

An Updated Process for Automated Deepspace Conjunction Assessment

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Abstract: *There is currently a high level of interest in the areas of conjunction assessment and collision avoidance from organizations conducting space operations. Current conjunction assessment activity is mainly focused on spacecraft and debris in the Earth orbital environment [1]. However, collisions are possible in other orbital environments as well [2]. This paper will focus on the current operations of and recent updates to the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) used at the Jet Propulsion Laboratory for NASA to perform conjunction assessment at Mars and the Moon. Various space agencies have satellites in orbit at Mars and the Moon with additional future missions planned. The consequences of collisions are catastrophically high. Intuitive notions predict low probability of collisions in these sparsely populated environments, but may be inaccurate due to several factors. Orbits of scientific interest often tend to have similar characteristics as do the orbits of spacecraft that provide a communications relay for surface missions. The MADCAP process is controlled by an automated scheduler which initializes analysis based on a set timetable or the appearance of new ephemeris files either locally or on the Deep Space Network (DSN) Portal. The process then generates and communicates reports which are used to facilitate collision avoidance decisions. The paper also describes the operational experience and utilization of the automated tool during periods of high activity and interest such as: the close approaches of NASA's Lunar Atmosphere & Dust Environment Explorer (LADEE) and Lunar Reconnaissance Orbiter (LRO) during the LADEE mission. In addition, special consideration was required for the treatment of missions with rapidly varying orbits and less reliable long term downtrack estimates; in particular this was necessitated by perturbations to MAVEN's orbit induced by the Martian atmosphere. The application of special techniques to non-operational spacecraft with large uncertainties is also studied. Areas for future work are also described. Although the applications discussed in this paper are in the Martian and Lunar environments, the techniques are not unique to these bodies and could be applied to other orbital environments.*

Keywords: Conjunction, Automated, Deepspace, Collision

1. Introduction

Conjunction assessment and the related activity of collision avoidance are currently areas of which attract high levels of attention from organizations that conduct space operations. Most current conjunction assessment activity is focused on the Earth orbital environment where there are many spacecraft and debris objects. However, Earth is not the only orbital domain in which there is interest in avoiding collisions in space. This paper will examine the process of conjunction assessment that has been implemented at the Jet Propulsion Laboratory (JPL) for the

two principal non-Earth orbital environments as of 2015: Mars and the Moon. Several of the world's space agencies have satellites in orbit around these bodies with additional future missions planned. Although the number of spacecraft currently operating in or planning operations in these orbital environments is relatively small compared to the Earth environment, the risk of collisions is higher than might be first expected. Missions designed for scientific sensing or communication relay purposes tend to have similar orbital characteristics, and 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 [3]. The MADCAP software has undergone significant updates since it was first implemented in 2012 [2]. This paper will describe the updated process and explain the output reports currently in use. The impact of specific environments, missions or events in influencing the enhancement of the MADCAP process will also be examined. The uncertainties associated with the MAVEN orbit were a primary driver of the move away from relying on close approach distances as the main conjunction metric, and towards using orbit crossing distances and timing. This also initiated the use of "time to event" variable polynomial based conjunction thresholds and the use of covariance data to establish thresholds. The inclusion of inactive spacecraft whose orbital predictions contain large uncertainties is also studied, and a brief description of the use of MADCAP for a collision avoidance maneuver study between NASA's Lunar Atmosphere & Dust Environment Explorer (LADEE) and Lunar Reconnaissance Orbiter (LRO) is presented. Finally, areas for future improvements to the MADCAP process are highlighted.

2. Conjunction Assessment Process

This section will discuss the principal aspects of the MADCAP method. MADCAP consists of a set of python scripts that utilize JPL's Mission-design and Operations Navigation Toolkit Environment (MONTE) software for infrastructure and essential computation. The multi-script architecture is not critical to describing the high-level process so for simplicity the discussion here will treat MADCAP as if it were a single script. Input parameters for the lower level scripts are created automatically by the top layer script, so effectively there is only a single parameterization accessible to the user. The next several sections discuss the key aspects of the MADCAP methodology in greater detail.

2.1. Parameterization

The principal feature that allows MADCAP to be used for conjunction assessment in an arbitrary orbital environment is the use of a parameter file containing inputs to be used by the script. The input parameters are specified in "parameter = value" format, and may appear in any order preferred by the user. For each orbital environment, a unique set of process parameters is maintained by the MADCAP team based on input from the mission management and navigation teams operating in that environment. The main parameters that establish the orbital environment are the specification of the central body and a list of at least two spacecraft (or other space

bodies). The parameters are not all listed here, but some of the general aspects they specify are described below:

- 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.

2.2. Automation

MADCAP is activated by an automated scheduling tool which initializes analysis based on a set timetable. It is currently scheduled to run automatically daily for both the Martian and the Lunar orbital environments. If an analysis is desired outside the automation framework, the script can be initiated manually from the Linux command line by executing the script and passing it the desired parameter file.

2.3. Obtaining Ephemeris Files

Ephemeris files for the spacecraft in the parameter list are automatically downloaded from the Deep Space Network's (DSN) Service Preparation System (SPS) Portal, which is the source of the ephemeris files used in predicts generation for all DSN tracking. One parameter specifies a set of keys associated with the navigation system engineering function that authenticates MADCAP to SPS and authorizes it to download the required ephemeris files.

