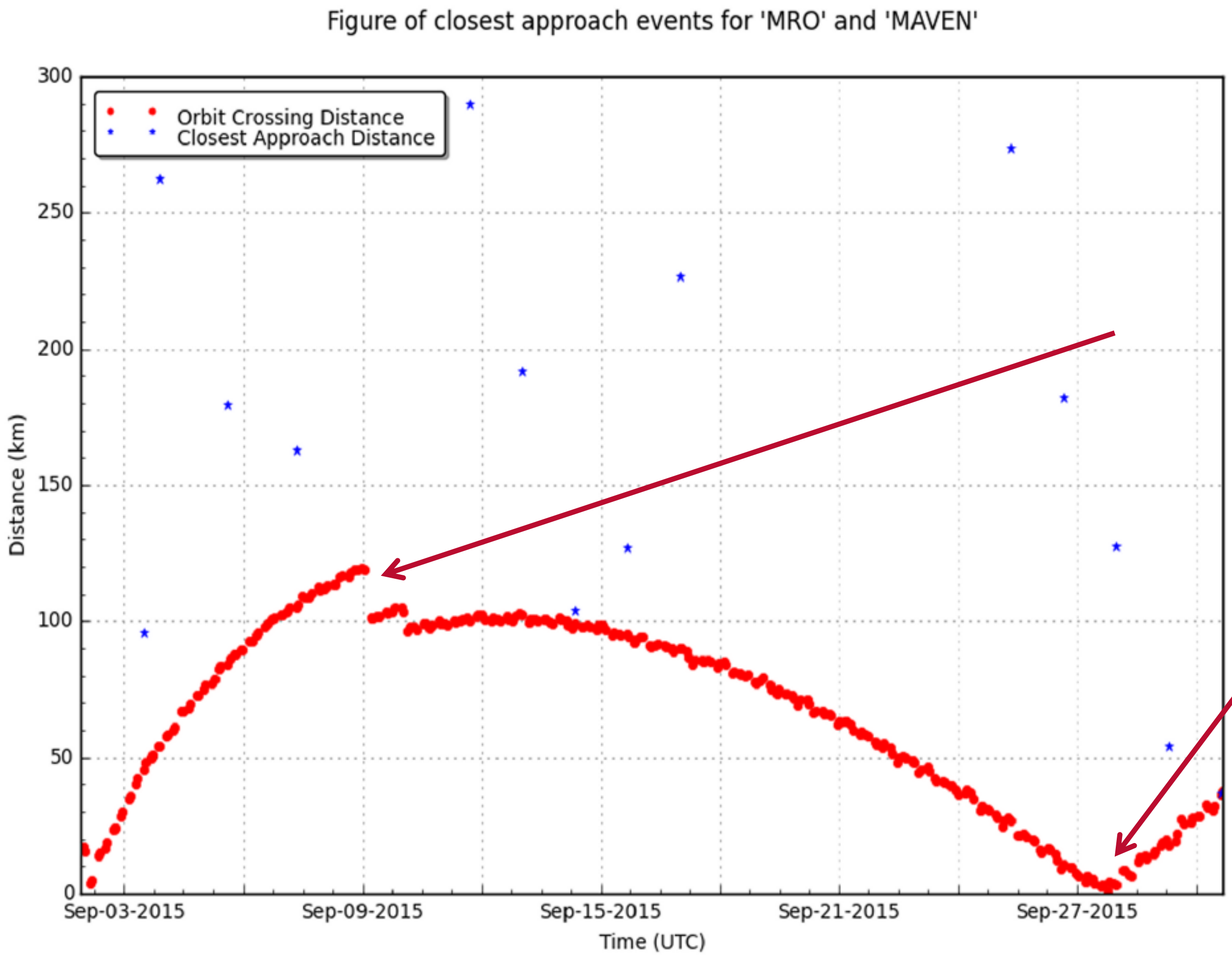
Red OX Distance Threshold (t) = OXD0 + (OXD1 * t) + (OXD2 * t^2)
Red OX Timing Threshold (t) = OXT0 + (OXT1 * t) + (OXT2 * t^2)
where t = CA Epoch - Ephemeris File Submit Time (in days)

Submit time to Deep Space Network's (DSN) Service Preparation System (SPS) Portal
(good general approximation of data cutoff time which is not available in ephemeris file)

Red thresholds are based on 3-sigma values. Thresholds listed as "P" are based on a quadratic fit of the 3-sigma values as a function of time to the event. The polynomial coefficients used are listed in the table above. Thresholds listed as "C" are based on 3-sigma covariance data provided by the mission.

