Automated Spacecraft Conjunction Assessment at Mars and the Moon

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Conjunction assessment and the related activity of collision avoidance are areas of current high interest in organizations that conduct space operations. Most current conjunction assessment activity focuses on the Earth orbital environment (spacecraft plus debris), however, Earth is not the only orbital domain in which there is interest in avoiding collisions in space. Several of the world's space agencies have satellites in orbit at Mars and the Moon, and additional future missions are planned. A question that has arisen at some recent mission reviews is the potential for collisions along the planned and/or current spacecraft trajectory. While the intuitive probability of collisions in these sparsely populated environments is very low, the consequences of a collision are catastrophically high. Intuitive notions may also be faulty due to factors including (a) many orbits of scientific interest have similar characteristics, and (b) surface spacecraft using relay services require periodic flyovers that may be shared among several orbiters. Analytic approaches can provide much more certain assessments of the probability of collisions than can intuitive approaches. This paper will describe the techniques used at the Jet Propulsion Laboratory to perform conjunction assessment at Mars and the Moon. In brief, the method involves automatically initiating analysis scripts, automatically downloading ephemerides from the Deep Space Network portal, adding supplementary ephemerides for planned and/or non-operational missions, performing pairwise comparisons of various user selectable conjunction attributes, preparing reports, and communicating the results to interested parties. For each orbital environment, a unique set of process parameters is maintained. The techniques discussed are not unique to any specific orbital environment, so they could be utilized for any orbital environment where multiple spacecraft operations may be contemplated. The paper will also discuss future work (e.g., adding an option to produce output in Consultative Committee for Space Data Systems Conjunction Data Message format).

Nomenclature

OBJ = combined object radius
x = distance along major axis
x_m = x component of projected miss distance
y = distance along minor axis
y_m = y component of projected miss distance
σ_x = major axis standard deviation for combined covariance
σ_y = minor axis standard deviation for combined covariance

I. Introduction

CONJUNCTION assessment and the related activity of collision avoidance are areas of current high interest in organizations that conduct space operations. Most current conjunction assessment activity focuses on the Earth orbital environment (spacecraft plus debris), however, Earth is not the only orbital domain in which there is

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interest in avoiding collisions in space. Specifically, several of the world's space agencies have satellites in orbit at Mars and the Moon, and additional future missions are planned for these orbital environments. This paper will examine the process of conjunction assessment that has been implemented at the Jet Propulsion Laboratory (JPL) for these two principal non-Earth orbital environments as of 2012. A question that has arisen at some recent mission reviews is the potential for collisions along the planned and/or actual spacecraft trajectory, even though the number of spacecraft currently operating in or planning operations in these orbital environments is relatively small.

II. Non-Earth Orbital Environments With Potential for Spacecraft Collisions

A. Conjunction Assessment at Mars

The first non-Earth environment for which there was interest in conjunction assessment and collision avoidance is Mars, where the United States National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have spacecraft in orbit and/or on approach. NASA operates the Mars Odyssey and Mars Reconnaissance Orbiter (MRO) missions at Mars, with the Mars Science Laboratory (MSL) on approach as this paper is being written. ESA operates the Mars Express (MEX) spacecraft. Since mid-2002, when the Mars Odyssey spacecraft joined the Mars Global Surveyor (MGS) in orbit at Mars, ad hoc collision avoidance studies have been conducted on an occasional basis for the Mars environment. The frequency of collision avoidance studies increased when MEX arrived on scene in late 2003, however, the analyses continued to be run manually on an ad hoc basis. The MRO aerobraking campaign in 2006 was also a major driver in conjunction assessment studies at Mars. During the aerobraking process, it was possible that MRO would cross the orbital paths of the three other operational spacecraft then at Mars or the two Martian moons, so a detailed collision avoidance strategy involving frequent conjunction assessments was developed.[1] Several agencies have recently announced interest in launching Mars missions (e.g., the Indian Space Research Organization (ISRO), Roscosmos, and the China National Space Administration (CNSA)), expanding the need for conjunction analysis in the future. The tracking data sources for Mars are presently the Deep Space Network (DSN) and the ESA Tracking Station Network (ESTRACK). Radar is not in use for tracking spacecraft at Mars.