Automated access to the ephemeris repository is desirable because the multiple navigation teams involved in navigating the various spacecraft upload their updated ephemeris files on a schedule that makes sense for their spacecraft, with no coordination required. MADCAP receives an XML formatted listing from SPS that itemizes the available ephemeris files for each spacecraft specified in the parameter file, parses the list to obtain the URL to use to access the file, downloads the predicts grade ephemeris file for each spacecraft that was most recently submitted by each of the navigation teams, and stores it in the location defined by the user in the input file. The most recent predicts grade ephemeris file for each spacecraft is selected finding by the largest predicts grade SPS file ID, which monotonically increases with time.

In addition to downloading the latest predicts grade Spacecraft and Planet Kernel (SPK) type ephemeris file available on SPS, MADCAP will also check if there are Consultative Committee for Space Data Systems (CCSDS) Orbit Ephemeris Message [4] (OEM) type ephemeris files available. If an OEM file is available and is based on the same input as the most recent SPK file, then it will be downloaded and checked for covariance data. If the file contains covariance data, then it will be used to calculate the thresholds explained in the following sections.

However, not every ephemeris file that is to be used for conjunction analysis is uploaded to the DSN SPS. For special cases, MADCAP also provides a means in the parameter file to indicate that an ephemeris should not be downloaded from SPS (e.g., if the spacecraft is not currently being tracked by the DSN, there may not be an ephemeris on SPS). For example, ephemeris files for ISRO's Chandrayaan-1 and JAXA's Ouna are no longer uploaded to the SPS. These spacecraft are no longer operational, but they are still in orbit and can be used in analyses if an appropriate ephemeris is available. Ephemeris files for this type of spacecraft can be added by specifying the file location in one of the MADCAP parameters. The trajectories being used for inactive spacecraft are long-term propagations based upon the last known state of the spacecraft. Though the uncertainty of the states in such an ephemeris is greater than that of current solutions, these long term predictions are better than nothing.

In addition, sometimes navigation teams wish to include more than one trajectory file in the analysis. MADCAP also allows a user to optionally specify one supplementary file per spacecraft that will be used in addition to the most recent predicts grade trajectory file downloaded from the SPS. For example, some missions wish to use the current orbit solution in the analysis, but also a reference trajectory for the mission. The reference ephemeris files are usually longer duration ephemeris files that represent a reference, baseline, or nominal trajectory. They often include some future planned maneuvers. The supplementary file can be a local file or the latest scheduling grade ephemeris file for the mission retrieved from SPS. In the latter case, the file is retrieved in a similar manner to that described above for predicts grade files. However, no covariance data is used for additional files.

Note that natural body ephemerides (e.g., a natural planetary satellite) may also be specified for analysis. For example, the ephemerides of the natural satellites Phobos and Deimos are analyzed by MADCAP for comparison with Mars spacecraft. This is an update to the original MADCAP process [2]. The planetary ephemerides are specified via local file, similar to the method used for non-operational spacecraft.

2.4. Trajectory Comparisons

MADCAP performs pairwise comparisons of the ephemerides of the spacecraft listed in the parameter file. Analysis for all combinations of two objects are performed (e.g., for spacecraft A, B and C, results are calculated for A-B, A-C, and B-C). Comparisons occur over the duration of the overlapping time period of the two ephemeris files analyzed, or from present time to the end of the overlap (as specified by the user). A search is carried out for the minimum relative distance between the two spacecraft analyzed. Each relative minimum is then considered a "Close Approach Event". The times of each close approach events are then printed to a table along with various orbit attributes selected at the discretion of the user. A few of the most used attributes are explained below.

One of the main attributes used to assess conjunctions is the minimum relative distance between the two spacecraft analyzed, called the close approach distance. The close approach distance is the simply the distance between the two spacecraft at the time of the close approach event. The

time of the event is reported as the close approach time. If spacecraft ephemerides with large downtrack uncertainties are used, it may be more useful to compare the minimum distance between orbits, since position within the orbit is not well known.

Minimum orbit crossing distances and times are also important conjunction attributes used by MADCAP. The search for orbit crossings is initiated at each closest approach event. The search is only performed near that closest approach event (within the time of the preceding and following closest approach events). If orbit crossings are found, the one with the minimum distance between orbits is established, and the distance between the orbits at this crossing is reported as the orbit crossing distance. The orbit crossing distance can be reported as “negative”. The sign of the orbit crossing distance is meant to convey information about which orbit is higher at the point at which the orbits cross. The convention used is: the orbit crossing altitude of the first spacecraft minus the orbit crossing altitude of the second spacecraft. “First” and “second” here refer to the order the spacecraft are listed in their pairing in the report, which is in turn dependent on the order the spacecraft are listed in the input parameter file. The general convention currently being used is to list the active spacecraft in order of their arrival at the central body, followed by inactive spacecraft in the same order, followed by natural satellites in order of their orbit size (smallest to largest). The time that each spacecraft is at the orbit crossing location is reported as the orbit crossing time for that spacecraft. The difference between these times is reported as the orbit crossing timing. The sign convention for timing is the time body 1 is at the crossing minus the time body 2 is at the crossing. If no crossings are found in the region searched, the orbit crossing distance is set to "99999999" and the time to "None".

Orbit crossing data calculations are inaccurate during periods of coplanarity between the two bodies compared. A refined algorithm was developed to calculate minimum orbit distances when orbits are coplanar. This algorithm has an increased run time, but provides more accurate results when orbits are coplanar or nearly coplanar. Thus, a check has been inserted to determine when the orbits being compared are coplanar (operationally defined as having angular momentum vectors within 5 degrees). For each close approach event, if the orbits are determined to be coplanar, the refined algorithm is used to calculate minimum orbit distances and timing which are reported as orbit crossing distances and timing in MADCAP reports. To avoid long run times for bodies which are often coplanar (e.g. Phobos v Deimos), the coplanar algorithm is only used for events within 60 days from the current time.