Ancillary Plot Example

MRO-MAVEN



Discontinuities in Orbit Crossing Distance show effect of planned maneuvers

Upcoming times of orbit closeness are much easier to discern via MADCAP plots

Special Cases

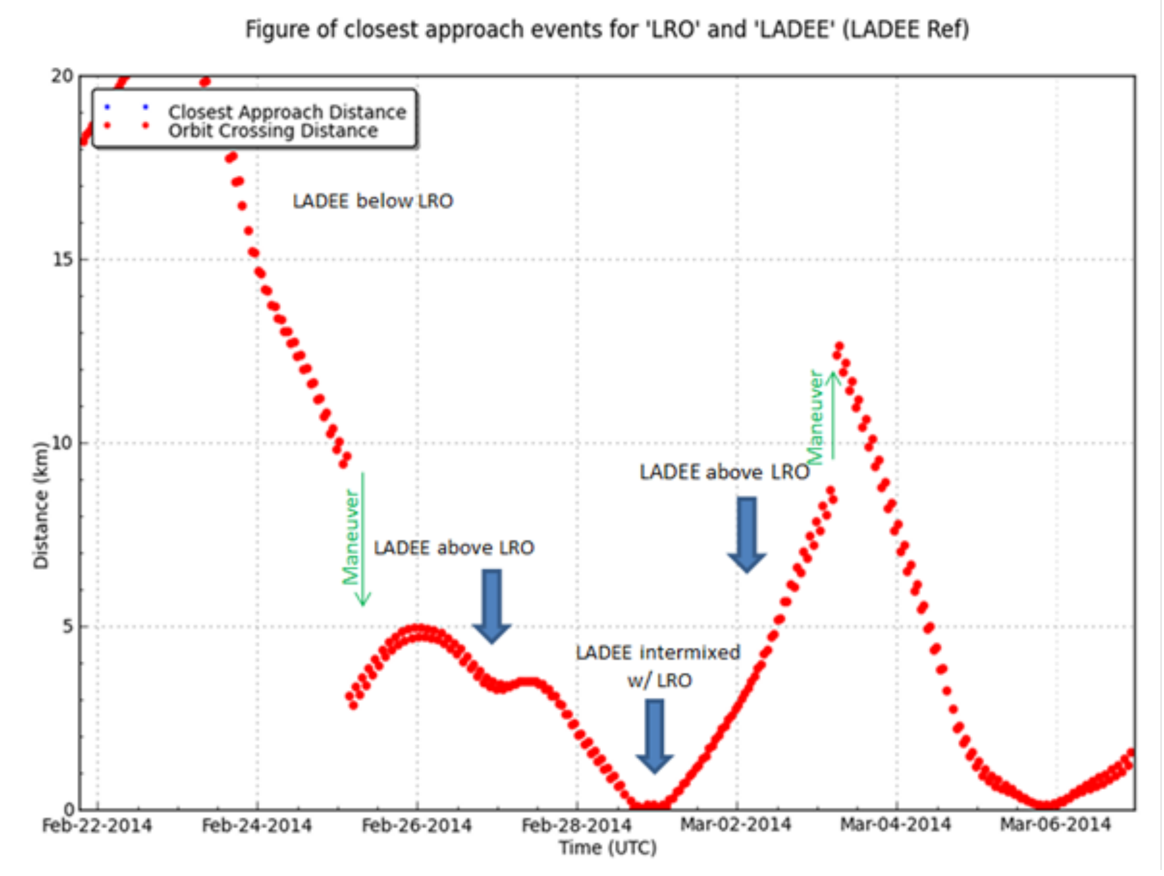
Supporting Collision Avoidance Maneuver Studies

In February of 2014, MADCAP showed OXD for LRO-LADEE pair would be less than 1 km for a few orbits.

LADEE navigation team designed several maneuvers to increase OXD.

Special MADCAP runs were conducted to test the impact of these maneuvers.

They did not yield desired results of increasing OXD for entire period of interest and across LADEE's maneuver dispersions.