B. Conjunction Assessment at the Moon

The second non-Earth environment for which there is major interest in conjunction assessment and collision avoidance is the Moon, where NASA has several spacecraft in orbit: the Lunar Reconnaissance Orbiter (LRO), GRAIL-A, GRAIL-B, ARTEMIS-P1, and ARTEMIS-P2. In addition, ISRO and the Japan Aerospace Exploration Administration (JAXA) have spacecraft in orbit at the Moon that are no longer actively being tracked (ISRO's Chandrayaan-1 spacecraft, which failed in 2009, and the Ouna spacecraft, which was a sub-satellite of JAXA's SELENE mission). The tracking data source for the Moon is presently the DSN. As at Mars, radar is not in use for tracking spacecraft at the Moon.

III. "MADCAP"

A process named "MADCAP" (MArs Deepspace Collision Avoidance Process) was developed at JPL to automatically and systematically examine various aspects of multiple spacecraft in orbit about Mars. MADCAP originated in the scripts that were run on an ad hoc basis for the purpose of occasionally calculating close approaches at Mars, first between two NASA spacecraft (MGS, Odyssey), and subsequently between one ESA and two to three NASA spacecraft (MEX, MGS, MRO, Odyssey). When an analysis was desired, an ephemeris was requested from ESA for the MEX spacecraft, and the analysis program was run manually. However, given that it is planned that the Mars-orbiting spacecraft remain in operations for a number of years, this ad hoc analysis was insufficient to properly understand the risk of potential collisions. Although the spacecraft are in relatively stable science orbits, they are modified periodically, e.g., in order to adjust orbit phasing for relay operations. The spacecraft are also subject to the standard environmental perturbations (e.g., atmospheric drag, gravity, solar radiation pressure). Due diligence suggested that JPL navigators always be prepared to answer the "how close are the orbits?" question whenever asked rather than having to arrange an ad hoc analysis on short notice. Hence MADCAP, which was created by wrapping an automation and reporting framework around the scripting that had been run manually in the past.

IV. Methodology

This section will discuss the principal aspects of the MADCAP method. MADCAP consists of a set of python and perl scripts that utilize JPL's MONTE next generation navigation 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 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.

After initialization, the script autonomously accesses the DSN Service Preparation Subsystem (SPS) portal and downloads the latest ephemerides for the spacecraft specified in a parameter file. Using these ephemeris files, and optionally adding some supplementary ephemerides for planned and/or non-operational missions, various user selectable attributes of the orbits of the spacecraft are pairwise analyzed. Output tables containing collision metrics for each spacecraft pair are created. If the value of a given attribute for a pair of spacecraft is less than a user specified minimum threshold (e.g., the minimum close approach distance) then a notification email is sent to a list of addresses specified in a parameter file. A summary file of the results of all closest approach distance analyses is also produced. Plots of a few conjunction attributes can also be generated.

The next several sections discuss the key aspects of the MADCAP methodology in greater detail.

A. Parameterization

Although its roots are at Mars, as noted above MADCAP is also used to analyze conjunctions at the Moon. The principal features that allow MADCAP to be used for conjunction assessment in orbital environments other than Mars are (a) the general purpose nature of the MONTE software, and (b) the use of a parameter file containing inputs to be used by the script. 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). For each orbital environment, a unique set of process parameters is maintained depending on the preferences of the mission management and the navigation teams involved at that environment. Several parameters are provided that allow detailed specification of the ephemeris files that should be used in the analysis (see "Ephemeris Files" below).

In a given parameter file, the user must specify the conjunction attribute upon which the analysis will be performed (e.g., the relative distance and speed at closest approach), along with the threshold that will trigger the user notification process. Other key parameters specify a list of data items that should be analyzed and printed/plotted and several parameters for use in calculating the probability of collision (coordinate system, the radii of the objects in kilometers (km), constant covariance sigmas (in km) and the covariance reference frame). The covariance sigmas are constant in the initial version of MADCAP because the true covariance data is not contained in the Spacecraft Planetary Kernel (SPK) ephemeris files available on the DSN Portal.

There are also several parameters used to specify directories to which ephemeris files should be downloaded, where to find a second file for a given spacecraft if it is desired to perform the analysis on more than one trajectory for the same spacecraft, and a directory where the output reports will be archived. Finally, there is a parameter that allows one or more email addresses to be specified for delivery of MADCAP reports.

