Navigating Chandrayaan-3

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Abstract: *On July 14, 2023, the Indian Space Research Organization (ISRO) launched Chandrayaan-3 (CH-3) from the Satish Dhawan Space Centre. As part of its operations plan, ISRO engaged the services of the Jet Propulsion Laboratory (JPL) Mission Design and Navigation (MDNav) Section for consultation, verification, and validation of its navigation operations. This arrangement built on the successful Chandrayaan-1 (CH-1) and Chandrayaan-2 (CH-2) lunar mission collaborations between ISRO/NASA-JPL MDNav, as well as the Mars Orbiter Mission (MOM) collaboration from 2012 to 2014. This paper will describe in detail the navigation effort performed by JPL MDNav in support of CH-3 to ensure that ISRO fulfilled its objectives of a soft landing on the Lunar surface. Primary ISSFD areas of interest addressed will be flight dynamics operations, tracking and orbit determination, and maneuver design.*

I. Introduction

Chandrayaan-3 is India's third mission to the Moon and a follow-on mission to Chandrayaan-2. Its objective was to perform a "Safe and Soft landing" near the South polar region of the moon. The CH-3 spacecraft (similar to Chandryaan-2) consisted of both a lander module and a propulsion module, which flew as a single entity until the lander and propulsion modules separated approximately six days before landing on August 17, 2023. The lander module proceeded to descend to the surface of the Moon on August 23, 2023. The lander carried a small rover, which was released shortly after landing.

As part of its operations plan, in early 2021, ISRO began discussions with NASA and the Jet Propulsion Laboratory (JPL) Mission Design and Navigation Section (MDNav) to engage JPL's services for consultation, verification, and validation of CH-3 navigation operations. The navigation support effort built on the successful lunar mission collaboration between ISRO and NASA/JPL MDNav on ISRO's Chandrayaan-1 mission (2008-2009), the Mars Orbiter Mission (MOM) (2012-2014), and Chandrayaan-2 (2017-2019). JPL MDNav was to validate ISRO's mission design and support the CH-3 mission in its objectives of achieving a soft landing on the Lunar surface. CH-3 successfully achieved the main mission objectives, a fact of major significance given that India was the first nation to successfully land a spacecraft in the south pole region of the Moon. CH-3's success was an incredible achievement given the many significant challenges.

II. The Team

CH-3's primary flight dynamics team consisted of a large contingent of personnel from ISTRAC (ISRO Satellite Tracking Center) and ISAC (ISRO Satellite Center) in India; ISRO had primary flight dynamics responsibility for the mission. JPL MDNav's role/responsibility was to provide navigation support in development, design, and operations for CH-3 and participate in JPL-ISRO Technical Interchange Meetings (TIMs) to support development and operations activities, and to develop and implement a JPL CH-3 navigation strategy. The JPL CH-3 navigation team consisted of a number of members of JPL's MDNav Section (orbit determination groups, flight path control group, system administrators), and the Deep Space Network (radiometric data conditioning, network operations engineering, scheduling, media calibration). [1]

III. CH-3 Preliminaries

One of the first things that had to be accomplished by JPL's Interplanetary Network Directorate was to renew a Technical Assistance Agreement (TAA) specifying the work with ISRO and get it approved by several US government agencies (NASA, the US State Department, and the US Department of Defense). Serious technical interchange could not start until such a document had been negotiated and approved by all parties. Because a previous JPL/ISRO TAA was Chandrayaan-2 specific, and had expired, it was necessary to update and renew the TAA for CH-3. A Space Act Agreement also had to be established before support could begin. This is an inter-agency agreement between NASA and ISRO defining the terms of support and the payment schedule. This Space Act Agreement was signed in February 2022.

The first planning teleconferences occurred in the spring of 2021. Questions asked in these early telecons by JPL MDNav covered overall mission design (e.g., planned mission duration at the Moon, science objectives, schedule margins), tracking plans (e.g., the amount of Deep Space Network (DSN) tracking required, uplink/downlink bands, which ISTRAC stations would be used, etc.). There were also many detailed questions regarding the spacecraft and its mission (e.g., commanded ΔV accuracy, orientation constraints, frequency of angular momentum desaturations), and expectations with respect to JPL's roles and responsibilities.

IV. Spacecraft

As mentioned earlier, The CH-3 spacecraft consisted of both a Lander Module and a Propulsion Module, which flew as a single entity until the lander and propulsion modules separated approximately six days before landing on August 17, 2023. In addition to carrying much of the propellant used in the mission, the Propulsion Module, shown in Fig. 1, also carried an instrument, the Spectro-polarimetry of HAbitable Planet Earth (SHAPE). The payload was used to make spectral and polarimetric measurements of Earth from the lunar orbit, and since December 4, 2023, for a reinserted Earth orbit. [2][3] The propulsion module carried a bi-propellant, 440 N engine, along with 8 smaller thrusters delivering 22 N each. The solar panel was mounted flush to the side of the Propellant Module, as opposed to the large panel which extended outward from the CH-2 Orbiter Module. This reduced torques caused by solar pressure.