3. Output Data

After the trajectory comparisons are completed, MADCAP checks the candidate conjunction events against specified thresholds and generates the output reports. There are two types of reports which are generated and sent out: Summary Report and Ancillary Data Report. These reports are described in the following sections.

3.1. Summary Report

The Summary Report is a report contained within the body of an email and sent out to a wide distribution. The purpose of the Summary Report is to inform recipients of any noteworthy

upcoming conjunction events at the bodies analyzed. Events which meet specified thresholds are listed along with the necessary information to interpret these events. Example Summary Reports are shown for the Martian environment in Appendix Section 8.1, and the Lunar environment in Appendix Section 8.4. A block by block explanation follows of the Summary Report sections follows:

Analysis Time

Each report starts with the time that the analysis was performed. This is for tracking purposes and to distinguish the report from other reports.

Conjunction Assessment Bodies and Types

This block of data identifies all of the bodies included in the analysis. Each body is uniquely identified by a body identifier - which is a number from 1 to the number of bodies included. In some instances, the body identifier includes an "r" or "a" after the number. The "r" stands for "Reference" file, while the "a" means "Additional" file. The reference ephemeris files are usually longer duration ephemeris files that represent a reference, baseline, or nominal trajectory. They often include some future planned maneuvers. An "additional" file is any other supplementary ephemeris file desired to be included in the analysis. It may be a test case representing a missed or off-nominal maneuver, or some other scenario. Only one file other than the primary can be included in the analysis (additional or reference). A unique ephemeris file is used for each of the different body identifiers in the table.

Red Events

This block of data is intended to focus the reader on all of the significant, near-term predicted conjunction events. The table includes data for all of the events that satisfy the "Red" thresholds and occur within some specified number of days in the future (currently set to 14 days). Only pairings of active spacecraft using predicts grade ephemeris files are included in the Red tables. If no "Red" events are detected, then a single line with the word "None" is included in the table.

There are three types of threshold categories: orbit crossing distance (OXD) thresholds, orbit crossing timing (OXT) thresholds, and close approach distance (CAD) thresholds. A conjunction event is considered "Red" when both the OXD and OXT for that event are less than the Red thresholds. The CAD threshold is not considered for Red events, but the CAD value is still listed for reference. The thresholds correspond to the 3-sigma uncertainties as follows: OXD-radial position uncertainty, OXT-downtrack timing uncertainty. The threshold values for both spacecraft in a pairing are calculated and compared for each event; the larger of the two thresholds is then used. The thresholds used are listed after the reported values of OXD, OXT, and CAD. If a covariance file is available, it will be used to calculate the Red Thresholds. Values are based on a linear interpolation of the position covariance matrices which bracket the event in time. If a covariance file is not available, Red thresholds 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 a table explained below. The source of the threshold is also listed (Body ID and P-polynomial or C-covariance).

Data for active spacecraft and natural bodies are displayed in this table. Data for inactive spacecraft and reference trajectories are not reported.

All Events

This table includes data for all of the events included in the analysis that have orbit crossing and close approach distances less than both the "All OXD" and "All CAD" thresholds for all pairings of active spacecraft. The OXT threshold is not used for the "All" events, but the timing values are still listed for reference. For any particular pairing of bodies, the analysis is performed from the analysis time through the end of the overlap of the two ephemeris files or for the entire overlap as determined by the input parameter file. The notes on sign convention and epoch time in the above "Red Block" section apply to the "All Block" as well.

Data for active spacecraft and natural bodies are displayed in this table. Data for inactive spacecraft are not displayed, but events from analysis using reference trajectories are included.

Notes

This block provides explanatory information to help interpret the Summary Report. Additionally, it lists the directory where output data are stored and a point of contact for further inquiries.

Red Thresholds – Polynomial Coefficients

The polynomial equations used to calculate Red threshold values for bodies without covariance data are described as follows:

$$\text{Red OX Distance Threshold (t)} = \text{OXD0} + (\text{OXD1} * t) + (\text{OXD2} * t^2)$$

$$\text{Red OX Timing Threshold (t)} = \text{OXT0} + (\text{OXT1} * t) + (\text{OXT2} * t^2)$$

where t = Close Approach Epoch – Ephemeris Submit Time (in days)

The six coefficients specified above are then listed for each body in a table (except for inactive spacecraft which are not considered for Red Events). Bodies using constant thresholds simply have zero values for OXD1, OXD2, OXT1, and OXT2.

Ephemeris submit time (to SPS) is used instead of analysis time to calculate the time to the event for polynomial evaluation. This is a more accurate estimate of the uncertainty of the predicted trajectory based on the available data when the prediction was made. The uncertainty of the prediction is based on the amount of time forward from the latest data available when the prediction was made, regardless of when the analysis was run. The ephemeris submit time provides a good general approximation of the data cutoff time which is not available in the ephemeris file. If a local Ephemeris file is used instead of one submitted to SPS, the analysis time will be used in place of the submit time.

All Thresholds – Constants

This table lists the constant “All” thresholds for OXD and CAD for each Body.

Ephemerides

This block explicitly lists the ephemeris files that were used in the MADCAP analysis for each Body ID, including their submit time, start time, and end time. Entries are colored blue and noted with an “*” if they have changed since the last MADCAP run. Files obtained locally will have the phrase “Analysis Time” in place of a submit time.

