Automated Spacecraft Conjunction Assessment at Mars and the Moon - A Five Year Update

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It is well known that the Earth has an ongoing problem with orbiting space debris. Some Earth orbiting missions have regular warnings of close approaches with debris or other satellites. At Mars and the Moon, due to the growing number of orbiter missions and the current inability to track orbital debris in these environments, the creation of a hazardous debris field must be avoided because a debris field would greatly complicate both existing and future operations. Work at the Jet Propulsion Laboratory in the area of automated spacecraft conjunction assessment at Mars and the Moon has been conducted over the past six years using a process called "MADCAP" ("Multimission Automated Deepspace Conjunction Assessment Process"). A paper introducing this work was presented at Space Ops in Stockholm, Sweden in 2012. In that inaugural paper, the then current state of operations was presented along with a number of items that were identified for potential future work. The fundamental design concepts of MADCAP have not materially changed in the last five years, however, since 2012 a number of the changes to MADCAP identified in the previous paper have been implemented. Some other previously planned work has not progressed appreciably; several of these items remain on a "parking lot" list. In addition to the items that were listed as prospective future work, JPL's Mars/Moon conjunction assessment efforts have also been extended in a few unplanned but important areas. This follow-up paper will provide a five year update on MADCAP operations at Mars and the Moon.

I. I. Introduction

THAT the Earth has an ongoing problem with space debris in its orbital environment, both Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO), is well known [1]. Some Earth orbiting missions have several warnings of close approaches with debris objects each month (for example, the Orbiting Carbon Observatory 2 (OCO-2)). Thankfully, the Earth's orbital environment is continuously surveyed by the Space Surveillance Network (SSN), which can track objects down to approximately 10 cm in radar cross section [2]. At Mars and the Moon, the growing number of orbiter missions makes the debris management job one of avoiding the creation of a hazardous debris field in the first place. An orbital debris environment does not honor national boundaries; once created by any space operator, either accidentally or intentionally, virtually all space programs with assets in the affected orbital environment are potentially subject to risks of collisions with debris.

NASA currently expends resources to monitor satellite conjunctions in environments with multiple orbiters. Earth's satellite and orbital debris environment is monitored by NASA's Conjunction Assessment Risk Analysis (CARA) program [3,4] located at the Goddard Space Flight Center (GSFC). Conjunction assessments were performed manually at Mars by NASA's Jet Propulsion Laboratory (JPL) starting in 2004 for the operational spacecraft there (Mars Global Surveyor, Odyssey, Mars Reconnaissance Orbiter, Mars Express) [5]. Automated spacecraft conjunction assessment at Mars and the Moon has been conducted by JPL using the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) starting in 2011 [6-8]; a paper introducing this work was presented at Space Ops in Stockholm, Sweden in 2012 [6]. In that inaugural paper, produced after approximately one year of operations, the then current state of operations was presented along with a number of items that were identified for potential future work. This follow-up paper will present an update that identifies which future work items identified in 2012 have been completed in the past five years, which have not yet been completed, and the current status of the overall effort. As in the 2012 paper, this paper will conclude by identifying a few items for potential future work. Planning for some of these is already in progress.

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II. The Orbital Debris Problem

NASA's Orbital Debris Program Office cites that approximately 18,500 objects in Earth orbit are officially cataloged by the US Space Surveillance Network (SSN), down to objects approximately 10 cm in radar cross section. Over half of these objects are "fragmentation debris", which includes satellite breakup debris and anomalous event debris. Figure 1 below displays a summary of all objects in Earth orbit officially cataloged by the SSN. [9]

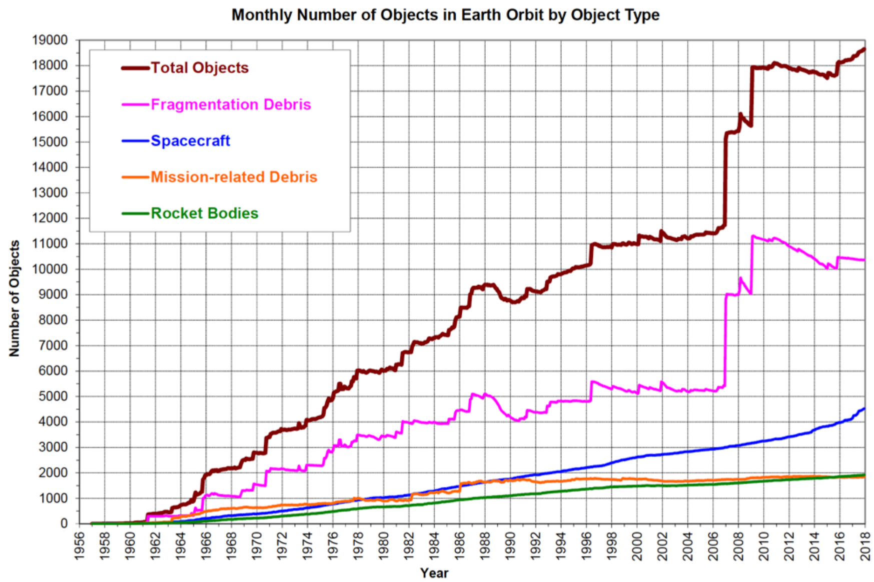

Fig. 1: Monthly Number of Cataloged Objects in Earth Orbit by Object Type [9]

Currently there is no known orbital debris field at the Moon or Mars, but it would be very undesirable to create one given that there is no way to realistically track the debris from Earth as is done with the Earth-based SSN. Such a debris field at the Moon or Mars would greatly complicate both existing and future operations in those orbital environments (both robotic and future human missions), because even small particle impacts are capable of causing spacecraft damage and generating additional fragmentation events. [1]