B. Analysis Scripts/Automated Initiation

MADCAP is activated by a Linux cron job on a schedule that is based on the ephemeris update frequency of the spacecraft operating in the environments under study. It is currently scheduled to run automatically twice weekly in the case of Mars, and daily in the case of the Moon. The script can also be initiated manually from the Linux command line by executing the script and passing it the required parameter file if an analysis is desired outside the automation framework.

C. Ephemeris Files

Ephemeris files for the spacecraft in the parameter list are automatically downloaded from the DSN's SPS Portal, which is the source of the ephemeris files used in predicts generation for all DSN tracking. Automated access to the ephemeris repository is desirable because the multiple 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 among the teams. MADCAP receives a listing from SPS that itemizes the available ephemeris files for each spacecraft specified in the parameter file, parses the list to select the ephemeris for each spacecraft that was most recently submitted by each of the navigation teams, then downloads and stores it in the location defined by the user in the input file. The most recent ephemeris file for each spacecraft is selected based on the largest SPS file ID, which monotonically increases with time.

However, not every ephemeris file that is desirable for conjunction analysis is uploaded to the DSN SPS. MADCAP also provides a means in the parameter file to indicate that an ephemeris should *not* be downloaded from SPS for special cases; 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, JAXA's Ouna, and NASA's Viking and MGS orbiters are not currently 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 non-operational spacecraft can be added by specifying an ephemeris file location 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. The trajectory being used for Chandrayaan-1 is based on the best quality reconstruction created by JPL Navigation using data primarily from the DSN and from the Johns Hopkins University Applied Physics Laboratory (APL) tracking station. The trajectory being used for Ouna was propagated at JPL using the Mean Elements Long Term Propagator functionality within JPL's MONTE navigation software based on orbital elements provided by JAXA. The Viking and MGS trajectories are not included in present analyses, but preparations to add them to the Mars environment parameters in the near future are underway.

In addition, sometimes navigation teams wish to include both a current solution and a longer term reference trajectory 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 trajectory file downloaded from the SPS.

Note that natural body ephemerides (e.g., a natural planetary satellite) may also be specified for analysis. For example, at Mars, close approaches of spacecraft to the natural satellites Phobos and/or Deimos may be of interest.

D. Orbit Comparisons

MADCAP performs pairwise comparisons for all combinations of two spacecraft [$\binom{n}{2} = \frac{n!}{(n-2)!2!}$], where "n" is the number of spacecraft listed in the parameter file. Comparisons occur over the duration of the overlapping time period of the two ephemeris files analyzed. A variety of conjunction attributes may be selected for analysis, as listed in Table 1.

Table 1. MADCAP Orbit Conjunction Attribute Options

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

The threshold values for the conjunction attribute of interest can be set differently for each spacecraft in the analysis by use of the threshold parameters. If the thresholds for two spacecraft being compared are different, then the maximum value of the two thresholds is used in the analysis, giving more conservative results.

E. Output Reports

MADCAP prepares various reports, which are written to file. Three types of reports are produced: detail, summary, and plots.

A detailed output table is created for each pair of spacecraft analyzed. The output tables contain the results of analysis of the conjunction attributes specified by the user, and are sorted by the conjunction attribute desired by the user. Each line in the output table will contain the 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. A sample detailed report is shown in Appendix B, Figure 1.

The summary report focuses on the "close approach distance" attribute, and categorizes the close approaches as green, yellow, or red depending on the magnitude of the close approach. The thresholds for these categorizations are established by the navigation team chiefs for the missions operating in the Mars and Lunar orbital environments. Those conjunction events categorized as red have two sections in the summary report. In one section appear all the red conjunctions predicted for a user selectable future time period (e.g. 14 days), and in a separate section immediately following the first appears the first red conjunction (if any) for each spacecraft pair throughout the overlap period between the two ephemerides. Conjunctions rated as green are generally not printed in the summary report. A sample summary report is shown in Appendix B, Figure 2.

MADCAP will also generate plots of several of the conjunction attributes if requested by the user, specifically, relative distance at closest approach, minimum orbit crossing distances, and/or minimum orbit distances. Included in the MADCAP parameter list are optional x-axis and y-axis limits for plots generated by MADCAP. A sample plot is shown in Appendix B, Figure 3.