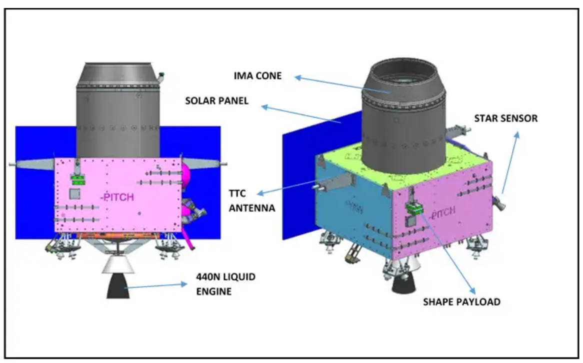

Fig. 1. Chandrayaan-3 Propulsion Module [2]

The Lander carried four instruments. The Radio Anatomy of Moon Bound Hypersensitive ionosphere and Atmosphere (RAMBHA) measures the near surface plasma (ions and electrons) density and its changes with time. Chandra's Surface Thermo physical Experiment (ChaSTE) carries out measurements of thermal properties of the Lunar surface. The Instrument for Lunar Seismic Activity (ILSA) measures seismicity around the landing site and delineates the structure of the Lunar crust and mantle. The LASER Retroreflector Array (LRA) is a passive experiment to understand the dynamics of the Lunar system. [2] Fig. 2 shows the location of these instruments on the Lander Module. The Lander Module also carried a bi-propellant propulsion system with 4 x 800 N throttleable thrusters, and 8 smaller thrusters of 58 N each. Fig. 3 shows an illustration of the integrated CH-3 spacecraft.

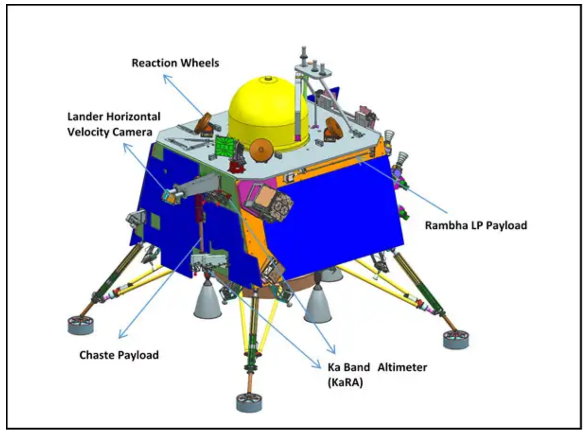

Fig. 2. Chandrayaan-3 Lander [2]

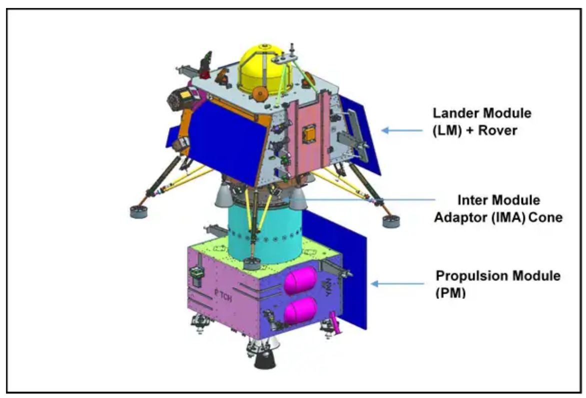

Fig. 3. Chandrayaan-3 Integrated Module [2]

The Lander carried a small rover, shown in Fig. 4, which deployed shortly after landing, and survived one Lunar day (14 Earth days). It carried two instruments: the Alpha Particle X-ray Spectrometer (APXS) and Laser Induced Breakdown Spectroscope (LIBS) for deriving the elemental composition in the vicinity of landing site. [2]

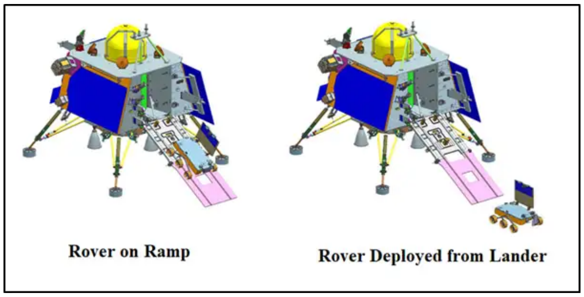

Fig. 4. Rover Views [2]

