Conjunction Assessment Process For Lunar Orbiters

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DOCUMENT CHANGE LOG

DATE	PAGES AFFECTED	REASON FOR CHANGE	VERSION/ REVISION
3/21/2022	All	Initial version	Initial

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1 Introduction and Brief History

In May 2005, NASA's Mars Odyssey and ESA's Mars Express (MEX) experienced a close approach (<10km with orbit crossing <1km). Uncertainties in the MEX trajectory led ESA to perform an avoidance maneuver. No formal process for conjunction assessment at Mars was in place at that time. In mid-2006, the MRO navigation team developed a collision avoidance (COLA) process that was used initially during aerobraking operations. MRO performed 27 aerobraking maneuvers, six of which were executed to avoid possible collisions with other spacecraft. In summer 2011, the MADCAP process (MArs Deepspace Collision Avoidance Program) was instituted for regular weekly monitoring of Mars Odyssey, Mars Express, and the Mars Reconnaissance Orbiter. Non-operating spacecraft such as MGS and the Viking 1 orbiter were also included. The process was progressively formalized, and in January 2012, a Lunar run was instituted given the presence of several Lunar orbiters concurrently at the Moon (Lunar Reconnaissance Orbiter, ARTEMIS-P1, ARTEMIS-P2, GRAIL-A, GRAIL-B). In June 2012, the MADCAP process was presented at the SpaceOps Conference in Stockholm, Sweden (reference 1).

In late 2014, a new release of the MADCAP software was produced and re-christened "Multimission Automated Deepspace Conjunction Assessment Process" given its use beyond the Mars orbital environment. Since that time, daily analysis runs have been instituted. Approximately annual software updates have been implemented with bug fixes and improvements to scheduling, processing, reports, and report distribution lists. Several conference papers have reported MADCAP progress (see references 2, 3).

This document describes the conjunction assessment process that routinely monitors Lunar-orbiting spacecraft trajectories for future orbit crossings and close approaches, as it exists today. In essence it follows the same process used for the Mars orbital environment. The process uses the aforementioned MADCAP automated navigation utility that executes on secure flight network computers at JPL. MADCAP is built upon JPL's Monte multimission navigation software. Requirements (reference 4) and a technical description/user guide (reference 5) for MADCAP are available in the AMMOS documentation in EPDM (do a find on "multimission conjunction assessment"). The process takes advantage of and depends upon the availability of ephemeris predictions provided to the DSN by flight projects (including non-NASA vehicles) for tracking and communications support. Summary Reports are sent to stakeholders by email via tailored email lists. As spacecraft (including non-NASA missions) are added to the existing fleet in orbit at the Moon, every effort will be made to include them in this process.

The process consists of Monitoring and Response Functions. The Monitoring Function is implemented via a daily Summary Report emailed to interested parties. The Response Function is invoked when there is a "red event" (i.e., spacecraft are predicted to be "too close") reported in the Summary Report. In these cases, a JPL MDNAV MADCAP Representative will work with the navigation team(s) involved to determine a course of action. In some cases, collision avoidance maneuvers are negotiated between the affected flight project teams. In the event a response plan cannot be agreed upon by the affected flight projects, the JPL MDNAV MADCAP Representative will chair a meeting with relevant decision makers to determine the final response via a Conflict Resolution Process.

A virtually identical process is also in use for Mars orbiters and objects at Sun/Earth Lagrange Points.