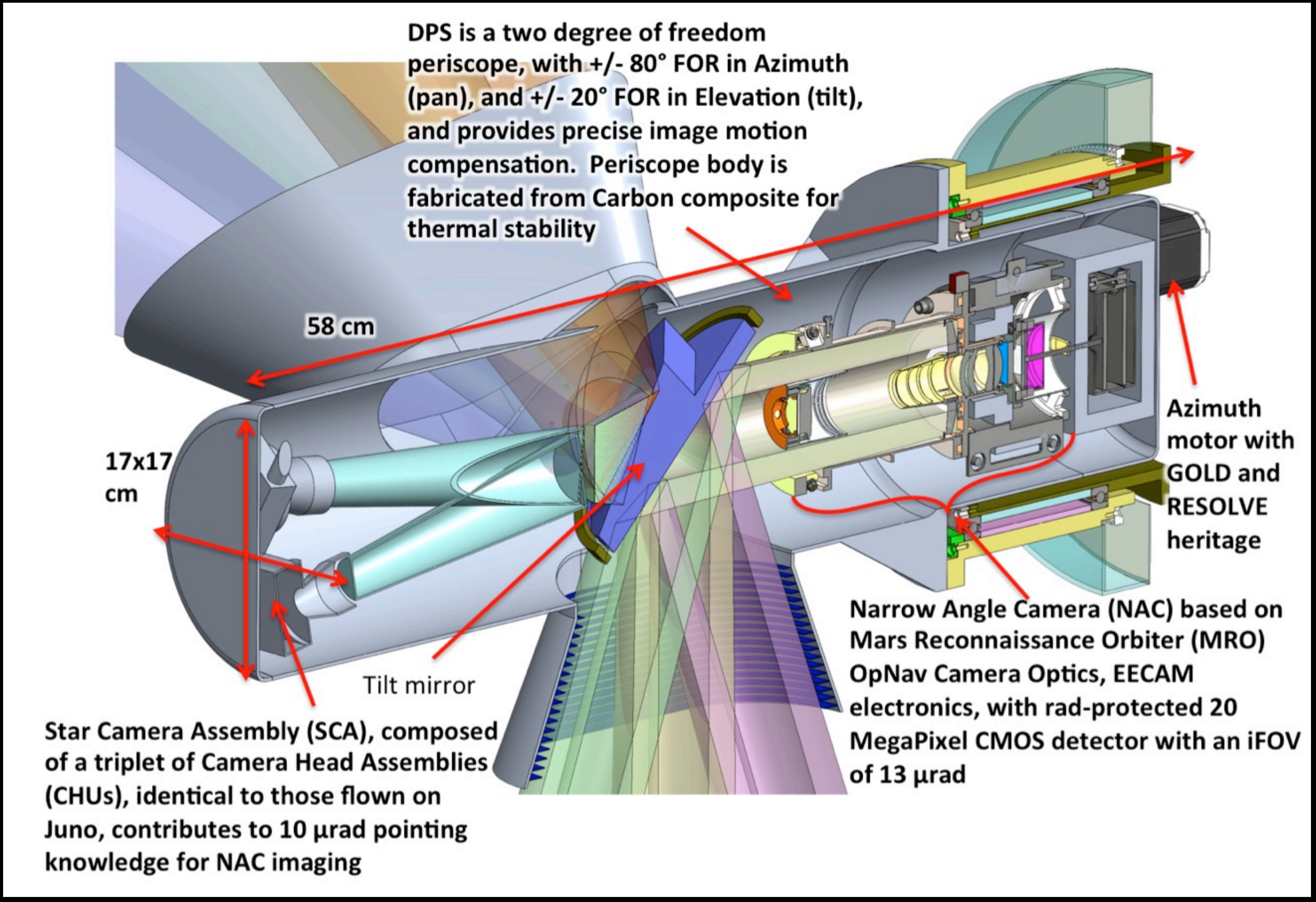
Future Work

- Integrated 3D visualization of conjunction in reporting
- Calculation and reporting of collision probability
- Including Inactive Spacecraft in Summary Report
- Automated special runs to support conjunction responses

Jet Propulsion Laboratory
California Institute of Technology

Backup Slides

Deep Space Positioning System (DPS) Concept



Collaboration with NASA/JPL MD/Nav

Five Benefits:

1. **Leverage decades of Deep Space development and operations experience**

2. **Deep bench of JPL personnel available to address surge needs and convey lessons learned**

3. **Mature tools and techniques:**
   – For design and flight of various mission types (landers, orbiters, impactors and flyby vehicles)
   – For incorporating DSN and onboard measurements (Doppler, Ranging, ∆DOR, OpNav, AutoNav, GPS)
   – For high precision trajectory reconstruction, prediction and optimal targeting

4. **Significant automation built into JPL tools enabling efficient use of workforce and cost competitive services**

5. **Future Robotic/Human mission interoperability – Not necessary to reproduce existing NASA/JPL capabilities.**

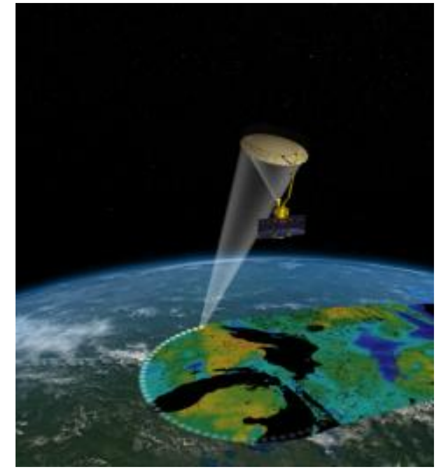
Selected Recent Accomplishments

NASA/JPL Missions

Cassini

Dawn

Juno

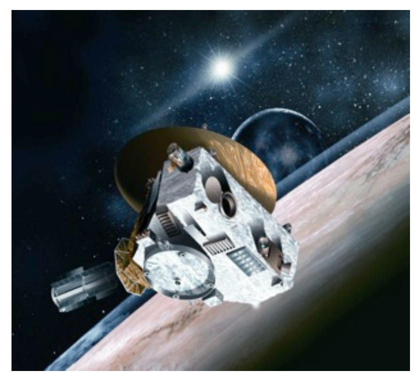


Soil Moisture Active Passive (SMAP)