F. Communicating Results

The MADCAP parameter file contains a list of email addresses to which the output reports will be sent; these are nominally fixed group email addresses that can be modified independently without having to change MADCAP parameters. Accommodations are made for normal engineering reporting and for management escalation reporting.

G. Decision Process

Current spacecraft in the Mars and Moon environments normally maintain a safe separation. However, occasional close approaches with low miss distance have warranted some escalation of communication and discussion as to whether any action was in fact necessary. At present no official decision-making process has been established for handling these events, but future work plans include the development of procedures and standards.

V. Collision Probability

Based on an argument from intuition, the probability of collisions in the sparsely populated Mars and Moon orbital environments is very low (effectively zero). However, the consequences of collision are catastrophically high: millions to billions of dollars/euros/yen/etc. in lost tax revenue investment, irreparable loss of science data, and the creation of a debris environment in otherwise pristine orbital environments are three obvious consequences. The international repercussions of spacecraft from two different nations/agencies colliding would also very likely be undesirable. Given world economy, spacecraft collisions and the resultant waste of tax revenue can potentially lead to reduced popular support for the world's space agencies, the many benefits of space exploration notwithstanding.

Intuitive notions regarding collision probability may also be faulty due to other factors. For example, many orbits of scientific interest have similar characteristics (e.g., equatorial orbits, polar orbits, sun-synchronous orbits, body-synchronous orbits, etc.). Also, particularly at Mars since 2004, surface spacecraft such as the Mars Exploration Rovers or the Mars Science Laboratory use relay services that require periodic flyovers in order to transmit science and engineering data. These flyovers may be shared among several orbiters such as MRO, Mars Odyssey, and MEX. Analytic approaches can provide much more certain assessments of the probability of collisions than can intuitive approaches. The problem of analyzing collision probability has been studied extensively in the Earth environment (see, for example, References 2 through 8), and similar analytic approaches can be utilized in other orbital environments where the potential for spacecraft collisions exists. After considering several different approaches to calculating the collision probability, an advisory group selected for MADCAP a technique based upon equation (1) of Reference 2:

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

"At the time of closest approach, a projection is done onto the plane perpendicular to the relative velocity (often called the collision plane), thereby reducing the dimensional complexity from three to two. For convenience, the axes of the collision plane can be aligned to correspond with the major and minor axes of the projected, combined, error ellipse."[2]

Assessing the probability of collision requires at minimum the trajectories of the spacecraft under study, estimates of the uncertainty in those trajectories, a common reference frame, and a model of the spacecraft. Trajectory uncertainties are generally provided via a covariance matrix; MADCAP has parameters that express constant covariance sigmas (in km) given that the actual covariance information is not available in the SPK ephemeris files. MADCAP accommodates two reference frames ("RTN" for the spacecraft radial-transverse-normal frame, and "XYZ" for the Cartesian frame). If the trajectories of the two spacecraft are not in the same reference frame, then the states in one of the trajectories need to be rotated into the frame of the other. The model of the spacecraft is assumed to be spherical so as to not require attitude information; the actual radius of the sphere (in km) may perhaps be enlarged by a "keep-out zone".

VI. Future Work

The development of MADCAP has been conducted using portions of several small budgets applicable to multimission software and operations, and it has grown in a "semi-organic" manner. While already useful, it has not yet reached its full potential. MADCAP has a number of areas where future work would be beneficial. Future work is anticipated in several areas as follows:

1) Determining the response when close approaches are "too close" has not yet been formalized. At the NASA Goddard Space Flight Center (GSFC), there is a well defined Collision Avoidance Risk Assessment (CARA)[9] process that is followed in the event that a close conjunction is predicted in the Earth orbital environment. Such measures are not presently formalized at JPL, but are executed on a case-by-case basis. Development of a standard response is desirable.
2) True covariance information needs to be added to improve the collision probability computation. As noted above, the covariance matrix data is not available in the SPK file structure, and "default" covariances are presently used; these are established based on the experience of the navigation team for the particular spacecraft. Incorporating "true" covariance information will require future work and will make the probability calculation more accurate. A change in the collision probability formulation may also be necessary.
3) Collaboration with GSFC, which is chartered by NASA with the conjunction assessment function for Earth orbiting satellites[10], would be desirable. Such a collaboration might focus on comparing techniques, process improvements based on technical interchange, cost-sharing, and formal division of labor (e.g., allocating the responsibility for conjunction assessment to JPL if the DSN is used to track the objects, or GSFC if Space Network/Near Earth Network and/or the United States Strategic Command (USSTRATCOM) is used to track the objects). Collaboration with ESA's Space Situational Awareness program[11] may also be a possiblity.
4) More sophisticated automation features than Linux "cron" are under consideration. Event driven automation may be feasible given that the SPS provides an email message when a new ephemeris file is accepted into its repository. MADCAP could subscribe to the messages from SPS and kickoff an analysis run any time an ephemeris for one of the specified spacecraft is uploaded by a navigation team. Also possible is incorporating MADCAP into a more general purpose automated ground navigation system that is currently being prototyped at JPL, in which case a process of polling SPS for the most current ephemerides would likely be implemented.
5) There are other current shared orbital environments of potential (though lesser) interest, specifically, the Sun-Earth Lagrange Points L1 and L2. At L1, NASA's Advanced Composition Explorer (ACE) and WIND spacecraft orbit, as does ESA's Solar and Heliospheric Observatory (SOHO) mission. At L2, NASA's defunct Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft, CNSA's Chang'e 2, and ESA's Herschel and Planck satellites orbit. L2 is also the destination of NASA's future James Webb Space Telescope (JWST). The L1 and L2 environments are quasi-stable and objects in these environments use halo or Lissajous orbits about the Lagrange point; because of the instability there is a need for orbit maintenance on a regular basis. An offset from L1 is also necessitated by the fact that the radio telescopes pointed directly at L1 also point directly at the Sun, so the radio interference would be prohibitive for tracking. Currently analysis of spacecraft orbits at Sun-Earth L1/L2 are not automated, though they could

easily be (for the Sun-Earth L1 environment, an experimental parameter file setup by one co-author took less than an hour). In the future, Earth-Moon L1/L2 may also become orbital environments of interest for conjunction assessment given current discussions regarding their use as destinations for human missions and/or far-side relay.[12]

6) In the not too distant future, it is anticipated that an international standard now in development by the Consultative Committee on Space Data Systems (CCSDS) will be available for communicating information about predicted conjunctions, specifically, the CCSDS Conjunction Data Message (CDM)[13]. This new message builds on the CCSDS Orbit Data Message standard already in use among many satellite operators. The CDM is an evolution of USSTRATCOM's recent efforts to share conjunction data; to meet the need of commercial and non-US satellite operators for actionable satellite conjunction geometry data, USSTRATCOM began sharing a Conjunction Summary Message (CSM) in July 2010. In October 2010, a collaboration with the CCSDS on an international standard message format was initiated. The goal of this collaboration is the CDM, which is targeted to eventually replace the CSM. Since its inception in October 2010, the CCSDS CDM draft standard has matured rapidly. Coordination to date of this international standard has involved achieving consensus by the international community on the content and format of the information deemed necessary for mitigating the consequences of satellite conjunctions. As of April 2012, the CDM is in the final stages of the CCSDS Standards Development Process[14] (at the time of this writing it is a "Red Book", which means that it has been made available for international review and comment). The CDM is primarily targeted towards implementation in the densely populated Earth orbital environment, however, provision is made within the standard to report conjunctions detected in orbital regimes other than Earth. It is anticipated that as part of the prototyping effort required by the CCSDS Standards Development Process, the option to select a CDM as a MADCAP output format will be made available. Once the CDM is completed, agencies and industry alike can use a common international standard to understand the nature of the geometry of a pending conjunction and decide on an optimal maneuver plan, if necessary. In the future, any organization that can detect a conjunction could send a CCSDS CDM to warn a satellite operator. That operator could receive multiple warnings from multiple detectors, but the format of the warnings would be standardized, thus simplifying their integration and the necessary decision-making process.