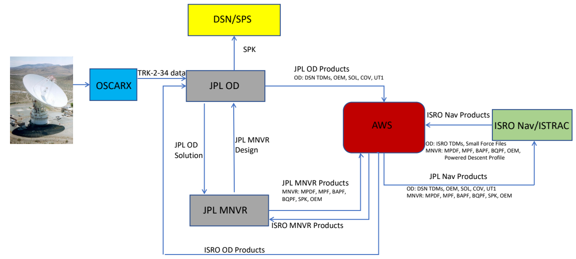

Fig. 5. Navigation Data Exchange Configuration

V. Interfaces and Models

The NASA/JPL navigation support for the CH-3 mission necessitated the exchange of many navigation data products in order to keep the efforts of the ISRO and JPL teams synchronized. Consequently, much of the early technical work required agreements between the two teams as to the interfaces and models that would be utilized to conduct the work. The secure data exchange was accomplished via an Amazon Web Services (AWS) cloud interface. Files were exchanged both from JPL to ISRO and from ISRO to JPL via this AWS interface. ISRO deposited files in their AWS bucket that were fetched by the JPL contingent, and JPL deposited files in their AWS bucket that were fetched by the ISRO contingent. A diagram of the interfaces is shown in Fig. 5.

ISRO provided maneuver designs, CCSDS format (Consultative Committee for Space Data Systems) Tracking Data Messages (TDMs) [4], and small forces data (angular momentum desaturations (AMDs)) to JPL. ISRO also delivered the Preliminary Orbit Determination (POD) files, which provided state information from the launch vehicle at separation.

JPL supplied navigation solutions, maneuver designs, CCSDS TDMs, and a large variety of ancillary files to ISRO. Among these files were filter solutions, trajectories, epoch covariance estimates, tracking data with media calibrations applied, Earth platform calibrations, and Lunar ground track predictions. Table 1 summarizes the maneuver related files passed from JPL to ISRO, and Table 2 summarizes the orbit determination (OD) related files delivered from JPL to ISRO. ISRO to JPL navigation files are shown in Table 3.

Files exchanged between the JPL Navigation Team and ISRO were defined according to a Navigation Interface Control Document (ICD) signed by both parties prior to the MOM mission. These same file formats continued to be used for the CH-2 and CH-3 missions. Contents of this document included: CCSDS Orbit Ephemeris Message (OEM) [5] Data Interface, Orbit Determination Solution File (SOL) Interface, Covariance (COV) File Interface, Maneuver Profile File (MPF) Interface, Burn Attitude Profile File (BAPF) Interface, Maneuver Target Profile File (MTPF) Interface, Maneuver Performance Data File (MPDF) Interface, Burn Quaternion Profile File (BQPF) Interface, On-Board Reconstructed Small Forces (SMF) Interface, CCSDS TDM Interface [4], UT1-UTC Table, among others.

Maneuver Files Delivered from JPL to ISRO	Contents
MPF (Maneuver Profile File)	Maneuver ΔV magnitude, direction, start time
MTPF (Maneuver Target Parameter File)	Maneuver target parameters including targeted orbital elements and Cartesian state
MTPF Diff (Maneuver Target Parameter File Difference File)	Differences between JPL and ISRO MTPFs
BAPF (Burn Attitude Profile File)	Burn attitude file containing RA, Dec
BQPF (Burn Quaternion Profile File)	Burn attitude file containing quaternions
OEM (Orbit Ephemeris Message)	Cartesian states in EME2000 at 60 second intervals

Table 1: Maneuver Files Delivered from JPL to ISRO

OD Files Delivered from JPL to ISRO	Contents
OEM (Orbit Ephemeris Message)	Cartesian states in EME2000 at 60 second intervals
SOL (Solution File)	Summary of tracking data used in solution, statistics mapped to future events, epoch state information including statistics and updated state
COV (Covariance File)	6 x 6 covariance matrix at solution epoch
TDM (Tracking Data Message)	Tracking data with media calibrations applied
UT1 (UT1-UTC Table)	UT1-UTC table with data every 15 minutes
EOP (Earth Orientation Parameter)	Earth precession, nutation, and polar motion data
GTK (Ground track)	Lunar ground track predictions

Table 2: OD Files Delivered from JPL to ISRO

Navigation files Delivered from ISRO to JPL	Contents
MPF (Maneuver Profile File)	Maneuver ΔV magnitude, direction, start time
MPDF (Maneuver Performance Data File)	Spacecraft mass, effective thrust, effective mass flow rates
MTPF (Maneuver Target Parameter File)	Maneuver target parameters including targeted orbital elements and Cartesian state
BAPF (Burn Attitude Profile File)	Burn attitude file containing RA, Dec
BQPF (Burn Quaternion Profile File)	Burn attitude file containing quaternions
OEM (Orbit Ephemeris Message)	Cartesian states in EME2000 at 60 second intervals

Table 3: Navigation Files Delivered from ISRO to JPL

VI. Navigation Plan

JPL MDNav's navigation plan for CH-3 involved the areas of schedule planning, spacecraft dynamic model generation, mission profile validations, navigation system analyses, training, and testing across all of these areas. After launch, the major navigation activities included orbit determination and flight path control (maneuver). Output products from JPL MDNav orbit determination and flight path control were all made available to the ISRO flight dynamics team on the AWS cloud server (note: henceforth, this is called "delivery"). Once the navigation plan was completed, the JPL MDNav task involved execution of that plan, encompassing all areas of navigation flight operations.