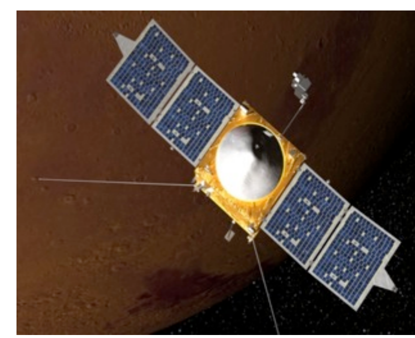
Partnership Missions

JAXA Hayabusa-2 Asteroid Sample Return

ESA Rosetta Comet Rendezvous/Landing



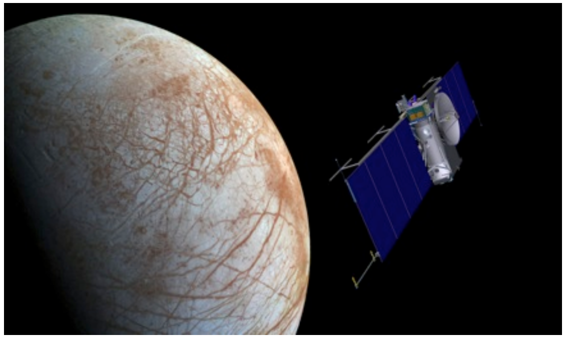
APL New Horizons Pluto



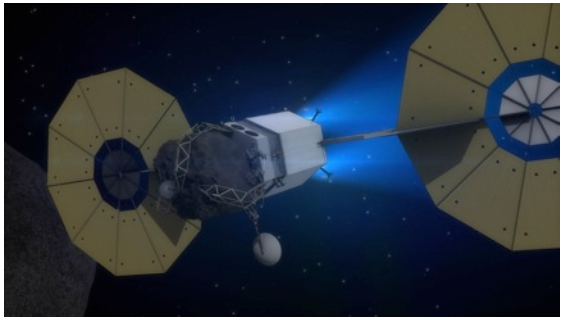
GSFC Maven Mars Orbiter

Selected Coming Attractions

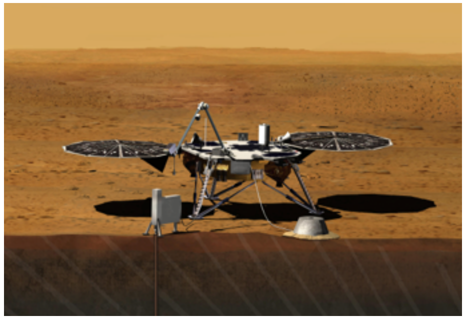
NASA/JPL Missions



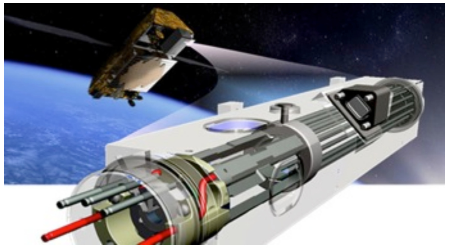
Europa Mission (+Lander?)



Asteroid Robotic Redirect Mission (ARRM)



InSight



Deep Space Atomic Clock

Partnership Missions

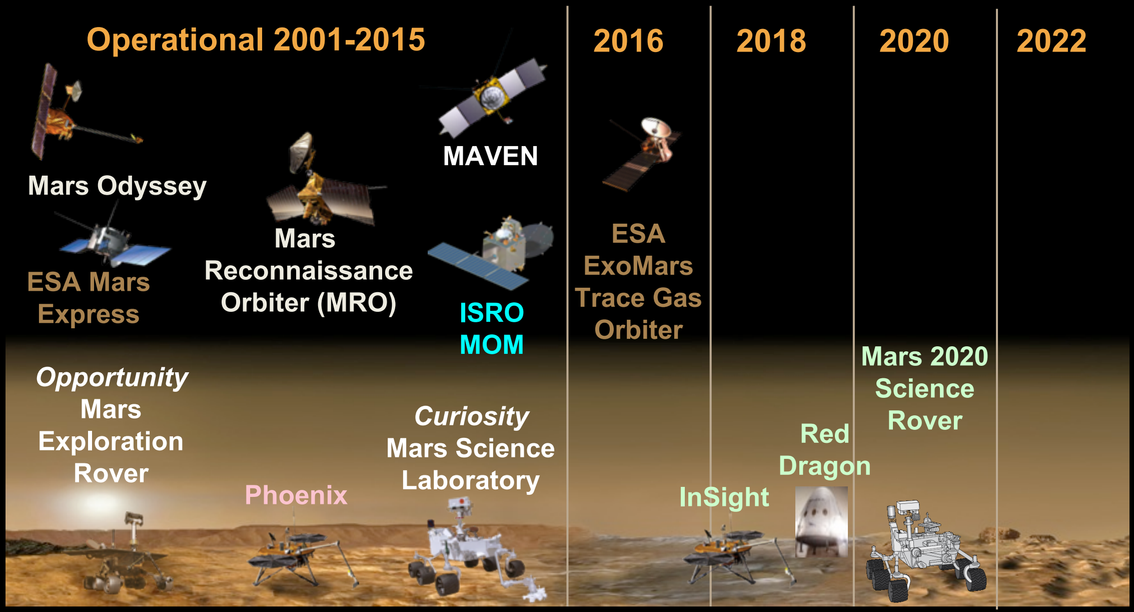
SpaceX Technology Demonstration (Mars EDL)

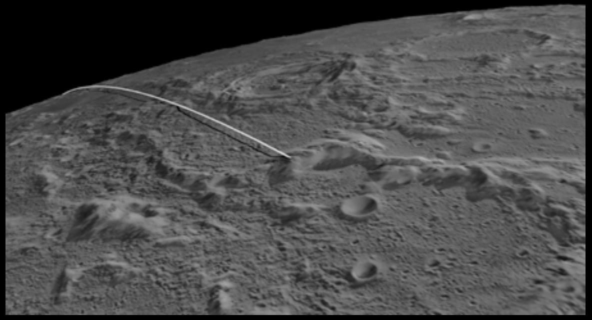
OSIRIS-REx

SLS EM-1

Pre-Decisional Information -- For Planning and Discussion Purposes Only

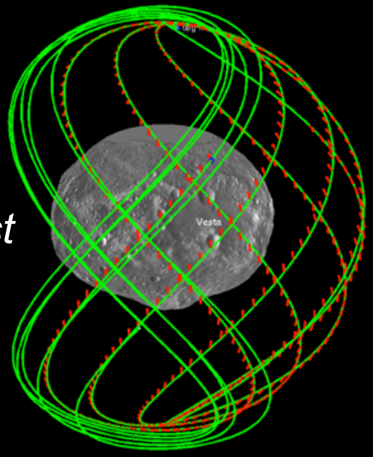
Mars, Lunar and Small Body Experience





GRAIL: Dual Spacecraft Formation (2011-2012)

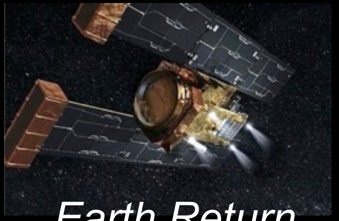
Dawn: Low Thrust Asteroid Orbiter



Deep Impact: Comet Tempel 1 Impactor (2005)

Re-Purposed as EPOXI: Hartley 2 Flyby (2010)

Stardust: Comet Coma Sample Return



Earth Return (2006)