VII. Conclusion

The techniques used at JPL for automated conjunction assessment at Mars and the Moon using MADCAP have been presented. The processes that have been implemented are not unique to any specific orbital environment, so they could be utilized for any orbital environment where operations of at least two spacecraft may be contemplated. MADCAP is currently in daily operation, and because of this current users are generating a number of ideas to improve it. Potential future work to enhance the current baseline operation has been outlined. The relatively near future likely holds the prospect of additional spacecraft at Mars, the Moon, Earth-Sun-L1/L2, and Earth-Moon-L1/L2. MADCAP can be used in all of these multi-spacecraft environments to ensure a safer orbital environment for all.

Appendix A
Acronym List

ACE	Advanced Composition Explorer
APL	Johns Hopkins University Applied Physics Laboratory
CARA	Collision Avoidance Risk Assessment
CCSDS	Consultative Committee for Space Data Systems
CDM	CCSDS Conjunction Data Message
CNSA	China National Space Administration
COLA	collision avoidance
CSM	Conjunction Summary Message (United States Strategic Command)
DSN	Deep Space Network
ESA	European Space Agency
ESTRACK	ESA Tracking Station Network
GSFC	Goddard Space Flight Center (NASA)
ID	file identifier (SPS)
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
km	kilometers
Ln	Lagrange Point "n" ($n \in \{1,2,3,4,5\}$)
LRO	Lunar Reconnaissance Orbiter
MADCAP	MArs Deepspace Collision Avoidance Process
MEX	Mars Express
MGS	Mars Global Surveyor
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
RTN	Radial-Transverse-Normal
SOHO	Solar and Heliospheric Observatory
SPK	Spacecraft Planetary Kernel
SPS	Service Preparation Subsystem (DSN)
URL	Uniform Resource Locator
USAF	United States Air Force
USSTRATCOM	United States Strategic Command
WMAP	Wilkinson Microwave Anisotropy Probe

Appendix B
Sample MADCAP Reports

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

# Calendar Date	Julian Date (days)	RELATIVE Distance (km)	RELATIVE Speed (km/s)	Collision Probability
06-MAY-2012 11:31:03.547	2456053.97990	14.05064	2.89753	0.00587
01-MAY-2012 10:23:40.970	2456048.93311	28.22475	2.90483	0.00229
03-MAY-2012 02:07:21.064	2456050.58844	55.77511	2.89525	0.00007
08-MAY-2012 03:14:48.459	2456055.63528	98.52263	2.89337	0.00000
04-MAY-2012 19:47:24.982	2456052.32459	101.18978	2.89296	0.00000
09-MAY-2012 20:54:47.876	2456057.37139	106.70121	2.89202	0.00000
04-MAY-2012 18:48:55.329	2456052.28397	117.16007	2.78184	0.00000
09-MAY-2012 19:55:59.805	2456057.33055	123.63937	2.77510	0.00000
06-MAY-2012 10:32:28.335	2456053.93922	156.52384	2.78277	0.00000
08-MAY-2012 04:12:23.166	2456055.67527	157.77379	2.77459	0.00000
01-MAY-2012 09:25:18.583	2456048.89258	161.40894	2.78341	0.00000
03-MAY-2012 03:05:11.955	2456050.62861	162.27488	2.78455	0.00000
09-MAY-2012 18:58:25.709	2456057.29058	178.92676	2.89047	0.00000
04-MAY-2012 17:51:02.803	2456052.24378	178.94706	2.89263	0.00000
08-MAY-2012 05:11:11.591	2456055.71611	184.02384	2.90152	0.00000
08-MAY-2012 02:16:15.138	2456055.59462	208.21421	2.78206	0.00000
03-MAY-2012 01:09:04.252	2456050.54797	209.51074	2.78897	0.00000
06-MAY-2012 12:28:35.422	2456054.01985	209.66565	2.78080	0.00000
01-MAY-2012 11:21:24.605	2456048.97320	211.00835	2.78628	0.00000
03-MAY-2012 04:03:45.035	2456050.66927	225.18690	2.90283	0.00000
01-MAY-2012 08:27:18.702	2456048.85230	254.57115	2.91349	0.00000
06-MAY-2012 13:27:26.398	2456054.06072	267.06229	2.91237	0.00000