The intentional destruction of the Fengyun-1C (FY-1C) weather satellite in a Chinese anti-satellite test in January of 2007 and the accidental collision between Cosmos 2251 and the operational Iridium 33 in February of 2009 are considered the worst Earth orbiter breakups in history [10]. According to the NASA orbital debris office, a total of 5579 fragments were cataloged by the United States Space Surveillance Network (SSN) for these two events, and over 4200 of them still remained in orbit as of April 2018 (2833 from Fengyun 1C, 1076 from Cosmos 2251, and 335 from Iridium 33) [11]. In addition to these cataloged objects, models predict that hundreds of thousands of fragments down to millimeter size were also generated during the breakups. These fragments are too small to be tracked by the SSN, but still pose risks to spacecraft operations. [12,13]

At Mars and the Moon, the growing number of orbiter missions, coupled with the current inability to track orbital debris in these environments, suggest that the debris management job must focus on avoiding the creation of a hazardous debris field in the first place. The necessity of this debris prevention function provided the inspiration for the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP). One of the primary virtues of MADCAP processing is that it works to preserve two important orbital environments that are currently free of a hazardous debris field. Once there is a collision of two objects in orbit around the Moon or Mars, a debris field would be created that could take many years to dissipate, depending on the altitude and several other factors [14]. It could require several years before a viable debris monitoring system could be put in place in these environments since debris monitoring would be impossible with Earth-based radars. During the time between debris field creation and the implementation of an adequate monitoring system (which has not been proposed or funded), all missions operating in the affected environment would run the risk of a catastrophic collision with untrackable debris, which would compound the problem. Such debris fields could affect the plans of any space operator that plans to send missions to the Moon or Mars, and there are several such plans in the works (e.g., ISRO's Chandrayaan-2 mission, NASA's Lunar Orbital Platform-Gateway, UAE's "Hope" mission, Elon Musk's SpaceX plans for Mars, etc.). The risk would be particularly great for human missions. One major potential source of lunar spacecraft is NASA's Space Launch

System/Exploration Mission 1 (SLS/EM-1) and SLS/EM-2. Current plans call for up to 13 cubesats on SLS/EM-1 and up to 40 cubesats on SLS/EM-2. This large number of spacecraft, several of which are lower budget or experimental spacecraft could potentially lead to more inactive, uncontrollable spacecraft in the lunar environment.

III. MADCAP Fundamental Design Concepts

The fundamental design concepts of MADCAP have not materially changed since their conception in 2011. A parameter file is setup for each orbital environment to be analyzed, which allows conjunction analyses in any orbital environment without modifying the underlying software. The parameters fall into a few general classes: environment (central body, coordinate system); bodies within the environment (active spacecraft, inactive spacecraft, natural bodies); thresholds used to classify conjunction events and control report generation; options for detailed reports and plots; and email lists for report participants. 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 bodies including natural satellites or debris). MADCAP is automatically initiated and automatically downloads the latest ephemerides from the Deep Space Network's (DSN) Service Preparation Subsystem (SPS) portal that were prepared by the navigation teams for tracking purposes. Two basic types of files are downloaded from SPS: "predicts grade" ephemerides and "scheduling grade" ephemerides. The predicts grade ephemerides represent the navigation team's best estimate of the spacecraft trajectory; these ephemerides are used in the generation of DSN pointing and frequency predicts. The scheduling grade ephemerides may represent a lower fidelity predict used for scheduling antenna time, or a "reference trajectory". Reference ephemeris files are usually longer duration ephemeris files that represent a reference, baseline, or nominal trajectory, and often include some future planned maneuvers. The reference ephemeris files are typically updated less frequently than predicts grade ephemerides.

In addition to downloading from SPS, missions have the option to include in the parameter file one supplementary ephemeris file to be included in the analysis. This ephemeris may be a test case representing an alternative scenario such as a "no-burn" option in the case of a planned maneuver, or some other scenario. Supplementary ephemerides for planned and/or non-operational missions and natural bodies that are not available on the SPS can also be added in this way, as can ephemerides from missions that are not using the DSN/SPS. MADCAP then performs pairwise close approach event searches among the objects listed in the parameter file using the collection of ephemerides. Comparisons occur for up to 100 days of the overlapping time period of the two ephemeris files analyzed (this duration can be adjusted by the MADCAP operations team if needed for special analyses). An event search is carried out for the minimum relative distance between the two spacecraft analyzed. Each relative minimum is classified as a "close approach event". Candidate close approach events are then evaluated against mission-established, risk-based thresholds prepared by the navigation teams to classify them as "red" or "not red". A "red event" is a close approach event 14 days or less in the future for which the selected orbital attribute is below the defined threshold values (several orbital attributes are instrumented). A red event requires some level of attention by a navigation team. Reports are prepared and communicated by email to interested parties.

Three types of reports are generated and distributed. A detailed output table is created for each pair of spacecraft analyzed, each line of which contains information on the conjunction attributes requested in the parameter file. Depending on the amount of overlap between the two ephemeris files in the comparison, these detailed reports can be quite long. MADCAP also generates two-dimensional plots of several of the conjunction attributes. The primary and most widely distributed report that most MADCAP users pay attention to is the Summary Report. It captures a large amount of information in a single, easily digested format. The reports are discussed in detail in Ref. [7] so they will not be described in detail here. A sample Summary Report is shown in the Appendix.

IV. Conjunction Assessment at Mars and the Moon Circa 2012

JPL's work with automated spacecraft conjunction assessment at Mars and the Moon was presented at Space Ops in Stockholm, Sweden in 2012 [6] after MADCAP had been in regular operations for about a year. The fundamental concepts of MADCAP had been designed and implemented, but there were many thoughts as to improvements.

As of 2012, the primary attribute for MADCAP's conjunction assessment was the "close approach distance" metric. MADCAP's Summary Report focused on this metric, and categorized the close approaches as green, yellow, or red depending on the magnitude of the close approach and the thresholds established by the navigation teams for the various missions. At that time, MADCAP could only use a "constant covariance" because there was no means to incorporate a covariance into the SPICE/SPK (Spacecraft Planetary Kernel) ephemeris files used by the DSN/SPS.