3.2. Ancillary Data Report

The Ancillary Data Report consists of an email with multiple attachments sent out for each body pairing. The options for attachments are the table of conjunction events explained in the previous section and a plot of the close approaches and/or orbit crossing distances for the specific pair. Emails are sent out for each pair which meets specified thresholds. Thresholds for close approach and orbit crossing are specified for each body analyzed. If both thresholds are met, then an email is sent out for each pair containing the desired ancillary data attachments. Various options for table sorting and plot x and y limits are available via the input parameter file. Examples of ancillary data products are available in the appendix.

4. Special Cases

4.1. Spacecraft with Rapidly Varying Trajectories

Prior to the arrival of the MAVEN spacecraft into Mars orbit in September 2014, the orbiters being tracked at Mars had all been in relatively stable, well-predicted orbits. The perturbations of MAVEN's orbit induced by the Martian atmosphere necessitated special consideration for the treatment of missions with rapidly varying trajectory predictions and less reliable long term downtrack estimates. In order to analyze such cases using the existing MADCAP tool, it proved more useful to focus on orbit crossing distances and timing in place of absolute close approach distances between two spacecraft.

Previously, in order to warn users of significant, near-term predicted conjunction events, events below a specified close approach distance threshold were flagged as “Red Events”. These thresholds were based on the total 3-sigma positional uncertainty of the spacecraft since the directions of closest approach are unknown and variable. Spacecraft with large downtrack uncertainties such as MAVEN would need to use larger thresholds which would let in many events and overwhelm users with events which may end up posing no real risk to the spacecraft.

If orbit crossing distance and timing are used instead of closest approach distance, the radial and downtrack errors can be examined separately. A larger threshold can be used for the timing which corresponds to downtrack error, with a smaller threshold on orbit crossing distance. This allows the elimination of events that are somewhat close in timing, but where the orbits do not get close to each other. This would help to reduce the problem of too many “false” Red Events; events which would not actually present any collision risk. Thus, the MADCAP script was updated to use orbit crossing distance and timing as Red Event thresholds instead of just the closest approach distance.

Although the script only looks ahead 14 days for Red Events, the MAVEN trajectory predication uncertainty could vary widely over this time due to the effects of the Martian atmosphere. It would thus be necessary to use the largest value of these 14 days as a threshold. However, this continues the problem of having too many “false” Red Events. The solution implemented was a variable threshold scheme based on the predicted time until a conjunction event. In the absence of covariance data in trajectory files, this method allows events to be assessed by risk level based on an uncertainty which changes as predictions are carried further in time. The MADCAP script was updated to allow for thresholds which are represented by a quadratic fit of the 3-sigma uncertainty values as a function of the time to the event.

These updates were implemented in the fall of 2014 when MAVEN entered into Martian orbit. However, polynomial uncertainty approximations still had to be based on conservative worst case scenarios. Thresholds based on trajectory covariance data would be able to provide much better estimates of the variation in state uncertainty over time. At that time, the MADCAP script was downloading and using SPK files from the DSN network which do not include covariance data. The DSN SPS accepts CCSDS OEM version 2 type files which can include covariance data, but no current Mars missions were creating or submitting files with covariance information. In order to utilize covariance data for thresholds, both the MADCAP script and the Mars missions’ navigation process required updating. MADCAP was modified in the summer of 2015 to be able to download OEM files from the DSN and extract covariance data from them to be used to calculate threshold values based on the timing of a conjunction event. Various Mars mission Navigation Teams also agreed to generate OEM trajectory files with covariance data and submit them to the DSN. The polynomial uncertainty approximations are still specified and used for files which do not contain covariance information. Currently, Mars navigation teams are starting their conversion to using OEMs with covariance data, with full implementation anticipated by end of calendar year 2015.

4.2. Inactive Spacecraft

Since there is no Mars or Lunar surface-based radar space surveillance network, non-operational spacecraft cannot be reliably tracked as is done for Earth orbiting spacecraft and debris. Thus, a conjunction assessment method for deepspace non-operational spacecraft must rely on long term propagation of last known trajectory information. This introduces large uncertainties and interesting challenges to the automated conjunction assessment process. Due to these large uncertainties, inactive spacecraft are currently not included in the Summary Report Tables and thresholds which trigger responses. However, they are included in the conjunction metric tables

and plots for informational purposes. While, it may be interesting to track the inactive spacecraft relative to active, the data are too unreliable to trigger a response from an active spacecraft's navigation team. A possible method for including inactive spacecraft in the daily summary reports is outlined in the future work section.

4.3. Supporting Collision Avoidance Maneuver Studies

In February of 2014, the automated MADCAP reports showed that the orbit crossing distance between the LRO and LADEE spacecraft would be less than 1 km for a few orbits. The LADEE navigation team designed several potential maneuvers to increase the orbit crossing distances over this period of close conjunctions. Special MADCAP runs were conducted to test out the impact of the possible maneuvers on the orbit geometries. The figure below shows that the maneuvers did not yield the desired results in terms of increasing orbit crossing distances for the entire period of interest and across LADEE's maneuver dispersions (Credit: Dr. Bulter Hine of NASA/Ames annotations on MADCAP standard report).