2 Driving Requirements

1. The MADCAP shall perform conjunction assessment analyses routinely for all maneuverable Lunar orbiting spacecraft.

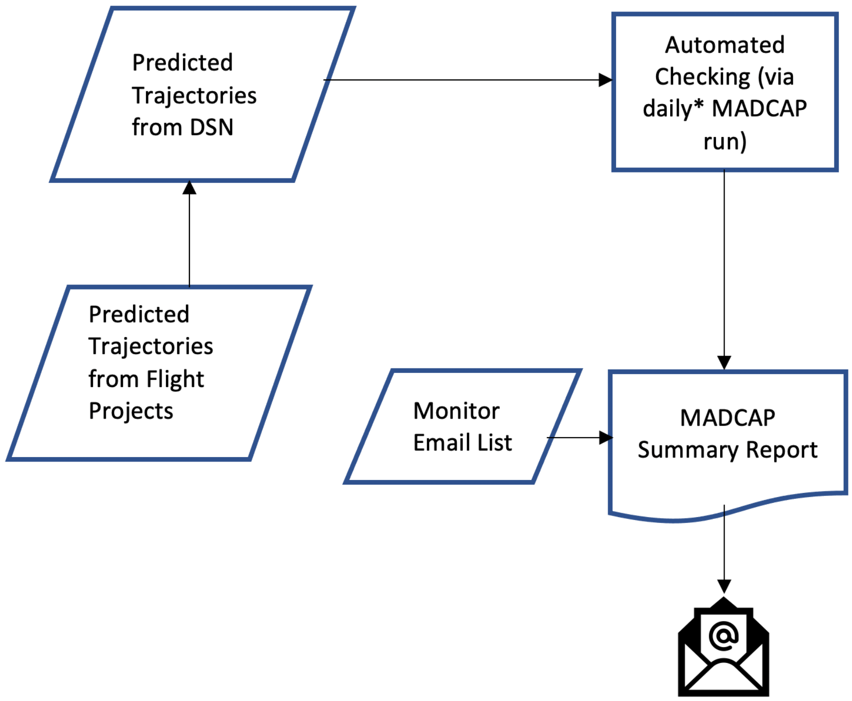
2. The MADCAP shall identify potentially high risk Lunar orbiter close approaches and communicate any to key stakeholders sufficiently in advance to enable an avoidance response.

3. The MADCAP shall maintain (on best efforts basis) estimated locations of non-functioning Lunar-orbiting spacecraft.

3 Procedure

MONITORING FUNCTION		
Step	**Who**	**Action**
1	JPL MDNAV (Mission Design and Navigation) MADCAP Rep	Ensure routine daily execution of monitoring software to identify predicted close approaches (orbit crossing distances and orbit crossing timings). Provide daily summary to “Monitoring” group. (See Section 4.)
2	MDNAV MADCAP Rep	Invoke "Response Function" when the daily summary report shows that any close approach (orbit crossing distance AND orbit crossing timing) within 14 days from run time falls below pre-defined thresholds (hereafter called a "red event").
RESPONSE FUNCTION		
3	MDNAV MADCAP Rep	Communicate with affected NAV Team Chiefs within 24 hours to confirm that they are aware of the reported red event.
4	MDNAV MADCAP Rep and Flight Project Navigation (NAV) Reps	Discuss options and agree to recommended response actions to red event, which may include actions by at least one and possibly both flight projects. Obtain approvals as necessary. Depending on the time-to-go until the red event, "watch" may be the initial action.
5	MDNAV MADCAP Rep	Within 24 hours of discussing with NAV Team Chiefs, communicate reported red event and proposed action outcome to the identified “Response” group. (See Section 5.) Invoke "Conflict Resolution Function" in the event that agreement on action cannot be obtained.
6	Flight Project(s) Nav	Prepare to implement agreed response action(s), e.g., design, build, and test of avoidance maneuver (if applicable).
7	All	Continue Monitoring Function while response action is prepared.
8	MDNAV MADCAP Rep	If response involves a maneuver, and if requested by flight project(s), execute a MADCAP test run (on best effort basis) to confirm planned avoidance maneuver (a) mitigates red event risk and (b) no new threshold violations result.
9	Flight Project(s)	Implement agreed response action(s) if/when desirable or necessary. Confirm proper execution.
10	All	Continue Monitoring Function (end of process).
CONFLICT RESOLUTION FUNCTION		
N/A	N/A	Next steps are conditional and only exercised if the normal process fails (e.g., high criticality event, flight projects cannot agree on response actions, there is disagreement with proposed response actions, lack of response by a flight project involved in red event, etc.)
11	MDNAV MADCAP Rep	Convene a meeting with decision makers of affected flight project teams. Discuss issues with candidate response actions. Negotiate and iterate until agreement is reached. This may involve concurrence with the NAV recommendation or an alternate response. This process may have to be modified for red events that do not involve NASA satellites. Determine appropriate escalation if agreement cannot be reached.
12	MDNAV MADCAP Rep	Communicate agreed action outcome to the identified “Response” group. (See Section 5.)
13	All	Go to Step 5 of Response Function.

4 Monitoring Function (Daily*)



*Frequency of execution used for current Lunar orbiters. Frequency can be increased/decreased if conditions render it necessary or desirable. Red event threshold values are based on each Project's three-sigma trajectory uncertainty estimates and are provided by the Project to the MADCAP Team.