VII. Orbit Determination (OD)

The Orbit Determination dynamic model included Newtonian gravitational acceleration for the planets, the Sun and the Moon. The planetary ephemeris DE421 [6] was used. During the Earth phase, the DTM (Drag Temperature Model) Earth atmospheric density model was used. [7] Relativistic accelerations were also included for the Earth and Sun. Spherical harmonic expansions of the Earth and Lunar gravity fields were included. The Earth model employed a 100x100 expansion. [8] The lunar model used a 150x150 expansion of the GL900C model for most of the mission, and a 300x300 expansion in the final few days prior to the landing. [9] See Table 4 for a summary of the models used.

The high-fidelity solar pressure model was based on a three-dimensional representation of the spacecraft structure. Three different solar pressure models were employed. The "composite" configuration with the Propulsion and Lander modules joined, was used prior to the vehicle separation in lunar orbit. The "module" configuration involved individual models for the Propulsion and Lander modules, used after separation. All these models used flat plates and cylinders oriented and sized in accordance with detailed data provided by ISRO. Specular and diffuse reflectivity coefficients were assigned for each component, often involving multiple material types, based on the same data. The spacecraft orientation was then modeled in accordance with the ISRO attitude plan, which varied by mission phase.

The periapsis altitude during the Earth phase was between 170 and 220 km (based on JPL OD), imparting a significant atmospheric drag perturbation. A DTM atmosphere model was used with a spherical spacecraft cross section. The DTM model 10.7 cm radio flux and Geomagnetic Indices, based on NOAA data, were updated daily.

The spacecraft attitude control used momentum wheels during quiescent operations. These momentum wheels required frequent desaturations (desats) using unbalanced thrusters. Pre-launch ISRO analysis was provided for a limited number of cases. Desats in-flight were frequent (20-40 per day) but very small, contributing a minor perturbation to the trajectory. Following separation in Lunar orbit, the Lander Module operation was purposely quiescent, and the vehicle experienced no desats in the final few days prior to landing. During the Earth orbit phase, the combined spacecraft attitude was maintained by thrusters during the drag passes.

Spacecraft tracking in support of JPL Navigation was conducted by DSN tracking stations. S-Band two-way Doppler was the main data type, supplemented with Sequential Ranging Assembly (SRA) range between the EBN-4 (Earth Bound Maneuver 4) design and LOI (Lunar Orbit Insertion) execution. Approximately 10-12 hours of DSN tracking per day was acquired, with a mix of four-eight hour passes from all three DSN tracking complexes. ISRO provided Bangalore 32m and 18m tracking on a limited basis. This data was examined but ultimately not used in the JPL OD process due to time constraints.

JPL Navigation provided orbit determination for the "composite" and Lander Module during all phases of the mission. The orbit determination filter estimated the spacecraft state, an overall solar pressure scale factor, maneuvers and desat events. Drag coefficient scale factors and range biases were treated on a per-event basis. Uncertainties associated with atmospheric media, Earth platform, tracking station locations, the Earth & Moon ephemerides and GMs were included in the filter assumptions.

JPL Navigation generated and delivered 62 orbit determination solutions for the composite and Lander Module vehicles. This data was provided to ISRO for mission planning and to the DSN for tracking predicts generation and scheduling. A preliminary and final OD was conducted prior to each maneuver to support the maneuver design process. A quick look post-maneuver OD was performed after each maneuver, between 1-2 hours after the burn. Solutions away from critical events were performed at least once per day to maintain trajectory knowledge and monitor for tracking or spacecraft anomalies. Each OD delivery provided to ISRO included trajectory reconstruction and prediction, epoch state vectors and filter covariances. A media calibrated version of the tracking data used in the solution was also provided, along with Earth platform calibrations. A prediction of the spacecraft ground-track was also included during the lunar phase. Typical OD solutions employed data arcs between maneuvers. Fitting through the burns and estimating the maneuver characteristics was only done for the maneuver quick-look solutions. There was no requirement for JPL Orbit Determination to provide maneuver reconstructions.

JPL Navigation also provided real-time Doppler residual display to ISRO during critical events such as TLI, LOI and powered descent.

Only one pass of post-separation tracking of the Propulsion Module was scheduled. JPL Navigation was unable to perform OD for this vehicle because no valid Doppler tracking data was acquired during the pass.