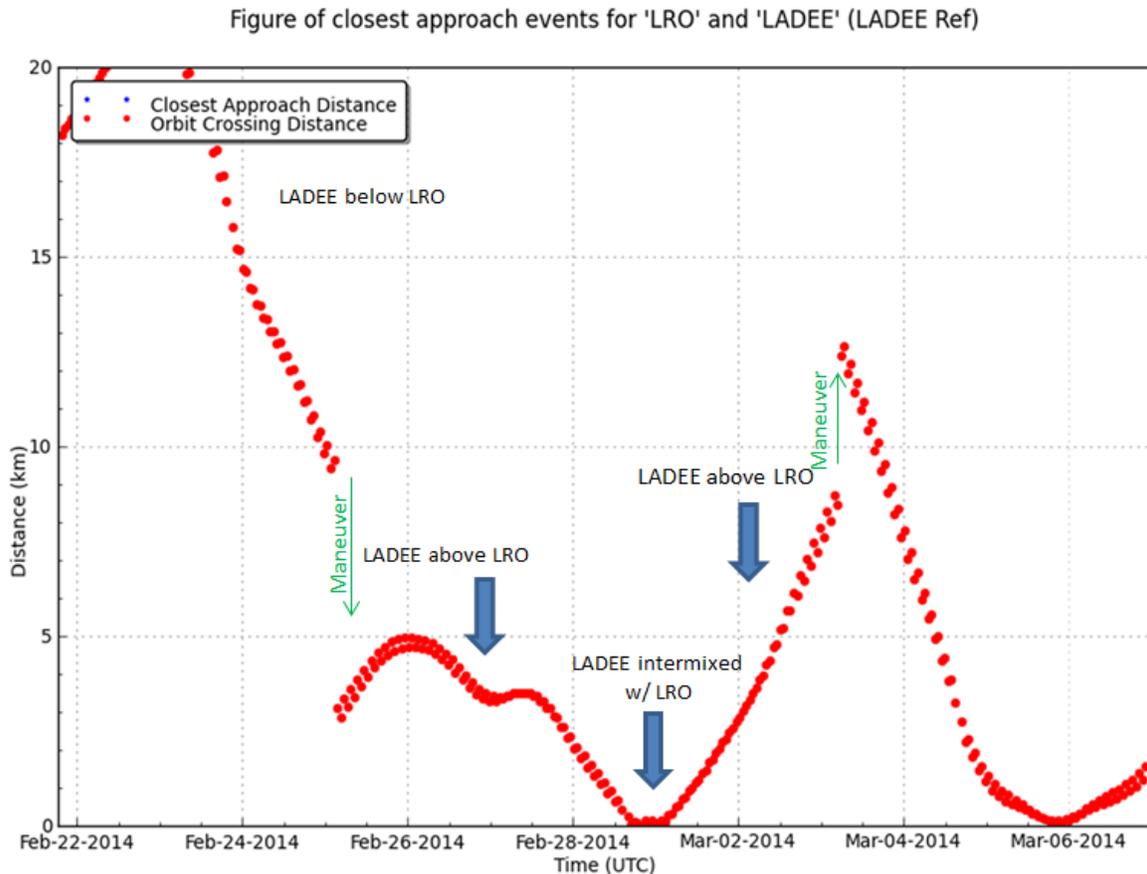


Figure 1. LADEE-LRO Close Conjunction in February 2014

Based on these MADCAP reports, both projects re-designed maneuvers to mitigate the risk of collision. LRO delayed a momentum wheel desaturation maneuver by 1 day to February 25th,

2014 and LADEE delayed an orbit maintenance maneuver by 2 days to February 27th 2014 to adjust periselene altitude. The LADEE maneuver was redesigned to maximize the in-track separation between the two spacecraft while keeping orbit crossing distance largely the same. The maneuver was retargeted to maximize the 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. These conditions were required to hold across a sweep of maneuver performance errors. 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. Working together through MADCAP, the projects were able to mitigate the risk and ensure the safety of both spacecraft.

5. Future Work

The development of MADCAP has been conducted using portions of several small budgets applicable to multimission software and operations, thus enhancements are continually being made to the process. While already useful, MADCAP has a number of areas where future work would be beneficial. Future work is anticipated in a several areas as follows:

5.1. 3D Visualization

The current plots sent out by MADCAP aid in the interpretation of how the spacecraft orbits and timing vary with respect to one another over time. However, they do not display much information on the geometry of the orbits at the time of the conjunction event. Much better insight would be gained from a three dimensional visualization of the spacecraft orbits at the time of the conjunction. Orbit crossing point geometry and timing can be easily interpreted visually from a three dimensional representation of the spacecraft trajectories. It could also be useful for discovering opportunities for one spacecraft to image another. Conjunction reports from MADCAP have been used in the past to identify such opportunities, though a visual representation of the spacecraft in their respective orbits would make this process much simpler. JPL's MONTE navigation software is being currently being enhanced to make generation of three dimensional orbital representations more seamless and straightforward. This improvement can be utilized by MADCAP to generate three dimensional images of the spacecraft orbits at the time of conjunction and include them as attachments in the emailed reports.

5.2. Collision Probability

The recent addition of covariance data used by MADCAP for calculating threshold values leads to the natural progression into using them to calculate collision probabilities. Since MADCAP does not track spacecraft attitude information, the calculation would necessarily be based on a keep out sphere specified around each spacecraft or natural body. The MADCAP script currently contains the capability to calculate collision probabilities based on constant covariance data and spherical spacecraft sizes provided as input parameters. [5-7] However, the algorithm used has not been extensively tested. This feature could be modified to use the covariance data

from the OEM files currently used for threshold calculations. This would allow for the calculations of collision probabilities for each conjunction event based on covariance data generated by the various missions. Of course, this would only be possible for pairs of spacecraft for which both have covariance data specified. Spacecraft in the Martian or Lunar environments cannot be reliably tracked from the surface of their orbited bodies, so it is necessary to have reliable covariance data provided by mission navigation teams in order to produce good probability results. The necessary covariance may not be available for all missions. In addition, spacecraft such as MAVEN during deep dip or inactive spacecraft may produce deceptively small collision probabilities even when close approaches are small due to their large positional uncertainties. For these reasons, calculating and publishing collision probabilities as supplementary information is a future MADCAP goal, though there is currently no plan to use probabilities as the main conjunction metric which triggers responses.