The MADCAP Summary Report is emailed to interested parties maintained in an email list (moon_madcap_monitor@list.jpl.nasa.gov) maintained by the MDNAV MADCAP Representative. The report is essentially open to subscription by parties interested in the Lunar orbital environment. It provides information about pairwise orbit crossing distances, orbit crossing timing, and closest approaches based on flight project determined thresholds. Lander and flyby missions are included in MADCAP analyses during final approach. The organizations and personnel represented in this list (as of publication date) include at least:

- <u>Lunar Orbiter Flight Projects (modified as missions are added/retired):</u>
  - NASA Lunar Reconnaissance Orbiter (LRO)
  - NASA ARTEMIS-P1
  - NASA ARTEMIS-P2
  - ISRO Chandrayaan-2 (CH2O)
  - ISRO Chandrayaan-1 (CH-1, inactive)
  - JAXA Ouna (inactive)
- JPL MDNAV Section Management Team
- MGSS Program Office
- NASA CARA Representative
- MADCAP Representatives

5 Response Notifications

The Response Report is sent to designated leadership with respect to the missions involved in a MADCAP "red event" (i.e., orbit crossing distance AND orbit crossing timing both below mission defined thresholds within 14 days from run time). A list of designated recipients for each interest group is maintained by the MDNAV MADCAP representative. Missions indicate who they would like to receive the red event messages. "Response" notifications are tailored for the missions involved in the red event and include a preliminary recommendation for addressing the situation (see Section 9). The organizations that are represented in this list (as of publication date) include:

- <u>Lunar Orbiter Flight Projects (generally two of the following):</u>
  - NASA Lunar Reconnaissance Orbiter (LRO)
  - NASA ARTEMIS-P1
  - NASA ARTEMIS-P2
  - ISRO Chandrayaan-2 (CH2O)
- JPL MDNAV Section Management Team
- MGSS Program Office
- NASA CARA Representative
- MADCAP Representatives

6 Non-NASA Vehicles Considerations

Non-NASA Lunar spacecraft (e.g., Chandrayaan-2, etc.) will be included in the MADCAP process to the extent that accurate trajectory prediction information is available. Use of the DSN for tracking and communication services by those missions facilitates but is not required for the Monitoring and Response functions.

7 Inactive Vehicles Considerations

Conjunction events for inactive Lunar orbiters are not included in the summary reporting messages. However, for ISRO's Chandrayaan-1 and JAXA's Ouna, end-of-mission orbital states are used to produce long-term future predictions of orbit crossings and close approach estimates and are available upon request. Given the large orbital uncertainties the orbit crossing and close approach data are of marginal value. Bands of inclination may be the only useful information.

8 Natural Body Considerations

There are no Lunar natural satellites. However, the use of MADCAP for monitoring close approaches of Near Earth asteroids at Lunar distance has been suggested. This would require adding the ephemeris of the Near Earth asteroid to relevant MADCAP runs. Ephemerides of Near Earth asteroids are prepared by the Solar System Dynamics group in the MDN Section. Conjunctions of a spacecraft and a Near Earth asteroid would be included in the summary reporting messages if added to a MADCAP run. Special considerations in threshold settings are necessary for the natural satellites given that (a) the ephemeris position is predicted with respect to the center of gravity of the body, and (b) the body has significant size compared to a spacecraft, and unlike a spacecraft cannot be treated as essentially a point mass.

9 Sample Response Message (Associated with Next Section)

From: David Berry <david.s.berry@jpl.nasa.gov>
Date: Wednesday, October 13, 2021 at 1:21 PM
To: <<list of recipients based on spacecraft in conjunction>>
Subject: FW: MADCAP -- Moon -- Summary -- 2 Red

All,

In today's MADCAP Summary report (shown below) 2 Red events were triggered for LRO and CH2O on 2021-10-20. These red events first manifested in yesterday's MADCAP report, however, today's report showed closer approach distances after ephemerides for both spacecraft were refreshed.

The recommendation at this time is:

To Be Determined. Based on email exchanges with both the LRO team and the CH2O team, there is apparent agreement that a collision avoidance activity of some nature is necessary. The MADCAP team is currently working to establish a meeting with LRO and CH2O to discuss options and determine a course of action, including the party that will maneuver.

An updated response message will be distributed when a plan has been agreed.

Justification for Recommendation
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ISRO has indicated that "no maneuver is planned for Chandrayaan-2 until November 1st week."

LRO has indicated that the spacecraft performed "a small momentum unload on 10/11 that likely made that pop up. LRO does not have any planned unloads between now and that close approach."