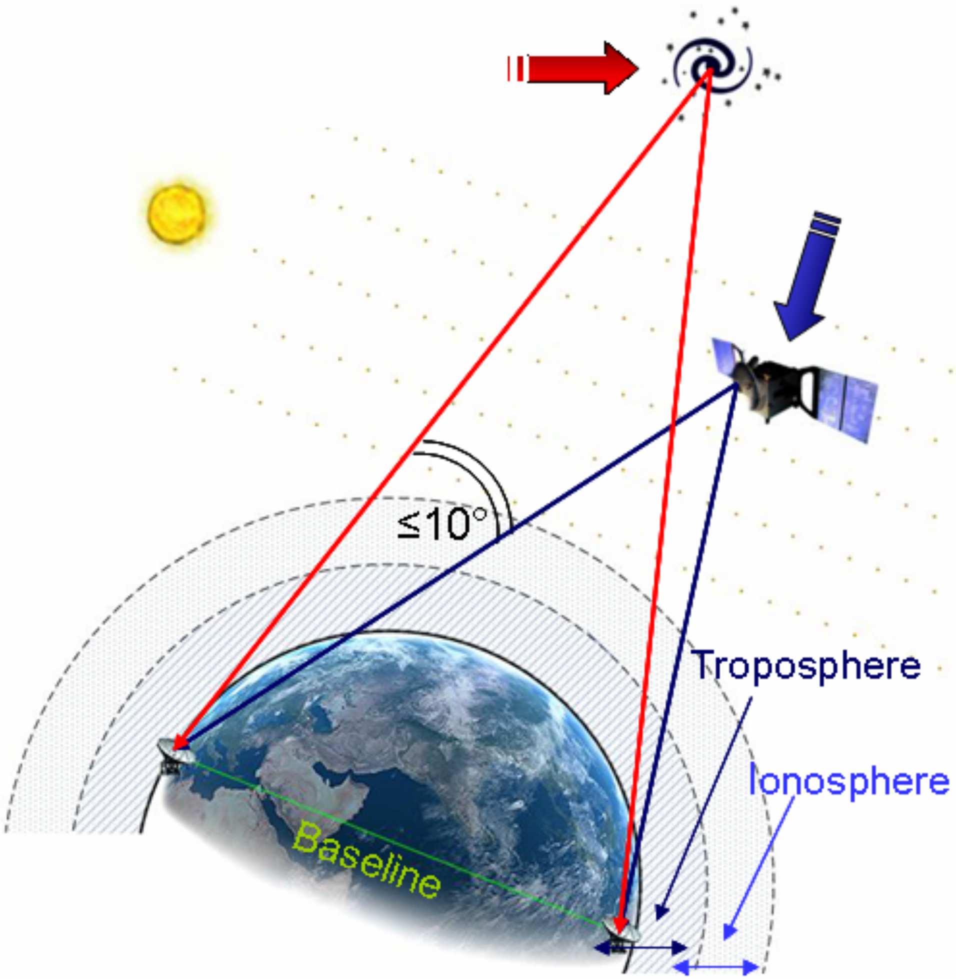
ΔDOR (Delta-Differential One-Way Range)

Essential Beyond Lunar Orbit

ΔDOR provides
Plane-of-Sky Information

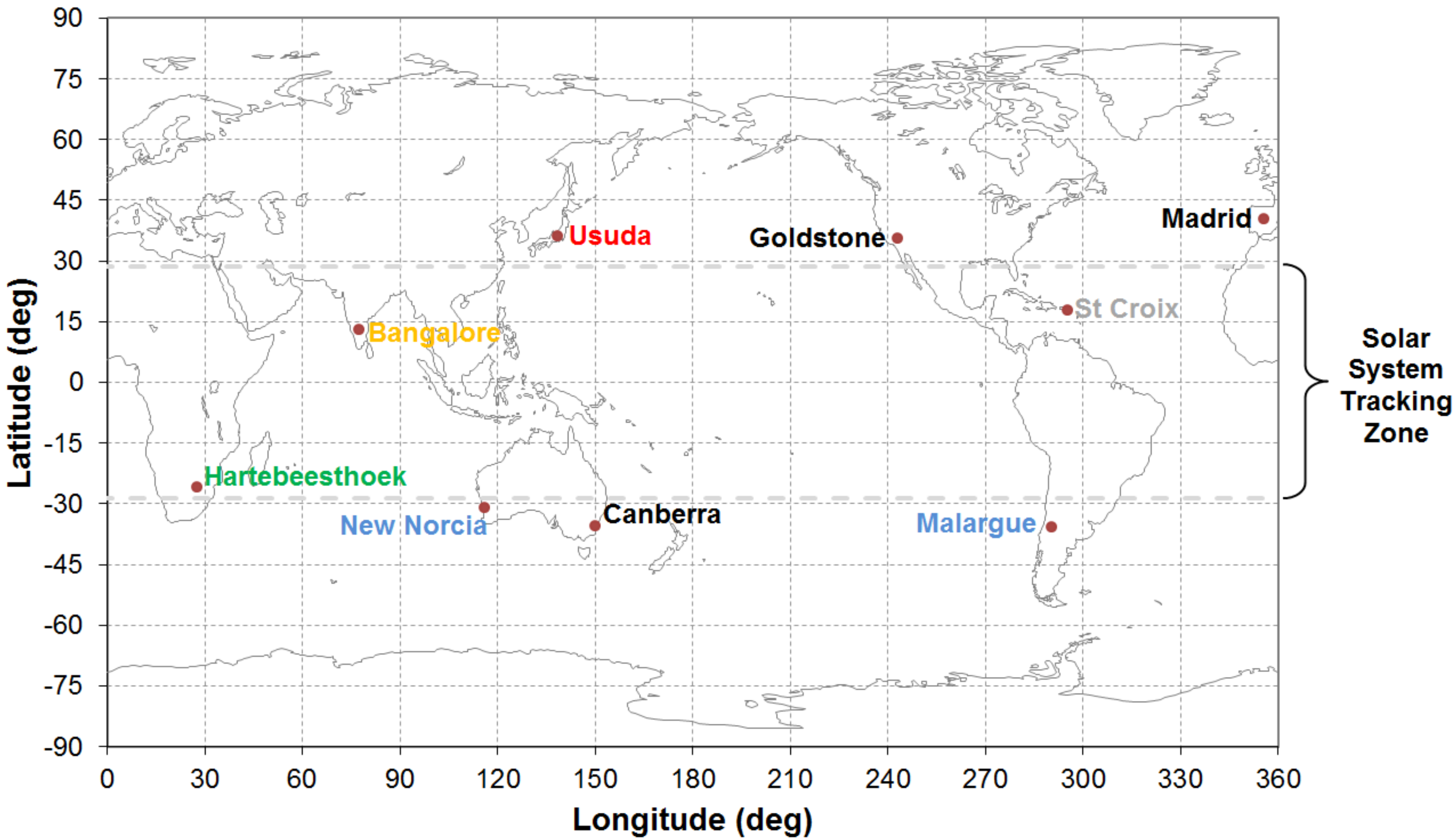
Complementary to
Line-of-Sight from
Doppler & Range