In the Stockholm paper, a number of items were identified for potential future work, including: formalize a process for responding when approaches are "too close"; refine uncertainty modeling to improve collision probability calculation; explore collaboration with NASA/GSFC and the European Space Agency's (ESA) Space Situational

Awareness (SSA) program; incorporate more sophisticated automation than Linux "cron"; include other shared orbital environments of potential interest (e.g., Sun-Earth L1/L2, Earth-Moon L1/L2); and provide an option to output a Consultative Committee for Space Data Systems (CCSDS) Conjunction Data Message (CDM), which was at the time an emerging international standard.

V. Conjunction Assessment at Mars and the Moon - Planned Changes Since 2012

Since 2012 a number of the planned changes to MADCAP identified in the previous paper have been implemented, as detailed in the following sections.

A. Responding to "Too Close" Situations

In 2012, a formal response to approaches that were "too close" had not yet been documented; the rare close approaches of the three Mars orbiters at the time (NASA's Mars Odyssey and Mars Reconnaissance Orbiter, and ESA's Mars Express) were handled on a case-by-case basis, not systematically. Occasional close approaches with low miss distance warranted some increased communication with navigation teams and discussion as to whether any action was in fact necessary. At the time it was acknowledged that a formal process would be desirable. Accordingly, such a formal process for responding to spacecraft approaches that are "too close" was collaboratively developed by JPL's Mission Design and Navigation Section and the Mars Program Office at JPL in late 2014, around the time that NASA's MAVEN and ISRO's Mars Orbiter Mission joined the environment. The succinct document "Conjunction Assessment Process For Mars Orbiters" discusses requirements, has procedure flowcharts for a "Monitor Process" and a "Response Process", and specifies who should receive notification of the events identified by MADCAP; it has since been lightly revised twice. [15]

In essence, the Monitor Process is realized in the MADCAP Summary Report that is emailed at the end of each analysis run. This report provides an overall assessment of the orbital environment and identifies both red events within 14 days of the analysis that satisfy certain criteria and "not red events" that are predicted beyond the 14 day horizon. The Response Process is triggered when there is a red event reported in a Summary Report. A member of the MADCAP team designated as the "MDNAV MADCAP Representative" is responsible for contacting the Navigation Team Chiefs for the two spacecraft involved in the conjunction, discussing possible options for mitigating the conjunction, working out a time table for actions that might be necessary, ensuring that the two navigation teams are communicating directly, and providing a status email to the key personnel identified in the process document. Key personnel include members of JPL's Mars Program Office, members of the project management teams for the two flight projects, and relevant members of the JPL Mission Design and Navigation Section (including the MADCAP team). In many cases the red events disappear "naturally" as the time to the event decreases and updated ephemerides are provided by the two navigation teams, especially if the events initially appear at the 14-day horizon for red events used by MADCAP. However, in some cases it has been necessary for at least one of the spacecraft to maneuver to avoid a potential collision. These maneuvers are usually scheduled as late as possible after the threat has been determined to be real because the trajectory uncertainties generally reduce as the time-to-event draws near.

B. What Is "Too Close"?

As part of the formalization of the Response Process, the operational definitions of "too close" have been significantly refined since 2012. This has primarily involved refinements of trajectory uncertainty modeling.

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 (an exception was when MRO was aerobraking). But since the periapsis altitude of the MAVEN science orbit dips into the Martian atmosphere, the spacecraft experiences atmospheric drag during each periapsis passage. The variability of the density of the atmosphere creates a downrange uncertainty that makes long range predictions of the position of the MAVEN spacecraft difficult. As a result, the uncertainty in the spacecraft position within its orbit can exceed 1000 kilometers when trying to predict the spacecraft position just a few days into the future. In order to analyze such cases using MADCAP, it proved more useful to focus on the orbit crossing distance (OXD) and orbit crossing timing (OXT) instead of the absolute close approach distances between two 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, eliminating events that are somewhat close in timing but where the orbits do not get close to each other. This helps reduce the problem of "false" red events; events which would not actually present any collision risk. Accordingly, MADCAP was updated to use orbit crossing distance and timing as the principal conjunction assessment metrics instead of using just the closest approach distance; the minimum orbit distance is used in place of orbit crossings when the orbits are close to coplanar.

Along with changing the conjunction attributes significantly, the changes in late 2014 also included a move away from fixed constant thresholds towards the instrumentation of dynamic polynomial-based or covariance-based data conjunction thresholds. 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. MADCAP 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. To simplify both the establishment of thresholds and reporting, the process was changed to focus only on "red" and "not red" conjunctions (instead of green, yellow, red). If an event has an orbit crossing distance and orbit crossing time less than both mission-established thresholds for these attributes, and it is less than or equal to 14 days in the future, it is then classified as a red event. It is "not red" if greater than 14 days in the future. The change in conjunction attributes did not require any logic changes in MADCAP given that "close approach distance", "orbit crossing distance", and "orbit crossing timing" were already criteria upon which MADCAP processing could be based, and classifying events based on thresholds was well established. However, the logic for establishing thresholds based on polynomials or covariance matrices did require significant changes and there were many necessary changes to the MADCAP Summary Report. For those Mars missions that agreed to use the new covariance matrix feature, process changes were also necessary. The polynomial coefficients and covariance matrices are provided by the navigation teams; the MADCAP team does not dictate these.

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

Red OX Distance Threshold = OXD0 + (OXD1 * t) + (OXD2 * t^2) [km] (1)
Red OX Timing Threshold = OXT0 + (OXT1 * t) + (OXT2 * t^2) [sec] (2)
where t = Close Approach Epoch - Ephemeris Submit Time (in days)

These six coefficients are then listed for each body in a table in the Summary Report (except for inactive spacecraft which are not considered for red events). Missions preferring constant thresholds simply have zero values for the linear and quadratic coefficients OXD1, OXD2, OXT1, and OXT2. For conjunction events beyond the 14-day horizon, only two types of threshold categories are used: orbit crossing distance (OXD) thresholds and close approach distance (CAD) thresholds.