Background
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Several years ago, JPL formalized a Conjunction Assessment Process for Orbiters at Mars and the Moon. In this process a recommended response by the JPL MDNAV MADCAP representative and the navigation teams involved is required when a close approach is predicted in less than 14 days to be within pre-defined threshold values. These events are flagged as "Red" events in the daily monitor email.

Regards,
David Berry
JPL MDNAV MADCAP Representative

10 Sample Monitor Message: Red Event with 2 Spacecraft

From: JPL MDNAV <jplmdnav@airmail.fltops.jpl.nasa.gov>
Reply-To: JPL MDNAV <jplmdnav@airmail.fltops.jpl.nasa.gov>
Date: Wednesday, October 13, 2021 at 10:07 AM
To: moon_madcap_monitor <moon_madcap_monitor@jpl.nasa.gov>
Subject: MADCAP -- Moon -- Summary -- 2 Red

Analysis Time: 2021-10-13 16:47:19 UTC

RED Threshold Updates: 0
ALL Threshold Updates: 0
Ephemeris Updates: 2

Conjunction Assessment Bodies and Types

Body	Name	Type
1	LRO	Active
1r	LRO	Active/Reference
2	ARTEMIS-P1	Active
2r	ARTEMIS-P1	Active/Reference
3	ARTEMIS-P2	Active
3r	ARTEMIS-P2	Active/Reference
4	CH2O	Active
5	Ouna	Inactive
6	CH1	Inactive

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

Bodies	OXD value/limit (km)			OXT value/limit (sec)			CAD value/limit (km)			Collision Probability	CA Epoch (UTC-SCET)
1-4	-0.0	1.7	4P	-0.1	4.5	1P	25.5	-----	--	no request	2021-10-20 04:47:11
1-4	-0.0	1.7	4P	-0.1	4.5	1P	0.1	-----	--	no request	2021-10-20 05:45:38

Bodies	OXD (km)	OXT (sec)	CAD (km)	CA Epoch (UTC-SCET)
1-4	0.9	375.7	492.9	2021-10-19 07:12:26
1-4	0.9	375.7	495.7	2021-10-19 08:10:50
1-4	0.8	341.0	445.3	2021-10-19 09:10:08
1-4	0.8	341.0	450.3	2021-10-19 10:08:32
1-4	0.6	306.5	397.8	2021-10-19 11:07:50
1-4	0.6	306.5	405.1	2021-10-19 12:06:15
1-4	0.5	272.1	350.4	2021-10-19 13:05:32
1-4	0.5	272.1	359.8	2021-10-19 14:03:57
1-4	0.4	237.7	303.3	2021-10-19 15:03:14
1-4	0.4	237.7	314.5	2021-10-19 16:01:40
1-4	0.3	203.3	256.2	2021-10-19 17:00:56
1-4	0.3	203.3	269.2	2021-10-19 17:59:22
1-4	0.3	169.0	209.2	2021-10-19 18:58:39
1-4	0.3	169.0	223.8	2021-10-19 19:57:05
1-4	0.3	134.7	162.5	2021-10-19 20:56:21
1-4	0.3	134.7	178.6	2021-10-19 21:54:48
1-4	0.3	100.7	116.0	2021-10-19 22:54:03
1-4	0.3	100.7	133.5	2021-10-19 23:52:30
1-4	0.3	66.9	70.2	2021-10-20 00:51:46