Planetary Ephemeris	DE-421
Gravity Model (Earth)	GGM02C (100x100)
Gravity Model (Moon)	GL900C (150 x 150, 300 x 300 for final Lunar phase)
Earth Atmosphere	DTM

Table 4. Models for CH-3

VIII. Flight Path Control / Maneuver Design

JPL MDNav's basic maneuver responsibility was to provide independent confirmation of ISRO-designed maneuvers for the Earth orbit phase, cruise, and Lunar orbit phase. This effort involved maneuver design and targeting, analysis, comparisons with ISRO designs, and real-time monitoring of maneuvers.

The agreed maneuver design process involved both an ISRO design and a JPL design based on the JPL orbit determination solution. ISRO would prepare the relevant interface files describing their maneuver design (MPDF, MTPF, BQPF, BAPF) and an MPF for validation (see Table 3). JPL then compared both designs with respect to several attributes (burn start time, burn duration, delta-mass, ΔV, right ascension, declination, and quaternions). The projected effects on the target orbit were also compared (e.g., orbital elements, B-plane coordinates during the trans-Lunar cruise and the LOI epoch). An additional analysis involved a propagation using the ISRO design with the JPL models and comparing this result with the propagated JPL design. The design parameters were analyzed and discussed during a maneuver teleconference, usually held ~7-8 hours before burn execution. In general, the differences between the two designs were very small. ISRO would ultimately make the decision as to which maneuver design would be implemented. On CH-3, the ISRO design was always chosen to be implemented.

IX. CH-3 Trajectory

A pre-launch analysis performed by JPL mission designers using early trajectory information provided by ISRO was used to verify the feasibility of ISRO's CH-3 trajectory design. This pre-launch validation was performed for every proposed launch date, and this trajectory served as a reference trajectory for that launch day. This analysis also confirmed that the ISRO trajectory design was feasible. An illustration of the CH-3 trajectory is shown in Fig. 6.

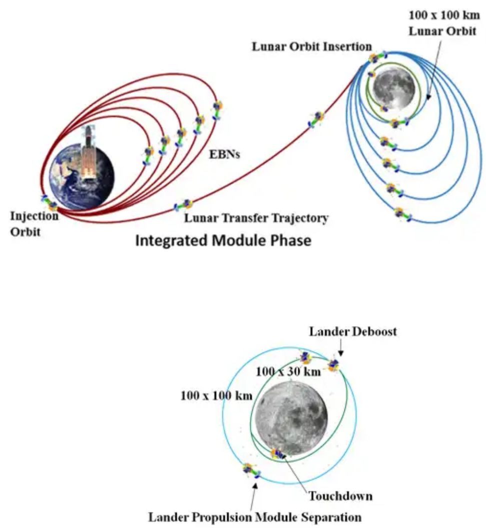

Fig. 6. CH-3 Trajectory [2]

X. CH-3 Launch Assessment

CH-3 was launched 14-Jul-2023 at approximately 09:05 UTC (2:05 AM PDT) from the Satish Dhawan Space Centre in Sriharikota, India on an ISRO LVM3 launch vehicle. Because the planned launch date changed late in the process, the actual launch day trajectory was received only one week in advance.

Predicts for DSN initial acquisition and tracking were based upon the first of two injection state deliveries from ISRO in text files received via email, called a 'POD' (Preliminary Orbit Determination). The first of these was delivered 24 hours before launch and the second shortly after injection. Launch and injection times given in the PODs are shown in Table 5.

POD	Launch	Injection
L-24 Hr	2023-07-14 09:05:17 (UTC)	2023-07-14 09:21:27.000 (UTC)
Launch	2023-07-14 09:05:17 (UTC)	2023-07-14 09:21:20.960 (UTC)

Table 5: CH-3 Launch & Injection Times from Launch Minus 24 Hours & Post Launch POD Deliveries

The state information in the Launch POD is generated on board the launch vehicle using Global Positioning System (GPS) data and telemetered to the ground. Experience with this delivery for CH-2 showed it was very useful for updating DSN pointing predicts when large deviations from the prelaunch nominal state occurred, and plans were in place to repeat that, if needed, for CH-3. However, that was not the case with the L-24 Hour POD being adequate for DSN tracking. The trajectory derived from the pre-launch POD is the reference for assessing the injection error based on analysis of DSN radiometric tracking.

Pre-launch analysis of the effect of injection errors on DSN pointing accuracy was based on 3-sigma values provided by ISRO for five osculating orbital elements at injection:

1) inclination
2) argument of perifocal passage
3) apoapsis altitude
4) periapsis altitude
5) right ascension of the ascending node

with angles in Earth Mean Equator of J2000 coordinates.