The MADCAP parameter file maintains several parameters for use in calculating the probability of collision (coordinate system, the radii of the objects in kilometers (km), and the covariance reference frame). In the initial version of MADCAP, constant "covariance" sigmas in kilometers were provided as parameters because the true covariance data is not contained in the SPICE/SPK ephemeris files available on the DSN/SPS. To correct this deficiency, a method of utilizing true covariance data provided by the spacecraft navigation team was added to MADCAP in summer 2015 by using the covariance matrix feature available in the CCSDS Orbit Ephemeris Message (OEM) Version 2 [16]. To use the covariance data, in addition to downloading the latest predicts grade SPK type ephemeris file available on SPS, MADCAP will also check to see if there are OEM files available on the SPS. If an OEM file is available that 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 conjunction thresholds for the analysis run. Various Mars mission Navigation Teams have 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 or in cases where the covariance data does not cover the portion of the ephemerides being analyzed. Currently, Mars navigation teams are starting their conversion to using OEMs with covariance data.

Covariance information can also improve the collision probability computation. A change in the collision probability formulation was also necessary to use the OEM covariance data. However, to date there has not been much interest from MADCAP customers in collision probability calculations, so they have not been routinely calculated.

C. Working With NASA CARA and ESA

JPL has been working on a somewhat informal basis with NASA's Conjunction Assessment Risk Analysis program. A division of labor has essentially been agreed upon, such that CARA monitors the Earth orbital environment, and JPL monitors the Lunar and Martian environments.

JPL's Mission Design and Navigation Section Manager has set an objective for the MADCAP team that MADCAP processing be as similar as is feasible to that of CARA processing. Conceptually such a collaboration might focus on comparing techniques, process improvements based on technical interchange, cost-sharing, etc. Pursuant to this objective, members of the MADCAP team have participated in a few CARA User Forums and also participated in development of the NASA Procedural Requirements (NPR) document on orbital debris and conjunction assessment that discusses CARA in some detail and includes some considerations referring to MADCAP [17]. The specifications for covariance matrix attributes provided to JPL's Mars orbiter navigation teams match those of the CARA program (i.e., one minute intervals between covariance matrices). There have also been team discussions regarding evaluation of incorporating into MADCAP the 3D probability method pioneered by CARA [18], though there has not been much emphasis since 2012 on calculating and reporting collision probability.

Work with ESA's Space Situational Awareness program has not explicitly commenced (though there has been some indirect work accomplished through the activities of the CCSDS Navigation Working Group). There was also significant coordination between JPL Navigation and ESA's European Space Operations Center navigation team during the aerobraking period of ESA's ExoMars Trace Gas Orbiter (TGO) mission. In fact, during this time the highest number of red events in a single analysis run was achieved over a sustained period. The frequency of red events jumped dramatically (new ones nearly each day), and some conjunctions would appear, then disappear, then reappear a day later. Until TGO aerobraking started, the MADCAP team had experienced an average of around 7 red events per year. During the TGO aerobraking end game, there was one MADCAP Summary Report that showed 9 for a single run; these were due to the very large uncertainties inherent in aerobraking operations, and many of them disappeared as the time to event and uncertainties decreased.

D. Improved Workflow Automation

In 2012, MADCAP was activated by a Linux cron job on a schedule based on the ephemeris update frequency of the spacecraft operating in the Mars and Moon environments. MADCAP was run daily for the lunar environment, but only run twice weekly for the Mars environment. In October/November 2014, the Mars run frequency was increased to daily given the larger number of spacecraft operating in the environment (MAVEN and MOM had both arrived within a few days of each other) and the characteristics of MAVEN's orbit (eccentric, with periodic deep dips into the Martian atmosphere that constituted a quasi-aerobraking effect). JPL Mission Design and Navigation's "TARDIS" (Traceable Automation with Remote Display and Interruptible Scheduler) workflow automation tool [19] was implemented to improve the invocation and workflow monitoring functions of MADCAP in late October 2014. Along with changing the invocation of the MADCAP runs, with TARDIS it was possible to incorporate several improvements to error control and logic flow in order to respond to some errors occasionally encountered in the daily operations (e.g., halting the run and not sending reports if the ephemeris downloads from SPS have failed).

Event driven automation was originally considered and is feasible given that the DSN/SPS provides an email message when a new ephemeris file is accepted into its repository. TARDIS could subscribe to the messages from SPS and kickoff a MADCAP analysis run any time an ephemeris for one of the spacecraft being monitored is uploaded by the navigation team. However, this event driven automation was subsequently eliminated from consideration given the asynchronous schedule with which missions upload ephemeris files. Several sets of reports would be distributed on particular days when Mars missions tend to upload ephemerides, subjecting customers to "incomplete" reports. Only the last report on a multi-update day would truly reflect the full set of recent updates.

E. Work Planned as of 2012, But Incomplete

Some other previously planned work has not progressed appreciably; several of these items remain on a "parking lot" list. In 2012 it was thought there might be interest in including monitoring of missions orbiting at L1/L2 Lagrange points. A parameter file was prepared and tested, but there has been no active interest in monitoring these orbital environments. The CCSDS Conjunction Data Message (CDM) [20], which was still under development in 2012, has now been used in flight operations for the past five years, primarily by the United States Air Force. Although the principal use of the CDM is in the densely populated Earth orbital environment, provision is made within the standard to report conjunctions detected in orbital environments other than Earth. In accordance with CCSDS policy, prototyping of the CDM was necessary prior to its becoming an international standard [21]; a simple prototype was built into MADCAP, but a full operations version has not been implemented. Though the CDM and the MADCAP Summary Report both focus on reporting information about conjunctions, one important difference between the two reports is that the CDM focuses in detail on one predicted conjunction, whereas the MADCAP Summary Report provides less information over a longer time frame and can encompass a large number of predicted conjunctions. The CDM's detailed focus on a single conjunction was not one of the MADCAP reporting design points.

VI. Unplanned Accomplishments Since 2012

Since 2012, JPL's Mars/Moon conjunction assessment efforts have also been extended in a few unplanned but important areas, as detailed in the following sections.