5.3. Including Inactive Spacecraft in Summary Reports

One method for including inactive spacecraft in the summary reports could be to effectively ignore thresholds on orbit crossing timing and close approach distance. The long runouts involved in estimating an inactive spacecraft's trajectory based on last known states make predictions of the spacecraft timing within the orbit effectively meaningless. However, the other orbital parameters are generally more stable and the prediction of the spacecraft orbit is more reliable. By only using orbit crossing distance as a threshold, and setting very high or no thresholds on orbit crossing timing and closest approach distance, only the spacecraft orbital geometry is compared. Thus, the very unreliable orbital position can be effectively ignored while still providing a warning for active spacecraft which pass near the orbits of inactive spacecraft. Red Events involving inactive spacecraft could be marked with a special designation (such as "Yellow") to convey that the event is listed for informational purposes only, and no response is required. The active mission involved would decide if any action should be taken.

5.4. Automated Special Runs

Special MADCAP runs are sometimes desired in cases when missions have trajectories they would like tested for conjunctions (see Section 4.3 above, for example). Currently, this involves sending the test file to a MADCAP engineer who will then setup a manual test run of the MADCAP script and send results to those interested. It would be possible to automate this process by implementing user requested runs triggered by submitting test ephemeris files to a repository which would kick off a supplemental run. This would help in situations such as the one described earlier for the LRO-LADEE conjunction, when conjunction assessment results were needed in a timely manner to aid in the design of a collision avoidance maneuver. MADCAP runs using different trajectory predictions (with or without maneuver, different size maneuvers) could be generated quickly and automatically. This would help response times during periods when close conjunctions have been reported and navigation teams are responding to the event.

6. Conclusion

This paper has presented the techniques currently used at JPL for automated conjunction assessment at Mars and the Moon. Much of the future work that was planned during the last presentation of this work has since been implemented. [2] Other unanticipated enhancements have also been applied in response to the needs of the varied missions which rely on MADCAP for conjunction assessment reporting. Some areas of potential future work to develop the current baseline operation have been outlined. MADCAP is currently in daily operation, and the unique attributes of the Mars and Lunar environments along with the various missions being served will continue to spur new improvements. Many new missions are planned to the Moon and Mars, so MADCAP can continue to be used to ensure a safer multi-spacecraft environment for all involved.

7. Acknowledgements

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8. Appendix

8.1 MADCAP Mars Summary Report Example

Note: The operational values of the MAVEN Red thresholds have been altered in this example in order to produce a Red event in the report.

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

Conjunction Assessment Bodies and Types

<u>Body Name</u>	<u>Type</u>
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

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

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

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

<u>Bodies</u>	<u>OXD (km)</u>	<u>OXT (sec)</u>	<u>CAD (km)</u>	<u>CA Epoch (UTC-SCET)</u>
---------------	-----------------	------------------	-----------------	----------------------------

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
3-4	4.1	-1812.4	2185.6	2015-09-27	04:51:35
3-4	3.6	2032.8	2669.7	2015-09-27	09:54:10
3-4	-2.5	-861.8	1162.2	2015-09-27	14:03:46
3-4	-3.0	89.1	127.3	2015-09-27	23:15:57
1-4	7.4	434.0	1048.0	2015-09-27	23:21:39
1r-4	7.4	434.0	1048.0	2015-09-27	23:21:39
3-4	-8.7	-2809.1	2917.7	2015-09-28	03:26:53
3-4	-6.6	1034.0	1469.6	2015-09-28	08:28:33
1-4	-2.4	1173.8	2750.8	2015-09-28	13:05:18
1r-4	-2.4	1173.8	2750.8	2015-09-28	13:05:18
1-4	-5.0	-951.2	2183.4	2015-09-28	17:22:24
1r-4	-5.0	-951.2	2183.4	2015-09-28	17:22:24
1-2r	-2.3	31.8	96.4	2015-11-27	20:05:38
1r-2r	-2.3	31.8	96.4	2015-11-27	20:05:38
2r-6	-30.2	18.7	47.4	2017-09-13	11:24:47

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/ztarzi/MADCAP_T/Mars/archive
 Point of contact: zahi.b.tarzi@jpl.nasa.gov

Red Thresholds -- Polynomial Coefficients

<u>Body Name</u>	<u>OXD0 (km)</u>	<u>OXD1 (km/t)</u>	<u>OXD2 (km/t^2)</u>	<u>OXT0 (sec)</u>	<u>OXT1 (sec/t)</u>	<u>OXT2 (sec/t^2)</u>
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)

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.

All Thresholds -- Constants

<u>Body Name</u>	<u>OXD (km)</u>	<u>CAD (km)</u>
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

All OX Distance Threshold = OXD

All CA Distance Threshold = CAD

Ephemerides

<u>Body Ephemeris</u>	<u>Submitted</u>	<u>Begin</u>	<u>End</u>
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 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.