Optical analogy is called
"Optical Astrometry".
Uses star catalog instead
of quasars.



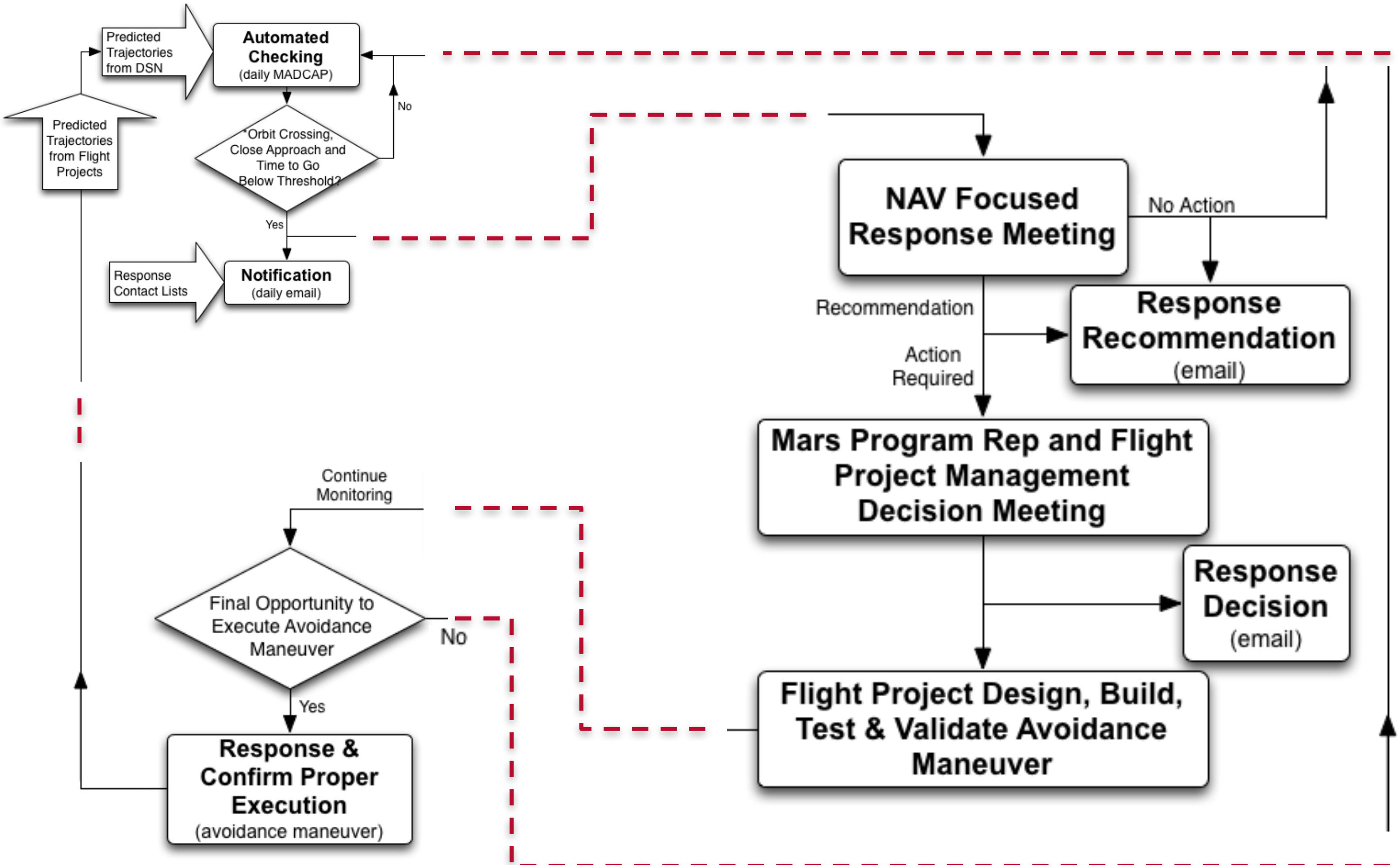
Deep Space Tracking Stations

NASA and non-NASA (CCSDS Tracking Data Exchanges In Place)



Conjunction Assessment Process

Response Flow



Summary Report Example - Mars

Notes

Notes

OXD means "Orbit Crossing Distance". OXT means "Orbit Crossing Timing". CAD means "Close Approach Distance".