Lacking a correlated 6x6 injection error covariance matrix, 3-sigma injection states were generated by applying these values as plus and minus 3-sigma values to the osculating values of the orbital elements of the nominal injection state. From these two perturbed states, plus and minus 3-sigma trajectories are generated and used to compute differences in parameters critical to DSN tracking, rise times and pointing during the initial passes. Also computed from these were errors in orbital period and orbital energy, C3.

To assess the CH-3 injection errors, differences in these 5 parameters and C3 were computed between the first JPL Navigation Team orbit estimate delivered to ISRO, od002_v1 (or od002) and the Launch-24 hour, pre-launch trajectory, and compared with the plus and minus 3-sigma trajectories described above. The results of this comparison are summarized in Table 6.

Orbital Element	Orbit Determination Solution 02 (od002) minus L-24 hr POD	3-Sigma Predicted Injection Error	**n-sigma computed Injection Error**	L-24 Hr POD	Units J2000
inclination (i)	2.89E-02	0.1	**0.87**	21.3	deg
argument of periapsis (ω)	8.18E-02	0.2	**1.23**	177.6	deg
right ascension of ascending node (Ω)	-7.15E-02	0.2	**-1.07**	8.874	deg
apoapsis altitude	-9.44E+01	496	**-0.57**	36565.8	km
periapsis altitude	-5.79E-01	3.5	**-0.50**	170.2	km
period (P)	-1.11E+02	584	**-0.57**	10:45:41	sec, hh:mm:ss
Orbital Energy C_3	-3.12E-02	0.16	**-0.58**	-16.20	km**2/ sec**2
Other orbital elements, L-24 Hr POD					
true anomaly (ν)				4.649	deg
eccentricity (e)				0.73538	

Table 6: CH-3 Injection Error Assessment

Various quantities are shown for the orbital parameters listed in column 1. Column 2 lists the differences between od002 and the L-24Hr POD trajectory. Column 3 is the predicted plus 3-sigma injection error. The n-sigma differences in column 4 are computed from the values in Columns 2 and 3.

For reference, column 5 lists the orbital parameter values in the L-24 hour POD state. For completeness, values of orbital elements not compared, true anomaly and eccentricity, appear at the bottom of the table.

If perturbations the size of all these predicted injection errors were present at injection, there would be a significant impact on meeting the DSN stringent pointing requirements. However, that was not evident in the DSN telecon performance nor in the assessment of the pointing differences between the navigation solutions and the ISRO pre-launch trajectory used for DSN pointing predicts on the day of launch.

The polarity of the injection error is based on the signs of the n-sigma injection errors in apoapsis and periapsis altitude, and C3. (The injection error in period merely reflects the errors manifested in the semi-major axis by the two altitude errors.) Based on those differences a value of -0.6 sigma is estimated for the injection error.

XI. Earth Orbit Phase

CH-3 had an Earth Orbit Phase consisting of 4 apogee-raising maneuvers to pump up the energy, concluding with the TLI (Trans-Lunar Injection). This is shown in Figure 5. All of these Earth Phase maneuvers utilized the CH-3 propulsion module's main 440 Newton Motor. Four Earth Bound Maneuvers (EBNs 1-4) were performed at perigee, increasing the orbital period. A single Earth Bound Apoapsis (EBA) maneuver, placed between EBN-1 and EBN-2, was performed at apoapsis to raise the periapsis altitude by about 50 km early in the Earth Phase.

For EBNs 1-4, the targets were semi-major axis (SMA) and argument of periapsis at the subsequent apoapsis. Though the target parameters are taken from the MTPF provided by ISRO at the post-maneuver apoapsis (as predicted by ISRO), the JPL maneuver design searches for the periapsis time consistent with the JPL dynamic model using ISRO parameters. The maneuver start time was allowed to float in order to realize the targeted parameters defined by ISRO. The effective thrust and mass flow rates varied for all maneuvers and were provided by ISRO in the MPDF. EBA-1 targeted cartesian elements DX, DY, and DZ, in EME2000, at the post-maneuver periapsis.

To ease the design of maneuvers that are aligned with the velocity vector, EBNs 1-4 were implemented in the velocity frame. This is a coordinate frame defined with X along the velocity vector, Y along the negative orbit normal, and Z along the negative (approximate) radius vector.

Due to the low altitude, the burns performed at perigee were not able to be observed by tracking stations. EBA-1, however, was able to be observed since it was executed at an apogee. Fig. 7 shows the real-time residuals during EBA-1. The solid green line is the predicted Doppler shift, and the diamond-shaped points are the observed Doppler points. The EBA-1 burn was quite accurate and the real-time Doppler points aligned nicely with the predicted line.