8.2 MADCAP Mars 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/jplmnav/MADCAP/Mars/Ephemerides/de410_Mars.boa
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/p_m_od60649-60652_61771_v1.bsp
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/MOEM_150817OAS_PREDICT_0001.CR.bsp
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/pf_psp_rec42493_42490_43263_p-v1.bsp
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/trj_orb_01755-01756_01914_v1_mvn.bsp
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/mom_spk_150813-150916_od297_v1_dsn.bsp
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/mar097_2010-2029.bsp
# /nav/home/jplmnav/MADCAP/Mars/Ephemerides/mar097_2010-2029.bsp
# /nav/home/jplmnav/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 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 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 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
25-AUG-2015 21:33:26.733 2457260.39823 4746.46172 5.14703 -3313.252 25-AUG-2015 21:41:46.273 25-AUG-2015 21:10:06.368 1899.91
25-AUG-2015 23:11:18.830 2457260.46619 5912.60710 4.95979 99999999.000 None 0
26-AUG-2015 00:34:39.417 2457260.52407 906.64630 6.77875 -474.287 26-AUG-2015 00:29:26.394 26-AUG-2015 00:39:53.648 -627.254
26-AUG-2015 01:31:05.866 2457260.56326 2160.15445 6.05457 -466.031 26-AUG-2015 02:21:36.527 26-AUG-2015 00:39:58.799 6097.73
26-AUG-2015 03:02:11.761 2457260.62653 6242.37688 4.89093 -3392.311 26-AUG-2015 03:18:09.702 26-AUG-2015 01:48:53.983 5355.72
26-AUG-2015 04:37:39.433 2457260.69282 3741.73790 5.48612 -449.086 26-AUG-2015 04:13:35.745 26-AUG-2015 05:17:50.881 -3855.14
26-AUG-2015 05:39:52.466 2457260.73602 896.31593 7.53803 -444.203 26-AUG-2015 06:05:41.359 26-AUG-2015 05:17:54.279 2867.08
26-AUG-2015 06:53:37.041 2457260.78723 4977.23744 5.09817 -3453.346 26-AUG-2015 07:02:15.649 26-AUG-2015 06:27:23.154 2092.49
26-AUG-2015 08:31:38.554 2457260.85531 5776.20479 4.98583 99999999.000 None 0
26-AUG-2015 09:52:57.665 2457260.91178 646.63365 6.95434 -429.173 26-AUG-2015 09:49:55.534 26-AUG-2015 09:55:44.184 -348.651
26-AUG-2015 10:50:12.481 2457260.95153 2459.18470 5.90220 -424.665 26-AUG-2015 11:42:08.996 26-AUG-2015 09:55:46.582 6382.41
26-AUG-2015 12:22:38.736 2457261.01573 6283.62854 4.88526 -3509.400 26-AUG-2015 12:38:44.032 26-AUG-2015 11:05:51.147 5572.88
26-AUG-2015 13:57:19.686 2457261.08148 3447.33662 5.58599 -410.265 26-AUG-2015 13:34:11.965 26-AUG-2015 14:33:39.097 -3567.13
26-AUG-2015 14:57:52.205 2457261.12352 943.05621 7.42406 -406.285 26-AUG-2015 15:26:21.432 26-AUG-2015 14:33:42.279 3159.15
26-AUG-2015 16:13:54.964 2457261.17633 5191.07844 5.05306 -3579.777 26-AUG-2015 16:22:54.195 26-AUG-2015 15:44:32.475 2301.72
26-AUG-2015 17:52:00.999 2457261.24446 5617.90716 5.01679 99999999.000 None 0
26-AUG-2015 19:11:09.154 2457261.29941 420.09764 7.12676 -388.851 26-AUG-2015 19:10:27.541 26-AUG-2015 19:11:32.999 -65.4585