1-4	0.3	66.9	88.7	2021-10-20	01:50:13
1-4	0.2	33.3	25.9	2021-10-20	02:49:28
1-4	0.2	33.3	44.1	2021-10-20	03:47:56
1-4	-0.0	-0.1	25.5	2021-10-20	04:47:11
1-4	-0.0	-0.1	0.1	2021-10-20	05:45:38
1-4	-0.3	-33.2	69.3	2021-10-20	06:44:53
1-4	-0.3	-33.2	44.0	2021-10-20	07:43:21
1-4	-0.7	-66.0	114.6	2021-10-20	08:42:36
1-4	-0.7	-66.0	87.6	2021-10-20	09:41:04
1-4	-1.1	-98.7	159.9	2021-10-20	10:40:18
1-4	-1.1	-98.7	130.9	2021-10-20	11:38:46
1-4	-1.6	-131.2	205.4	2021-10-20	12:38:01
1-4	-1.6	-131.2	174.0	2021-10-20	13:36:29
1-4	-2.2	-163.6	250.7	2021-10-20	14:35:44
1-4	-2.2	-163.6	216.9	2021-10-20	15:34:12
1-4	-2.8	-196.1	296.1	2021-10-20	16:33:27
1-4	-2.8	-196.1	259.8	2021-10-20	17:31:54
1-4	-3.3	-228.5	341.3	2021-10-20	18:31:11
1-4	-3.3	-228.5	302.7	2021-10-20	19:29:37
1-4	-3.9	-261.1	386.3	2021-10-20	20:28:54
1-4	-3.9	-261.1	345.6	2021-10-20	21:27:20
1-4	-4.6	-293.8	431.3	2021-10-20	22:26:37
1-4	-4.6	-293.8	388.7	2021-10-20	23:25:03
1-4	-5.2	-326.6	476.2	2021-10-21	00:24:20
1-4	-5.2	-326.6	432.0	2021-10-21	01:22:45
1-4	-4.9	-426.8	475.4	2021-10-21	03:20:28
1r-4	17.4	446.8	460.2	2021-11-05	06:16:27
1r-4	17.6	410.3	413.2	2021-11-05	08:14:07
1r-4	17.6	373.9	366.3	2021-11-05	10:11:47
1r-4	17.6	373.9	491.0	2021-11-05	11:10:23
1r-4	17.6	337.7	319.4	2021-11-05	12:09:27
1r-4	17.6	337.7	443.9	2021-11-05	13:08:04
1r-4	17.5	301.6	272.5	2021-11-05	14:07:07
1r-4	17.5	301.6	396.8	2021-11-05	15:05:45
1r-4	17.4	265.6	225.8	2021-11-05	16:04:47
1r-4	17.4	265.6	349.8	2021-11-05	17:03:26
1r-4	17.2	229.8	179.2	2021-11-05	18:02:27
1r-4	17.2	229.8	302.9	2021-11-05	19:01:08
1r-4	17.1	194.0	133.2	2021-11-05	20:00:07
1r-4	17.1	194.0	256.0	2021-11-05	20:58:49
1r-4	16.9	158.3	88.1	2021-11-05	21:57:47
1r-4	16.9	158.3	209.3	2021-11-05	22:56:30
1r-4	16.7	122.7	46.7	2021-11-05	23:55:27
1r-4	16.7	122.7	162.6	2021-11-06	00:54:11
1r-4	16.5	87.2	30.3	2021-11-06	01:53:07
1r-4	16.5	87.2	116.2	2021-11-06	02:51:52
1r-4	16.1	51.8	62.8	2021-11-06	03:50:46
1r-4	16.1	51.8	70.2	2021-11-06	04:49:33
1r-4	15.6	16.5	105.7	2021-11-06	05:48:26
1r-4	15.6	16.5	26.7	2021-11-06	06:47:13

1r-4	14.9	-18.8	150.2	2021-11-06	07:46:06
1r-4	14.9	-18.8	28.9	2021-11-06	08:44:54
1r-4	14.0	-53.9	194.8	2021-11-06	09:43:45
1r-4	14.0	-53.9	72.5	2021-11-06	10:42:35
1r-4	12.9	-88.9	239.4	2021-11-06	11:41:25
1r-4	12.9	-88.9	117.9	2021-11-06	12:40:16
1r-4	11.8	-123.8	283.8	2021-11-06	13:39:05
1r-4	11.8	-123.8	163.5	2021-11-06	14:37:56
1r-4	10.6	-158.4	327.8	2021-11-06	15:36:45
2-3	-34.0	1354.5	467.9	2021-11-09	10:14:37
1r-2r	-130.9	7071.1	135.0	2021-11-20	20:34:20
2r-3r	-246.7	897.7	363.5	2021-11-22	22:24:54
1r-2r	-118.4	7328.2	354.7	2021-11-23	22:53:30
1r-2r	-165.1	321.6	417.8	2021-12-03	07:53:37
1r-2r	-51.4	377.2	466.0	2021-12-31	08:39:30
1r-3r	-490.4	7032.6	490.6	2022-01-05	21:48:03
1r-2r	-427.6	-4.1	427.6	2022-01-19	00:33:16

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 not covered by the predicts file. Reference trajectories use the same thresholds as the nominal trajectories.
The note after the probability value listed for RED events refers to the source of covariance data used for the probability calculation, with the following definitions:
C - Covariance data provided by the mission in OEM format.
P - A covariance converted from the RED threshold polynomial coefficients listed below.
N - No covariance data, worst case covariance assumed for this body.
No Data - Probability could not be calculated due to a lack of covariance data from both bodies.
For more information, please see the point of contact listed below.