Data for active spacecraft and natural bodies are displayed in the tables above. Data for inactive spacecraft are not displayed, but they are available in the conjunction metric tables and plots, which have been stored in the output directory listed below. Data for reference trajectories are not considered for Red events, but are considered in the All section. Reference trajectories use the same thresholds as the nominal trajectories.

For more information, please see the point of contact listed below.

Analysis time:	2015-09-01 17:52:47 UTC
Active spacecraft:	Odyssey, Mars Express, MRO, MAVEN, MOM
Natural bodies:	Phobos, Deimos
Inactive spacecraft:	MGS
Output directory:	/nav/home/jplmdnav/MADCAP/Mars/archive
Point of contact:	MADCAP_Mars@jpl.nasa.gov

Summary Report Example - Mars

All Thresholds

All Thresholds -- Constants

All OX Distance Threshold = OXD

All CA Distance Threshold = CAD

Body	Name	OXD (km)	CAD (km)
1	Odyssey	10	100
2	Mars_Express	10	100
3	MRO	10	300
4	MAVEN	10	3000
5	MOM	20	100
6	Phobos	45	100
7	Deimos	60	200

Summary Report Example - Mars

Ephemerides

Ephemerides

Body	Ephemeris	Submitted	Begin	End
1	p_m_od60822-60824_61929_v1.bsp	2015-08-31 23:20:47 UTC	30-AUG-2015 19:28:51 UTC	29-NOV-2015 23:58:51 UTC
1r	p_m_od60822-60824_61929_v1.bsp_V0.1	Analysis Time	30-AUG-2015 19:28:51 UTC	29-NOV-2015 23:58:51 UTC
2	MOEM_150831OAS_PREDICT__0001.CR.bsp	2015-09-01 10:25:36 UTC	20-AUG-2015 23:56:29 UTC	22-SEP-2015 16:48:51 UTC
2r	MOEM_140303OAS_SCHED____0001.CR.bsp	2015-01-14 18:20:28 UTC	29-DEC-2013 07:09:00 UTC	31-DEC-2018 23:58:51 UTC
3	pf_psp_rec42582_42579_43435_p-v1.bsp	2015-08-27 16:28:29 UTC	27-AUG-2015 06:08:51 UTC	01-NOV-2015 23:58:51 UTC
4	trj_orb_01793-01794_01952_v1_mvn.bsp	2015-08-31 19:41:08 UTC	31-AUG-2015 13:03:51 UTC	30-SEP-2015 17:18:51 UTC
5	mom_spk_150823-150928_od299_v3_dsn.bsp	2015-08-31 19:47:49 UTC	23-AUG-2015 13:00:00 UTC	28-SEP-2015 12:00:00 UTC
6	mar097.2010-2029.bsp	Analysis Time	29-DEC-2009 23:58:53 UTC	01-JAN-2030 23:58:51 UTC
7	mar097.2010-2029.bsp	Analysis Time	29-DEC-2009 23:58:53 UTC	01-JAN-2030 23:58:51 UTC
8	p_141031-151031-061212_10yr_nominal.nio	Analysis Time	31-OCT-2014 05:28:52 UTC	31-OCT-2015 06:28:51 UTC

Ephemeris submit time to SPS

Local files, analysis time used for polynomial threshold calculation

Ephemeris files for the bodies analyzed are listed in the table above. Files which have been updated since the last run are marked with an "*" and colored blue.