A. Improved Analysis Methods

Orbit crossing distance calculations are inaccurate during periods of coplanarity between the two bodies. A refined algorithm was developed to calculate minimum orbit distances when orbits are coplanar or nearly coplanar; it has an increased run time, but provides more accurate results in this situation. A check has been inserted to determine when the orbits being compared are coplanar (operationally defined as having angular momentum vectors within an operator specified parameter value). 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 vs. Deimos), the coplanar algorithm is only used for events within 60 days from the analysis time.

B. Improved Knowledge of Non-Operational Spacecraft/Objects

One thing the MADCAP team has been interested in for some time is how to best include non-operational spacecraft left in the Moon and Mars orbital environments. Long-term orbital predictions can be easily produced by simply propagating a previously known state, but these predictions typically contain large uncertainties, particularly with respect to the orbit phase. Because of these uncertainties, the identification of conjunction events between one active and one inactive spacecraft, or two inactive spacecraft, is somewhat suspect. In 2014, MADCAP started including inactive objects in its analysis, and produces the detailed reports and plots for pairs of objects that include at least one inactive object (satellite or natural object), but warnings via the Summary Report are not produced. 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.

If a spacecraft is not currently being tracked by the DSN, there generally will not be an ephemeris on SPS. For example, ephemeris files for ISRO's Chandrayaan-1, JAXA's Ouna, and NASA's MGS and Viking[5] orbiters are not uploaded to the SPS. These spacecraft are no longer operational, but they are still believed to be in orbit and can be used in analyses if an appropriate ephemeris is available. Ephemeris files for this type of non-operational spacecraft can be added by specifying an ephemeris file path in one of the MADCAP parameters. Though the uncertainty of the states in such ephemerides is greater than that of current solutions, these long-term predictions are better than nothing.

NASA's SLS/EM-1 mission will orbit the Moon in the relatively near future (schedule still TBD). In preparation for this mission, engineers at NASA's Johnson Space Center (JSC) were aware of the dead satellites at the Moon and inquired of JPL whether knowledge of these trajectories could be improved so the EM-1 trajectory could be planned to avoid them. This inquiry led the MADCAP team to consider using the DSN's Goldstone Solar System Radar (GSSR) [22] to detect the dead satellites and improve their trajectories for use in MADCAP runs. Optical telescopes are unable to search for small objects hidden in the bright glare of the moon, so radar seemed the only plausible method. While using Earth-based radars to observe Chandrayaan-1 and Ouna seemed feasible, success was not certain.

To test the concept, and potentially improve the knowledge of trajectories for non-operational lunar orbiters, between 02-Jul-2016 and 23-Sep-2016, JPL conducted five radar tracks using a variety of different transmit/receive configurations and a variety of radio telescopes in an attempt to locate the ISRO Chandrayaan-1 and JAXA Ouna spacecraft (see Table 1). Chandrayaan-1 had stopped operating in 2009, and Ouna was last contacted in 2010. MADCAP had been using trajectories for the Chandrayaan-1 and Ouna satellites based on propagations of their last known states. Uncertainties were acknowledged to be significant, but no better trajectories were available. Using the GSSR, JPL was successful in locating the Chandrayaan-1 orbiter (a cube about 1.5 meters on each side with a large solar panel 2.15 meters x 1.8 meters that significantly increased its radar cross section), obtaining sufficient observations to significantly improve the knowledge of the trajectory [23]. It was found that the orbit plane was essentially unchanged, but the downtrack position was significantly out of phase compared to the prior runout. It was necessary to shift the position of Chandrayaan-1 by nearly 180 degrees, or about half a cycle from the old orbital estimates from 2009 [23,24]. MADCAP is now using this updated trajectory, but it has now been about 1.5 years since it was produced so it has undoubtedly degraded again somewhat. JPL did not successfully locate the Ouna spacecraft despite several attempts, though it is thought to still be in orbit. One "candidate" observation of Ouna was obtained in late August 2016, but it could not be confirmed before the end of the experiment. Scheduling the GSSR was difficult because it was a very constrained resource, and the available funding for the experiment was exhausted by the end of fiscal year 2016. Earth-based radar detection of dead satellites at the Moon was challenging and required a reasonably good a priori trajectory (+/- 100 km). Due to the a priori requirement and the resource contention issues, it was concluded that the GSSR is not particularly suitable for a broad search similar to those within the capability of the US SSN [2]. As of this writing there are klystron issues that prevent the GSSR from operating at full power.

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[5] Drew Jones, "Viking1 Orbit Propagation Study", JPL Internal Report, 2 March 2017.

Table 1. Dead Lunar Orbiter Radar Observations Summary

Date	Objective	Transmit	Receive	Results Summary
02-Jul-2016	(1) Detect calibration satellite (2) Detect Chandrayaan-1 (Doppler)	DSS-14 (X-band)	Green Bank Telescope	(1) Calibrator detected (2) Candidate echo
03-Jul-2016	(1) Confirm Chandrayaan-1 detection (Doppler, range)	DSS-14 (X-band)	Green Bank Telescope	(1) Chandrayaan-1 confirmed
31-Jul-2016	(1) Detect Ouna (2) Confirm Chandrayaan-1	DSS-14 (X-band)	Green Bank Telescope DSS-13	(1) No Ouna detection (2) Detection, but predicted time was off due to error in orbit determination.
26-Aug-2016	(1) Detect Ouna (2) Confirm Chandrayaan-1	Arecibo (S-band)	Green Bank Telescope	(1) Candidate Ouna echo (2) Chandrayaan-1 confirmation
23-Sep-2016	(1) Detect Ouna (2) Confirm Chandrayaan-1	DSS-14 (X-band)	Arecibo	(1) Ouna not confirmed (2) Chandrayaan-1 confirmation

Work by JPL researcher Dr. Marina Brozovic shows how unlikely it is to use Earth based radars to detect a debris field at Mars. In Fig. 2 below[6], the "D" in the legend is the diameter of a metallic spherical spacecraft. The plot shows that even if such a spacecraft had a diameter of 50 meters, it could only be detected to about 10 lunar distances (approximately 4 million kilometers). Mars at its closest to Earth (during opposition) is around 56 million kilometers (approximately 140 lunar distances), i.e., dead satellites at Mars could not be detected using Earth-based radars due to the distance (echo power decay).