Analysis time:	2021-10-13 16:47:19 UTC
Active spacecraft:	LRO, ARTEMIS-P1, ARTEMIS-P2, CH2O
Natural bodies:	None
Inactive spacecraft:	Ouna, CH1
Output directory:	/nav/home/jplmdnav/MADCAP/Moon/archive
Point of contact:	MADCAP_Moon@jpl.nasa.gov
MADCAP build:	3.1.2

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	LRO	0.1500	0.0125	0.0005	1.8750	0.2671	0.0184
2	ARTEMIS-P1	0.1370	-0.0024	0.0089	0.0100	2.8154	0.0045
3	ARTEMIS-P2	0.1370	-0.0024	0.0089	0.0100	2.8154	0.0045
4	CH2O	0.0000	0.2509	0.0000	0.0000	0.1490	0.0005

Red OX Distance Threshold = OXD0 + (OXD1 * t) + (OXD2 * t^2) [km]
Red OX Timing Threshold = OXT0 + (OXT1 * t) + (OXT2 * t^2) [sec]
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	LRO	1	40
2	ARTEMIS-P1	500	500
3	ARTEMIS-P2	500	500
4	CH2O	500	500

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*	14day_20211013_01.bsp	2021-10-13 11:50:42 UTC	13-OCT-2021 00:00:00 UTC	27-OCT-2021 00:00:00 UTC
1r	558day_20211012_01.bsp	2021-10-12 11:55:39 UTC	12-OCT-2021 00:00:00 UTC	23-APR-2023 00:00:00 UTC
2	192.THEMIS_B.SHORT_TERM.2021_285.oem.bsp_V0.1	2021-10-12 10:35:30 UTC	12-OCT-2021 00:00:00 UTC	11-NOV-2021 00:00:00 UTC
2r	192.THEMIS_B.LONG_TERM.2021_104.oem.bsp_V0.1	2021-04-14 17:57:45 UTC	14-APR-2021 00:00:00 UTC	13-APR-2027 00:00:00 UTC
3	193.THEMIS_C.SHORT_TERM.2021_285.oem.bsp_V0.1	2021-10-12 10:36:36 UTC	12-OCT-2021 00:00:00 UTC	11-NOV-2021 00:00:00 UTC
3r	193.THEMIS_C.LONG_TERM.2021_104.oem.bsp_V0.1	2021-04-14 18:01:40 UTC	14-APR-2021 00:00:00 UTC	13-APR-2027 00:00:00 UTC
4*	ISRO-CH2-2021-10-12-OD814-286-v1.xsp.bsp	2021-10-13 11:30:10 UTC	12-OCT-2021 07:00:00 UTC	11-NOV-2021 09:00:00 UTC
5	ouna_191201_230101_150608_SMM0710031456-jpl-ekl.bsp	Analysis Time	01-DEC-2019 00:59:23 UTC	31-DEC-2022 23:58:23 UTC
6	traj_ch1_010920-011022.bsp	Analysis Time	31-AUG-2020 23:58:50 UTC	30-SEP-2022 23:58:50 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 "*".

11 References

1. Berry, D. et al., "Automated Spacecraft Conjunction Assessment at Mars and the Moon", Paper 1262983, 12th International Conference on Space Operations, Stockholm, Sweden, 11 June 2012.

2. Tarzi, Z., Berry, D., Roncoli, R., “An Updated Process for Automated Deepspace Conjunction Assessment” Paper AAS 14-373, 25th International Symposium on Space Flight Dynamics, Munich, Germany, October 2015.

3. Berry, D., Tarzi, Z., Roncoli, R., Wilson, R., “Automated Spacecraft Conjunction Assessment at Mars and the Moon-A Five Year Update”, Paper 2810036, 14th International Conference on Space Operations, Marseille, France, May 2018

4. Berry, D., Tarzi, Z., "Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) Requirements", MGSS DOC-001813, Revision E, February 8, 2022.

5. Tarzi, Z., “Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) Software Description and User's Guide,” MGSS DOC-000664, Revision G, 05 Nov 2020, https://ind-lib.jpl.nasa.gov/docushare/dsweb/Get/Version-189955.

6. Demcak, S., “MAVEN Navigation Response to MOR RFA-003: Collision Avoidance Process,” JPL Internal Document IOM-343A-13-001.

12 Acknowledgment

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