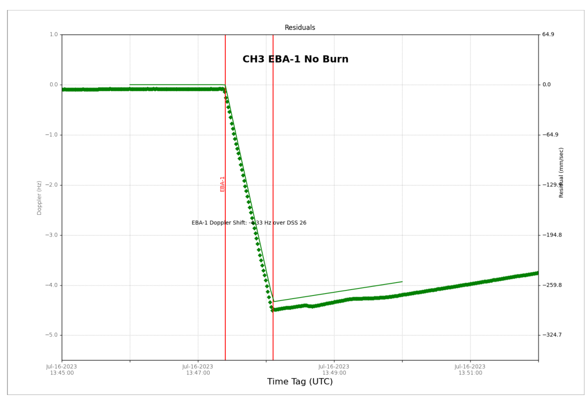

Fig. 7. EBA-1 Doppler Residual Plot

EBN-1 was successfully executed approximately 21.5 hours after launch. EBA-1 was performed the following day. A total of four burns, EBN-1, EBA-1, EBN-2, and

EBN-3 were executed in the first 6 days after launch. A summary of the Earth Phase burns is shown in Table 7.

Burn	Date (UTC)	Post Burn SMA (km)	Post Burn Perigee Alt. (km)	Post Burn Period (hr:min)	Planned ΔV (m/s)	Executed ΔV (m/s)	Magnitude Error (%)
EBN-1	15-JUL-23 06:34:49.4	27266	175.7	12:27	77.73	78.11	0.492
EBA-1	16-JUL-23 13:47:23.8	27406	221.7	12:28	4.72	4.82	2.1
EBN-2	18-JUL-23 09:17:25.5	32176	227.5	15:58	109.18	109.20	0.023
EBN-3	20-JUL-23 09:07:08.9	42174	230.3	23:56	144.60	144.60	~0.0
EBN-4	25-JUL-23 08:47:12.8	70053	242.6	51:15	185.02	185.03	0.004

Table 7. Earth Orbit Phase Maneuvers

XII. Trans-Lunar Injection

On 31-Jul-2023, CH-3's Trans-Lunar Injection (TLI) maneuver was performed. This 21-minute burn at perigee completed the series of main engine burns and imparted the necessary ΔV for the spacecraft to leave Earth orbit and begin the brief (5 day) cruise to the Moon. TLI was implemented in the velocity frame and targeted to B-Plane [10] coordinates given in EME2000. Similar to the EBNs, though the target parameters were taken from the MTPF provided by ISRO at the post-maneuver perilune (as predicted by ISRO), the JPL maneuver design searched the periapsis time consistent with the JPL dynamic model using ISRO parameters. Also similar to the EBNs, the maneuver start time was allowed to float in order to realize targets defined by ISRO.

ISRO sent LOI orbit determination requirements. These delivery uncertainties are summarized in Table 8.

Parameter	LOI requirement and uncertainty (3-sigma)
RAAN	271.19° +/- 0.1°
Inclination	88.48° +/- 0.05°
Perilune	202 km +/- 5 km

Table 8: LOI Delivery Parameters and Uncertainties

The post-TLI (od024_v1) B-Plane plot is shown in Fig. 8. The plot shows the grey lunar impact curve, the LOI B-Plane target is the green "+" sign, the box encompassing the 3-sigma LOI target parameters is green. The small cluster of points labeled "01-AUG-2023" shows the location of od023_v1, od024_v1 and three solutions using alternate strategies. Note that the "01-AUG-2023" label is arbitrary and only intended the help see the cluster of solutions. The target box is approximately 16 km high (B•R) and 11 km wide (B•T).

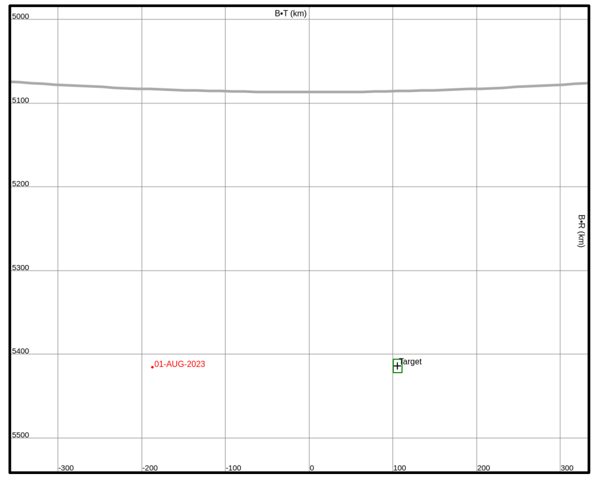

Fig. 8: Post-TLI B-Plane Plot

XIII. TCM-1

During CH-3's 5-day cruise, TCMs (Trajectory Correction Maneuvers) were planned to use only the Attitude Control System (ACS) thrusters to setup the critical main engine LOI burn on August 5, 2023. The mission plan included opportunities for two statistical maneuvers (TCM-1 and TCM-2) during the cruise to the Moon, and one prior to the Powered Descent Burn (TCM-3). These statistical maneuvers were placed to fine-tune the trajectory for an accurate Lunar Orbit Insertion (LOI) burn. On an ideal trajectory, with no errors, these maneuvers would not be executed. However, even with the very small maneuver execution errors propagating from the TLI burn, ISRO decided to perform TCM-1 to be as accurate as possible on approach to the Moon. Like TLI, TCM-1 was targeted to B-Plane parameters. However, unlike TLI, TCM-1 was implemented in the EME2000 frame. TCM-1 was very accurate and ISRO decided that TCM-2 was not necessary. Table 9 summarizes the TLI burn, which sent CH-3 on its cruise to the Moon, and TCM-1, the only statistical maneuver performed during the entire mission.