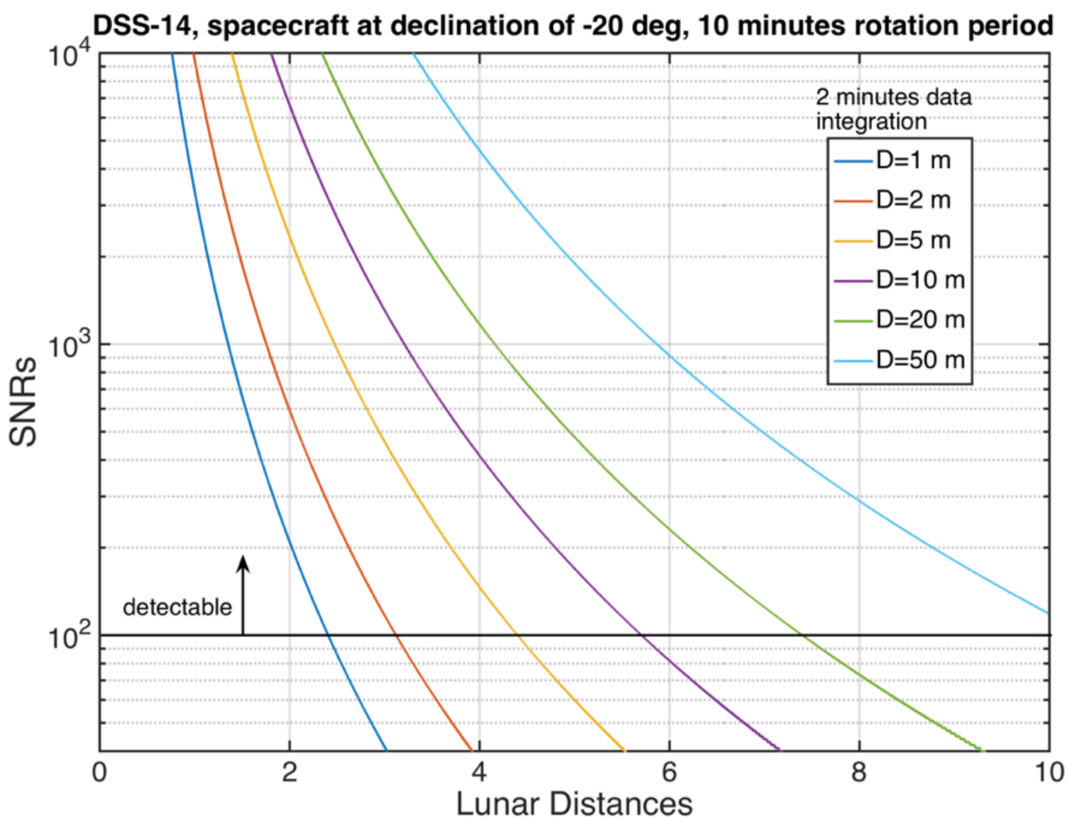

Fig. 2: Radar Detectability of Metallic Sphere at N Lunar Distances

[6] Personal communication, Marina Brozovic to David Berry.

C. Improved Reporting

Since 2012 there have been a number of improvements and enhancements to the set of reports produced at the conclusion of each MADCAP run. A number of these newer features were presented in 2015 at the International Symposium on Space Flight Dynamics [7]; this section will focus on a few of the notable changes since 2015.

In the past five years, most of the improvements in MADCAP reporting have appeared in the Summary Report, the purpose of which 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. The Summary Report provides information about the bodies included in the analysis and whether they are active, inactive, or a natural body; about the ephemeris files and whether they are predicts grade, reference, or something else; about the event thresholds and the method used to establish them; and a variety of important information about the ephemeris files used in the run (name, span, and submit date). This report is contained within the body of an email and sent out to a wide distribution. As previously noted, this essentially constitutes the "Monitor" function of the "Conjunction Assessment Process for Mars Orbiters" [15], providing a "quick look" that conveys whether or not there is an observation that requires further attention. If a red event is identified, the "Response" function is activated.

In 2012, it was necessary to actually open a MADCAP Summary Report to determine if there had been any red events in a given analysis run. In May 2015, the number of red events identified in a given run was added to the email subject line (zero to n events). Thus a Summary Report recipient could determine if a given report contained anything meriting a response without opening the email; this feature allows a recipient to ignore the Summary Report if the number of red events is zero.

Until August 2017, it was necessary to compare successive MADCAP Summary Reports to determine if there had been any changes from one run to the next. In an updated release of MADCAP software, counters for changes in the run compared to the previous run were added at the top of the report; there were counters for the number of ephemeris file updates that had occurred and the number of thresholds that had changed. The changed items were colored blue and flagged with an asterisk "*" so they stood out from the normal black text of the report.

Internally, MADCAP sends text messages to its operations team at the end of each run to confirm that it has in fact run, with an additional text message when any red events are identified in the run. This facilitates a timely response by the MADCAP team, and is particularly useful over weekends or holidays. Text messages are not at this time provided outside the MADCAP team, though they could potentially be offered in the future.

D. "Renaming the Baby"

One relatively minor change that was implemented was to rename the MADCAP program. In the beginning (2011), it had been named the "*MArs* Deepspace *Collision Avoidance* Process" (MADCAP) given that funding for the effort was primarily provided via the Mars Exploration Program, and the Mars environment was the first extraterrestrial environment of interest for study with MADCAP. However, a bit later some funding to support the lunar environment was obtained from the GRAIL mission and NASA/CARA. Several enhancements were then implemented based on lunar mission requests. To better reflect the large number of applicable missions, the multiple environments, and the functions involved, the MADCAP acronym was re-purposed and the process was re-christened the "*Multimission Automated* Deepspace *Conjunction Assessment* Process".

VII. Conjunction Assessment at Mars and the Moon - A New List of Future Plans

As in the 2012 paper, this paper concludes by identifying a few items for potential future work. Planning for some of these is already in progress, though budgeting for actual implementations is still uncertain.