Ancillary Table Example

MRO-MAVEN

```
# Table of closest approach events for 'MRO' and 'MAVEN'
# Begin Time:  24-AUG-2015 20:33:35.9162 UTC
# End   Time:  23-SEP-2015 10:58:51.8176 UTC
# Central Body:  Mars
# Coordinate System:  IAU Mars Pole
# Output Time System:  UTC    (UTC-ET =   -68.1827 sec [at begin time])
# Ephemeris files supplied by user:
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/de410_Mars.boa
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/p_m_od60649-60652_61771_v1.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/MOEM_150817OAS_PREDICT__0001.CR.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/pf_psp_rec42493_42490_43263_p-v1.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/trj_orb_01755-01756_01914_v1_mvn.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/mom_spk_150813-150916_od297_v1_dsn.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/mar097.2010-2029.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/mar097.2010-2029.bsp
#   /nav/home/jplmdnav/MADCAP/Mars/Ephemerides/p_141031-151031-061212_10yr_nominal.nio
#
#       Calendar              Julian           R E L A T I V E          Distance (km)          Minimum  Orbit  Crossing   T i m e s
#         Date              Date (days)     Distance (km)  Speed (km/s)   Min Crossing   MRO                        MAVEN                        Time Diff (s)
24-AUG-2015 20:38:38.019   2457259.36016      1797.36113      6.25271    99999999.000   24-AUG-2015 21:24:28.846   None                                     0
24-AUG-2015 21:34:26.963   2457259.39892      1357.26593      6.57642        -610.100   24-AUG-2015 22:19:56.019   24-AUG-2015 20:52:07.839           5268.18
24-AUG-2015 23:00:45.741   2457259.45886      6007.54936      4.92479       -3000.269   24-AUG-2015 23:16:32.831   24-AUG-2015 21:57:32.637           4740.19
25-AUG-2015 00:37:59.631   2457259.52638      4560.89264      5.24668        -592.039   25-AUG-2015 00:11:59.350   25-AUG-2015 01:30:05.160          -4685.81
25-AUG-2015 01:46:16.797   2457259.57381       738.10131      7.65703        -585.979   25-AUG-2015 02:04:08.845   25-AUG-2015 01:30:10.752           2038.09
25-AUG-2015 02:53:21.395   2457259.62039      4238.84423      5.27334       -3066.474   25-AUG-2015 03:00:42.186   25-AUG-2015 02:36:06.624           1475.56
25-AUG-2015 04:30:28.022   2457259.68782      6126.63705      4.92544    99999999.000   25-AUG-2015 04:52:48.468   None                                     0
25-AUG-2015 05:57:27.598   2457259.74824      1488.22072      6.42511        -562.349   25-AUG-2015 05:48:12.987   25-AUG-2015 06:08:07.443          -1194.46
25-AUG-2015 06:53:08.054   2457259.78690      1598.37287      6.39817        -554.944   25-AUG-2015 07:40:21.841   25-AUG-2015 06:08:09.716           5532.12
25-AUG-2015 08:21:08.971   2457259.84802      6104.78614      4.91050       -3130.449   25-AUG-2015 08:36:59.521   25-AUG-2015 07:14:36.546           4942.98
25-AUG-2015 09:57:55.821   2457259.91523      4305.60942      5.31523        -542.163   25-AUG-2015 09:32:26.531   25-AUG-2015 10:46:02.839          -4416.31
25-AUG-2015 11:04:06.877   2457259.96119       809.08888      7.65464        -537.560   25-AUG-2015 11:24:39.909   25-AUG-2015 10:46:05.588           2314.32
25-AUG-2015 12:13:23.008   2457260.00929      4500.78793      5.20507       -3187.562   25-AUG-2015 12:21:15.803   25-AUG-2015 11:53:04.817           1690.99
25-AUG-2015 13:50:56.824   2457260.07705      6028.92938      4.94037    99999999.000   25-AUG-2015 14:13:25.416   None                                     0
25-AUG-2015 15:16:10.130   2457260.13623      1189.34858      6.60271        -516.378   25-AUG-2015 15:08:51.078   25-AUG-2015 15:24:03.823          -912.745
25-AUG-2015 16:12:03.689   2457260.17504      1869.79014      6.22202        -508.483   25-AUG-2015 17:00:57.455   25-AUG-2015 15:24:08.075           5809.38
25-AUG-2015 17:41:38.351   2457260.23725      6181.69253      4.89998       -3264.826   25-AUG-2015 17:57:31.124   25-AUG-2015 16:31:48.213           5142.91
25-AUG-2015 19:17:47.598   2457260.30402      4031.78658      5.39418        -496.757   25-AUG-2015 18:52:57.457   25-AUG-2015 20:01:56.970          -4139.51
25-AUG-2015 20:21:56.531   2457260.34857       858.61772      7.61533        -491.469   25-AUG-2015 20:45:08.907   25-AUG-2015 20:01:57.812           2591.09
```

Time of Closest Approach | CAD | OXD | Time at Orbit Crossing | OXT

No crossings found in the region searched
(within the time of preceding and following close approach events)

Special Cases

Rapidly Varying Trajectories

Prior to arrival of MAVEN in September 2014, orbiters at Mars were all in relatively stable, well-predicted orbits.

Perturbations of MAVEN's orbit induced by the Martian atmosphere necessitated special consideration.

Previously, only CAD was used as a threshold and all thresholds were constant values.

If used for MAVEN, this would result in using a very large threshold to account for downtrack uncertainties which grow large over a short time interval due to the atmospheric drag.

This would lead to many “false” Red events: events which would not actually present any collision risk, but are categorized as Red due to large thresholds in place due to greater uncertainty at later times and in all directions.

Special Cases

Rapidly Varying Trajectories

Initial Update:

- Orbit Crossing Distance and Timing used instead of close approach distance for Red events.
  - Radial and downtrack errors can be examined separately: A larger threshold can be used for OXT (downtrack error), smaller threshold on OXD (radial error).
  - Allows elimination of events that are somewhat close in timing, but where the orbits do not get close to each other.
- Quadratic polynomial can be used as a threshold instead of constant value.
  - In the absence of covariance data, this allows events to assessed by risk level based on an uncertainty which changes as predictions are carried further in time.

Later Update:

- MADCAP was modified to be able to download files from the DSN with covariance data and use them to calculate Red thresholds.
  - Thresholds based on trajectory covariance data would be able to provide much better estimates of the variation in state uncertainty over time.
  - Values are based on a linear interpolation of the position covariance matrices which bracket the event in time.

Special Cases

Inactive Spacecraft

- Non-operational spacecraft cannot be reliably tracked at Mars & the Moon.
- Ephemerides with long-term propagations based upon the last known state of the spacecraft are used.
- These propagations contain large uncertainties and so are too unreliable to trigger a response from an active spacecraft.
- They are not included in the Summary Report Tables, but are in the ancillary data report for informational purposes only.
- A future method for inclusion may involve considering only an OXD threshold to eliminate the evaluation of unreliable downtrack position and only compare the less uncertain orbit.

Special Cases

Supporting Collision Avoidance Maneuver Studies

<u>Based on these MADCAP reports:</u>

- LRO delayed a momentum wheel desaturation maneuver by 1 day and LADEE delayed an orbit maintenance maneuver by 2 days to adjust periselene altitude.
- The LADEE maneuver was retargeted to maximize in-track distance between LADEE and two subsequent crossings of LRO such that the distance at closest approach would be greater than 1 km in the radial direction and greater than 4 km in the in-track direction.
- Special MADCAP runs were again conducted to evaluate the risk of a number of different post-maneuver trajectories including maneuver execution and orbit determination errors.
- The above requirements were met and the maneuvers successfully implemented.