26-AUG-2015 20:09:28.919 2457261.33992 2766.46673 5.76493 -383.922 26-AUG-2015 21:02:37.810 26-AUG-2015 19:11:34.028 6663.78
26-AUG-2015 21:43:03.525 2457261.40490 6301.81853 4.88187 -3635.671 26-AUG-2015 21:59:14.201 26-AUG-2015 20:22:57.459 5776.74
.
.
.

```

8.3 MADCAP Mars Ancillary Plot Example, MRO-MAVEN

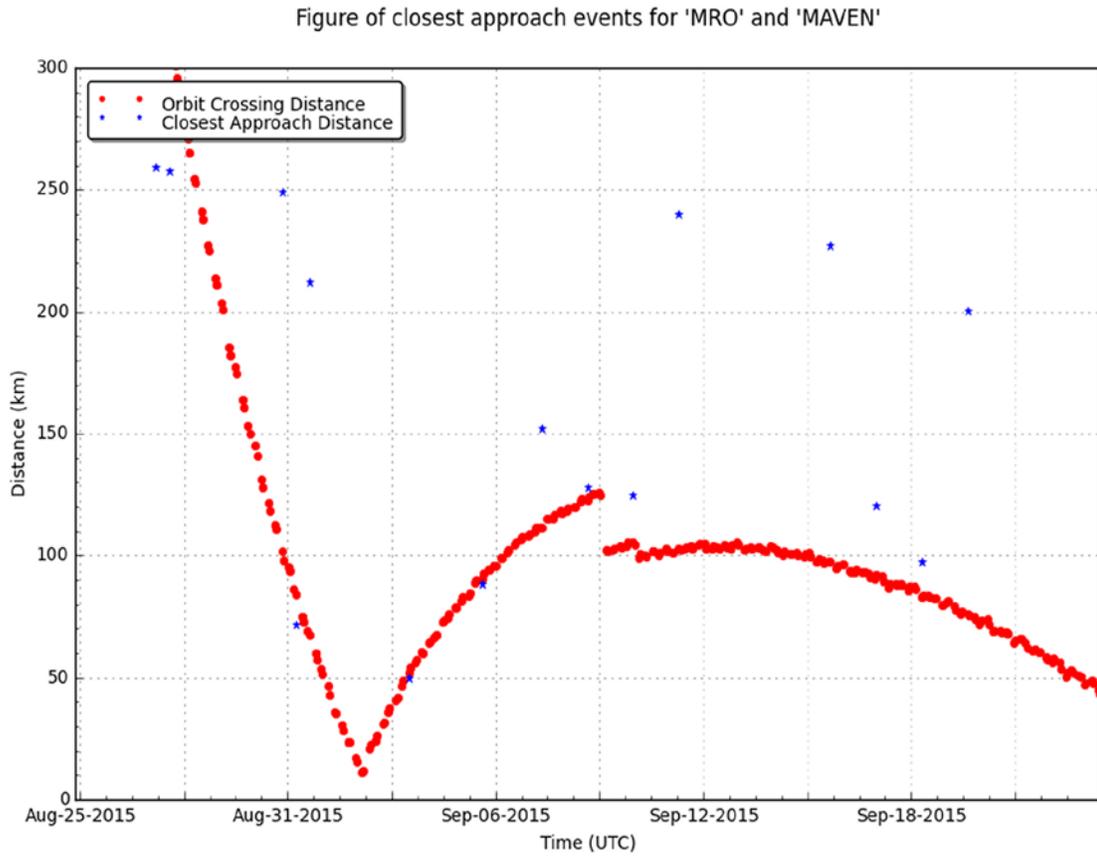


Figure 2. MRO-MAVEN Example Conjunction Plot

8.4 MADCAP Lunar Summary Report Example

Analysis Time: 2015-08-24 16:00:14 UTC

Conjunction Assessment Bodies and Types

<u>Body Name</u>	<u>Type</u>
1 LRO	Active
1r LRO	Active/Reference
2 ARTEMIS-P1	Active
2r ARTEMIS-P1	Active/Reference
3 ARTEMIS-P2	Active
3r ARTEMIS-P2	Active/Reference
4 Ouna	Inactive
5 CH1	Inactive

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)

None

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

Bodies OXD (km) OXT (sec) CAD (km) CA Epoch (UTC-SCET)

2r-3r	-57.7	-142.4	243.6	2015-09-24 06:08:35
2r-3r	-57.7	-144.3	111.8	2015-09-24 08:36:41
1r-2r	-302.4	182.7	429.4	2015-10-03 18:33:46

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: 2015-08-24 16:00:14 UTC
Active spacecraft: LRO, ARTEMIS-P1, ARTEMIS-P2
Natural bodies: None
Inactive spacecraft: Ouna, CH1
Output directory: /nav/home/jplmnav/MADCAP/Moon/archive
Point of contact: MADCAP_Moon@jpl.nasa.gov

Red Thresholds -- Polynomial Coefficients

<u>Body Name</u>	<u>OXD0 (km)</u>	<u>OXD1 (km/t)</u>	<u>OXD2 (km/t^2)</u>	<u>OXT0 (sec)</u>	<u>OXT1 (sec/t)</u>	<u>OXT2 (sec/t^2)</u>
1 LRO	20.0000	0.0000	0.0000	300.0000	0.0000	0.0000
2 ARTEMIS-P1	20.0000	0.0000	0.0000	300.0000	0.0000	0.0000
3 ARTEMIS-P2	20.0000	0.0000	0.0000	300.0000	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)

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.

All Thresholds -- Constants

<u>Body Name</u>	<u>OXD (km)</u>	<u>CAD (km)</u>
1 LRO	500	500
2 ARTEMIS-P1	500	500
3 ARTEMIS-P2	500	500

All OX Distance Threshold = OXD

All CA Distance Threshold = CAD

Ephemerides

<u>Body Ephemeris</u>	<u>Submitted</u>	<u>Begin</u>	<u>End</u>
1 14day_20150824_01.bsp*	2015-08-24 12:58:12 UTC	24-AUG-2015 00:00:00 UTC	07-SEP-2015 00:00:00 UTC
1r 558day_20150821_01.bsp	2015-08-21 13:42:21 UTC	21-AUG-2015 00:00:00 UTC	01-MAR-2017 00:00:00 UTC
2 192.THEMIS_B.SHORT_TERM.2015_233.oem.bsp_V0.1	2015-08-21 02:45:40 UTC	21-AUG-2015 00:00:00 UTC	20-SEP-2015 00:00:00 UTC
2r 192.THEMIS_B.LONG_TERM.2015_064.oem.bsp_V0.1	2015-03-05 18:26:38 UTC	05-MAR-2015 00:00:00 UTC	06-OCT-2015 23:59:59 UTC
3 193.THEMIS_C.SHORT_TERM.2015_233.oem.bsp_V0.1	2015-08-21 02:46:43 UTC	21-AUG-2015 00:00:00 UTC	20-SEP-2015 00:00:00 UTC
3r 193.THEMIS_C.LONG_TERM.2015_064.oem.bsp_V0.2	2015-04-06 18:48:26 UTC	05-MAR-2015 00:00:00 UTC	06-OCT-2015 23:59:59 UTC
4 ouna_150812_160101_150608_SMM0710031456-jpl-ekl.boa	Analysis Time	11-AUG-2015 23:58:51 UTC	31-DEC-2015 23:58:51 UTC
5 spk_ch1_150601_160101_150602_jpl-ekl_SCID-86.bsp	Analysis Time	31-MAY-2015 20:29:41 UTC	01-JAN-2016 21:51:59 UTC

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.