A. User Requested Runs

Though typically MADCAP is invoked by automation, the capability to initiate an unscheduled run is preserved for several reasons. MADCAP can be executed manually from the Linux command line, passing it the required parameter file, if an analysis is desired outside the automation framework. This capability is utilized by the MADCAP team when new releases are tested, and also when it is necessary to restart the process after an error from which recovery is not automated. In February 2014, this capability was also used for a special collision avoidance study between NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) and the Lunar Reconnaissance Orbiter (LRO). The special study was conducted because MADCAP reports showed that the orbit crossing distance between LRO and LADEE would be less than 1 km for a few orbits. As described in Ref. [7]:

> 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 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. Based on these MADCAP reports, both projects redesigned 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.

This use of MADCAP to conduct special ad hoc analyses helped both projects avoid a potential collision, but it required a substantial time allocation by some members of the MADCAP operations team for a number of weekend runs using special ephemeris files. It also inspired the idea of allowing flight projects to conduct ad hoc studies on their own, i.e., "user requested runs". Such a feature would allow users to run studies at essentially any time without involving the MADCAP operations team (with some blackout limitations during regularly scheduled MADCAP operations runs). A high-level concept for such a capability has been brainstormed, but is not yet implemented.

B. Enhanced Visualization of Orbit Conjunctions

The current two-dimensional (2D) 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 could be gained from a three-dimensional (3D) visualization of the spacecraft orbits at the time of the conjunction. JPL's Monte navigation software is being enhanced to make generation of 3D orbital representations more seamless and straightforward. It may be possible for MADCAP to utilize this improvement to generate 3D images of the spacecraft orbits at the time of conjunction and include them as attachments in the emailed reports. The MADCAP team has been exploring this new capability.

C. Collision Probability (2D and 3D)

The recent addition of covariance data used by MADCAP for calculating threshold values leads to a natural progression into using the data to calculate collision probabilities. Since the data sources used by MADCAP (SPICE SPK files, OEMs) do not contain spacecraft attitude information, MADCAP cannot take attitude into account in any probability calculations. Thus the calculation is necessarily based on a keep-out sphere around each spacecraft or natural body. MADCAP has the capability to calculate 2D collision probabilities based on spherical spacecraft radii provided as input parameters [6] and the covariance data from OEM files currently used for threshold calculations. It has been suggested that MADCAP implement the 3D collision probability algorithm that NASA/CARA is using for Earth orbiters [18]. The 3D algorithm does not depend upon some of the simplifying assumptions used in calculating the 2D collision probability (e.g., 2D assumes a straight trajectory, 3D allows use of a more realistic curvilinear trajectory; 2D assumes a static covariance size and orientation, 3D allows the size and orientation of the volume defined by the covariance to vary with time).

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 the Response Process. We have also commenced initial research into a different metric for establishing red event thresholds to address a concern that has arisen with the current method of using covariances to calculate thresholds (and collision probability) for spacecraft in highly elliptical orbits.

D. Work with NASA/JSC on SLS/EM-1 and SLS/EM-2 Missions

The MADCAP team has been discussing with NASA/JSC the use of MADCAP to perform conjunction assessments including the large number of cubesats planned for co-manifest on NASA's SLS/EM-1 and SLS/EM-2. As noted previously, current plans call for up to 13 cubesats on SLS/EM-1 and up to 40 cubesats on SLS/EM-2. Options under consideration include an implementation of the User Requested Run feature in JPL's MADCAP implementation, and establishing a second instantiation of MADCAP at NASA/JSC. It is possible that there could be a near-term implementation of the CDM in order to support the SLS/EM-1 and SLS/EM-2 missions. NASA/JSC is familiar with the CDM, and may be interested in receiving CDMs for conjunction events that occur in cis-lunar space during these missions.

VIII. Conclusion

This paper has presented an update on the techniques used at JPL for automated conjunction assessment at Mars and the Moon using the MADCAP software. Much of the future work that was planned during a previous presentation in 2012 has since been implemented to some degree. Other unanticipated enhancements have also been applied in order to improve MADCAP's conjunction assessment analysis and reporting. Some further areas of potential future work to improve the current operation have been outlined.

MADCAP provides a "watchdog" infrastructure service at the Moon and Mars, extraterrestrial environments likely to experience an increase in exploration activity by spacefaring nations, where there are already multiple objects in orbit. Assuming accurate trajectories for future missions are made available on a regular basis, MADCAP can provide analyses to help prevent a debris field from being created, benefitting all spacefaring nations wishing to explore these shared orbital environments.

IX. Appendix - A Sample MADCAP Summary Report

From: JPL MDNAV <jplmdnav@airmail.fltops.jpl.nasa.gov>
Date: Monday, March 5, 2018 at 2:56 PM
To: mars_madcap_monitor <mars_madcap_monitor@jpl.nasa.gov>
Subject: MADCAP -- Mars -- Summary -- 1 Red

Analysis Time: 2018-03-05 21:33:54 UTC

RED Threshold Updates:	0
ALL Threshold Updates:	0
Ephemeris Updates:	5

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	TGO	Active
6r	TGO	Active/Reference
7	Phobos	Natural
8	Deimos	Natural
9	VIKING1	Inactive
10	MGS	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)
3-4	-1.6 5.5 4P	84.4 254.2 4P	68.4 ----- --	2018-03-16 17:57:50

All (Conjunction Data < 'All' Thresholds for <= 100 days)