Figure 1. Sample MADCAP Detail Report (sort by Relative Distance, Ascending)

```
Collision Analysis was performed between SC01, SC02, SC03, SC04, SC05, and SC06 using
the following ephemerides:

SC01.SHORT.oem.bsp_V0.634          28-FEB-2012 00:00:00 UTC - 17-MAR-2012 00:00:00 UTC
SC01.LONG.oem.bsp_V0.19 (Ref)      18-FEB-2012 00:00:00 UTC - 12-FEB-2013 00:00:00 UTC
SC02.SHORT.oem.bsp_V0.637          28-FEB-2012 00:00:00 UTC - 17-MAR-2012 00:00:00 UTC
SC02.LONG.oem.bsp_V0.17 (Ref)      18-FEB-2012 00:00:00 UTC - 01-AUG-2012 00:00:00 UTC
spk_SC03_jpl-nam-tpm.bsp           31-MAY-2010 23:58:53 UTC - 31-DEC-2013 23:58:53 UTC
spk_SC04_noburn.bsp                21-FEB-2012 08:00:00 UTC - 29-FEB-2012 23:59:59 UTC
spk_SC05_reference_traj.bsp (Ref)  24-FEB-2012 17:15:00 UTC - 05-JUN-2012 07:11:50 UTC
spk_SC05_od108v1.bsp               26-FEB-2012 13:00:00 UTC - 07-MAR-2012 23:59:59 UTC
spk_SC05_reference_traj.bsp (Ref)  24-FEB-2012 17:30:00 UTC - 05-JUN-2012 07:11:11 UTC
SC06-short_01.bsp                  28-FEB-2012 00:00:00 UTC - 13-MAR-2012 00:00:00 UTC
SC06-long.bsp_V0.1 (Ref)           18-FEB-2012 00:00:00 UTC - 20-OCT-2012 00:00:01 UTC

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

SC04-SC05 (SC04 Ref)                     19.76 km     01-MAR-2012 00:49:18 UTC
SC04-SC05 (SC04 Ref)                     10.26 km     01-MAR-2012 02:43:52 UTC
SC04-SC05 (SC04 Ref)                      0.80 km     01-MAR-2012 04:40:43 UTC
SC04-SC05 (SC04 Ref)                      1.27 km     01-MAR-2012 05:20:46 UTC
SC04-SC05 (SC04 Ref)                      8.42 km     01-MAR-2012 06:56:27 UTC
SC04-SC05 (SC04 Ref)                     18.13 km     01-MAR-2012 08:46:52 UTC
SC04-SC06 (SC04 Ref)                     11.63 km     03-MAR-2012 14:37:48 UTC
SC04-SC06 (Both Ref)                     11.82 km     03-MAR-2012 14:37:48 UTC
SC05-SC06 (SC05 Ref)                     11.83 km     10-MAR-2012 07:27:40 UTC
SC05-SC06 (Both Ref)                     12.39 km     10-MAR-2012 07:27:40 UTC

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

SC04-SC05 (SC04 Ref)                      0.80 km     01-MAR-2012 04:40:43 UTC
SC04-SC06 (SC04 Ref)                     11.63 km     03-MAR-2012 14:37:48 UTC
SC04-SC06 (Both Ref)                     11.82 km     03-MAR-2012 14:37:48 UTC
SC05-SC06 (SC05 Ref)                     11.83 km     10-MAR-2012 07:27:40 UTC
SC05-SC06 (Both Ref)                     10.13 km     26-MAY-2012 23:31:33 UTC

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

SC04-SC06                               137.29 km     29-FEB-2012 07:10:33 UTC
SC04-SC06 (SC06 Ref)                    136.78 km     29-FEB-2012 07:10:33 UTC
SC03-SC06                                39.24 km     29-FEB-2012 10:10:08 UTC
SC03-SC06 (SC06 Ref)                     39.45 km     29-FEB-2012 10:10:08 UTC
SC04-SC05                                28.57 km     29-FEB-2012 22:55:07 UTC
SC05-SC06                                23.99 km     01-MAR-2012 22:54:45 UTC
SC05-SC06 (SC06 Ref)                     23.98 km     01-MAR-2012 22:54:45 UTC
SC03-SC05                               129.79 km     04-MAR-2012 11:32:00 UTC
SC01-SC05 (Both Ref)                    175.00 km     26-MAR-2012 03:21:24 UTC
SC01-SC06 (Both Ref)                    186.87 km     11-APR-2012 02:26:47 UTC
SC01-SC02 (Both Ref)                    190.13 km     23-APR-2012 18:04:30 UTC
SC03-SC05 (SC05 Ref)                    118.59 km     24-APR-2012 19:25:44 UTC
SC01-SC04 (Both Ref)                    157.92 km     18-MAY-2012 20:09:11 UTC
SC03-SC04 (SC04 Ref)                    116.37 km     22-MAY-2012 23:03:05 UTC
SC04-SC05 (SC05 Ref)                     45.17 km     05-JUN-2012 06:18:10 UTC
SC04-SC05 (Both Ref                      45.17 km     05-JUN-2012 06:18:10 UTC
SC01-SC03 (SC01 Re)                      68.86 km     27-JUN-2012 20:06:28 UTC

The collision metric tables and plots have been archived in: /COLA/MADCAP/Moon/archive
```