Bodies	OXD (km)	OXT (sec)	CAD (km)	CA Epoch (UTC-SCET)
3-4	-10.0	-1336.7	1143.7	2018-03-16 08:49:23
3-4	-9.1	5397.9	2719.6	2018-03-16 09:46:21
3-4	-5.9	2741.8	1624.3	2018-03-16 13:49:28
3-4	-1.6	84.4	68.4	2018-03-16 17:57:50
3-4	0.4	-2562.3	2197.2	2018-03-16 22:03:50
3-4	3.3	4171.1	2164.1	2018-03-16 22:59:17
3-4	8.1	1512.8	1093.3	2018-03-17 03:05:32
3-4	9.4	-1142.4	981.4	2018-03-17 07:13:50
1-6	9.9	-35.6	79.2	2018-04-14 14:52:20
1r-6	9.9	-35.6	79.2	2018-04-14 14:52:20
1-6r	9.9	-35.6	79.2	2018-04-14 14:52:20
1r-6r	9.9	-35.6	79.2	2018-04-14 14:52:20
1-6	9.6	7043.4	88.1	2018-04-27 22:07:50
1r-6	9.6	7043.4	88.1	2018-04-27 22:07:50
1-6r	9.6	7043.4	88.1	2018-04-27 22:07:50
1r-6r	9.6	7043.4	88.1	2018-04-27 22:07:50
1-6	9.2	6997.3	97.3	2018-05-20 08:07:34
1r-6	9.2	6997.3	97.3	2018-05-20 08:07:34
1-6r	9.2	6997.3	97.3	2018-05-20 08:07:34
1r-6r	9.2	6997.3	97.3	2018-05-20 08:07:34
1-6	9.8	3.6	10.7	2018-05-20 13:03:03
1r-6	9.8	3.6	10.7	2018-05-20 13:03:03
1-6r	9.8	3.6	10.7	2018-05-20 13:03:03
1r-6r	9.8	3.6	10.7	2018-05-20 13:03:03
1-6	7.7	45.0	56.2	2018-05-20 15:01:15
1r-6	7.7	45.0	56.2	2018-05-20 15:01:15
1-6r	7.7	45.0	56.2	2018-05-20 15:01:15
1r-6r	7.7	45.0	56.2	2018-05-20 15:01:15

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 for events at least 14 days ahead from the analysis time. Reference trajectories use the same thresholds as the nominal trajectories.

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

Analysis time:	2018-03-05 21:33:54 UTC
Active spacecraft:	Odyssey, Mars Express, MRO, MAVEN, MOM, TGO
Natural bodies:	Phobos, Deimos
Inactive spacecraft:	VIKING1, MGS
Output directory:	/nav/home/jplmdnav/MADCAP/Mars/archive
Point of contact:	MADCAP_Mars@jpl.nasa.gov
MADCAP build:	2.04.0

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	1.3357	0.3322	0.0042	0.0100	3.9752	1.7560
5	MOM	0.2498	0.0014	0.0012	0.0100	33.0089	0.3246
6	TGO	1.0000	0.0000	0.0000	3000.0000	0.0000	0.0000
7	Phobos	30.0000	0.0000	0.0000	15.0000	0.0000	0.0000
8	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. Lines for coefficients which have been updated since the last run are colored blue, and each line's body is marked with an "*". Thresholds listed as "C" are based on 3-sigma covariance data provided by the mission.

All Thresholds -- Constants

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	TGO	10	100
7	Phobos	45	100
8	Deimos	60	200

All OX Distance Threshold = OXD
All CA Distance Threshold = CAD

All thresholds are always constants. The constants used are listed in the table above. Lines for constants which have been updated since the last run are colored blue, and each line's body is marked with an "*".

Ephemerides

Body	Ephemeris	Submitted	Begin	End
1	p_m_od71869-71873_72975_v1.bsp	2018-02-27 00:05:46 UTC	25-FEB-2018 21:13:50 UTC	27-MAY-2018 23:58:50 UTC
1r	p_m_od71869-71873_72975_v1.bsp_V0.1	Analysis Time	25-FEB-2018 21:13:50 UTC	27-MAY-2018 23:58:50 UTC
2*	MOEM_180305OAS_PREDICT__0001.CR.bsp	2018-03-05 14:00:47 UTC	22-FEB-2018 12:35:36 UTC	27-MAR-2018 19:22:41 UTC
2r	MOEM_180122OAS_SCHED____0001.CR.bsp	2018-01-23 15:52:01 UTC	21-JAN-2018 01:08:49 UTC	01-JAN-2022 00:00:00 UTC
3	pf_psp_rec54351_54346_55121_p-v1.bsp	2018-03-01 18:11:07 UTC	01-MAR-2018 03:48:50 UTC	30-APR-2018 14:07:50 UTC
4*	trj_orb_06667-06670_06831_v1_mvn.bsp	2018-03-05 19:06:52 UTC	05-MAR-2018 03:48:50 UTC	04-APR-2018 16:48:50 UTC
5*	mom_spk_180301-180501_od494_v1_dsn.bsp	2018-03-05 21:22:58 UTC	01-MAR-2018 14:30:00 UTC	01-MAY-2018 12:00:00 UTC
6*	TOEM_180305OAS_PREDICT__0001.CR.bsp	2018-03-05 11:52:54 UTC	04-MAR-2018 23:49:28 UTC	16-JUL-2018 04:46:38 UTC
6r*	TOEM_180302OAS_SCHEDULE_0001.CR.bsp	2018-03-05 14:55:08 UTC	26-FEB-2018 08:51:18 UTC	02-NOV-2019 14:49:42 UTC
7	mar097.2010-2029.bsp	Analysis Time	29-DEC-2009 23:58:53 UTC	01-JAN-2030 23:58:50 UTC
8	mar097.2010-2029.bsp	Analysis Time	29-DEC-2009 23:58:53 UTC	01-JAN-2030 23:58:50 UTC
9	viking1_nominal_01032017_01032019.bsp	Analysis Time	28-FEB-2017 23:58:50 UTC	28-FEB-2019 23:58:50 UTC
10	p_171030-181030-061214_10yr_nominal.nio	Analysis Time	30-OCT-2017 05:28:50 UTC	30-OCT-2018 06:28:50 UTC

Ephemeris files for the bodies analyzed are listed in the table above. Lines for files which have been updated since the last run are colored blue, and each line's body is marked with an "*".

X. Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract to the National Aeronautics and Space Administration. The authors thank members of JPL's Mission Design and Navigation Section who contributed to the requirements development and incremental improvement of the MADCAP, particularly those involved in orbital navigation operations at Mars and the Moon. Special thanks are extended to colleagues who reviewed early drafts of this paper and offered comments.
Clearance number CL#18-????.

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