Figure 2. Sample MADCAP Summary Report (Sort by Close Approach Date)

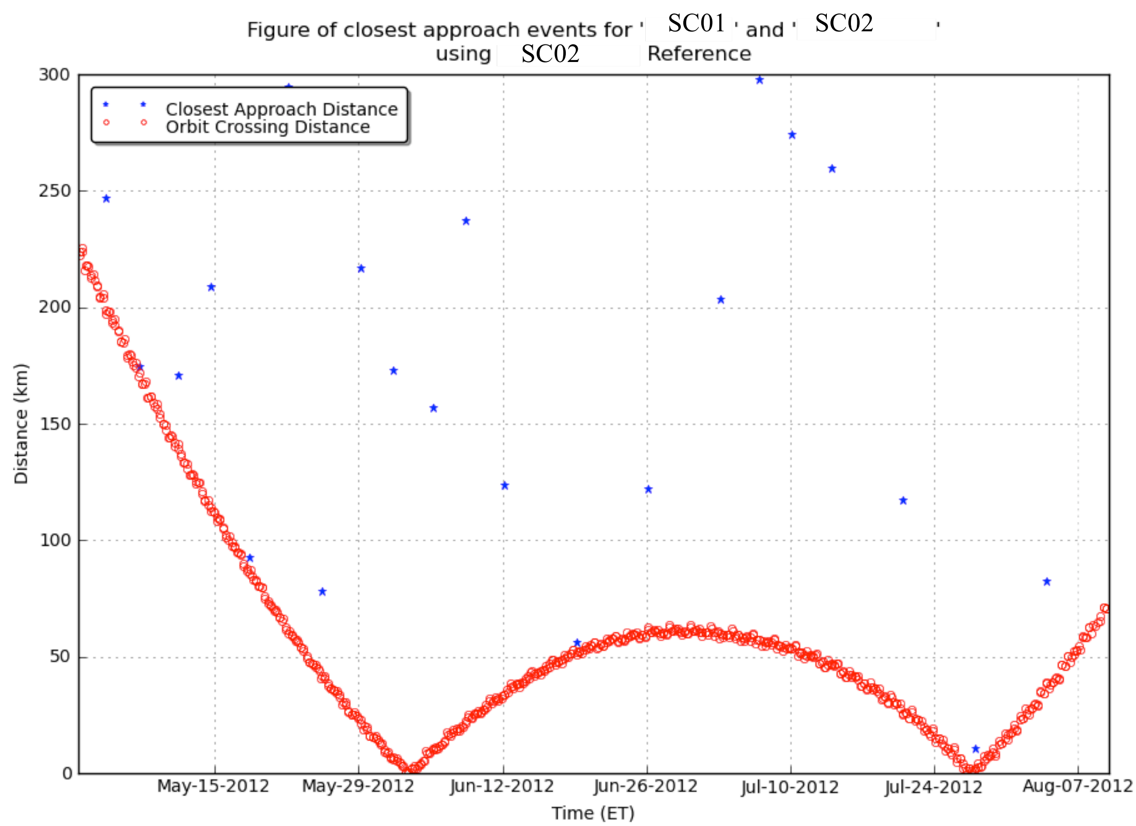

Figure 3. Sample Mars Collision Metrics Plot.

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