Burn	Date (2023) Time (UTC)	Post Burn B•R (km)	Post Burn B•T (km)	Target Time (UTC)	Planned ΔV (m/s)	Executed ΔV (m/s)	Magnitude Error (%)
TLI	31-JUL 18:32:52	5414.0	105.5	05-AUG 14:00:20	172.59	172.67	0.04
TCM-1	02-AUG 19:00:00	5412.7	105.4	05-AUG 13:57:46	0.95	0.95	0.06

Table 9: Summary of TLI and TCM-1

Figure 9 shows the real-time residual plot of TCM-1. The solid green line is the predicted Doppler shift during the burn, and the red dots are the real-time Doppler that was observed. The actual Doppler tracking data residuals lined up very well with the predicted Doppler residual line.

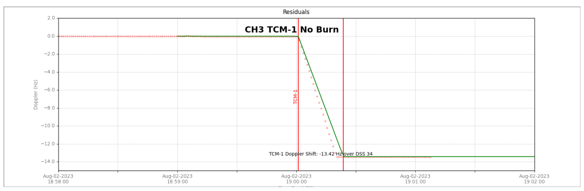

Fig. 9. TCM-1 Real-time Residuals

The post-TCM-1 B-Plane plot is shown in Fig. 10. It is clear that TCM-1 brought the CH-3 trajectory within the target box. Two OD solutions, od025_v1 and od026_v1, are shown very close to the target. The ellipse for the od026_v1, shown in red, is smaller because additional tracking data was available for this solution. Because TCM-1 brought the trajectory so close to the target, ISRO decided that TCM-2 was unnecessary.

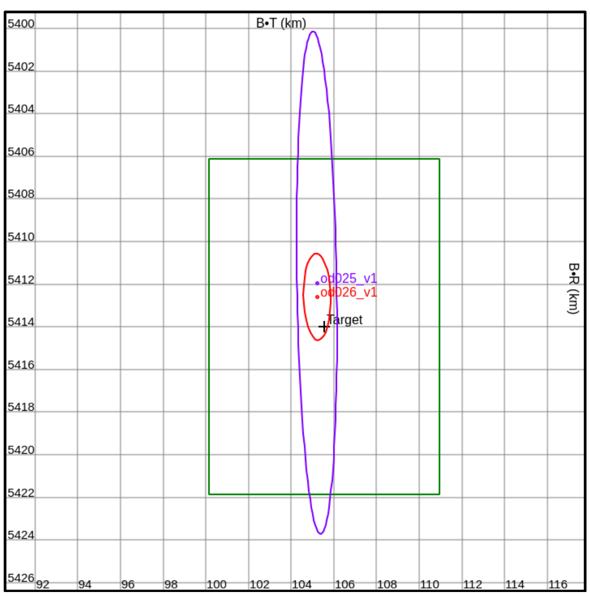

Fig. 10. Post-TCM-1 B-Plane Plot

XIV. Lunar Phase

The CH-3 Lunar Orbit Phase consisted of a Lunar Orbit Insertion (LOI) burn, also known as LBN-1 (Lunar Bound Maneuver 1), and 4 apogee-lowering maneuvers (see Figure 5). It also included the separation of the Lander Module and the Propulsion Module, two de-orbit burns, and concluded with the Powered Descent Burn, which was the final burn to lower the Lander to the Lunar surface. LBNs 1-4 utilized the CH-3 Propulsion Module's main 440 Newton Motor. The first four Lunar Bound Maneuvers (LBNs 1-4) were designed to be performed at perilune, in the anti-velocity direction, lowering the orbital period. LBNs 1-4 were implemented in the velocity frame, and the targets were semi-major axis (SMA) and argument of periapsis at the subsequent apoapsis. LBN-5, a smaller burn, used the eight 22 N thrusters. LBN-5 was implemented in the EME2000 frame, and targeted DX, DY, and DZ in the EME2000 frame at the following apoapsis. Though the target parameters are taken from the MTPF provided by ISRO at the post-maneuver apoapsis (as predicted by ISRO), the JPL maneuver design searches for the periapsis time consistent with the JPL dynamic model using ISRO parameters. The maneuver start time was allowed to float in order to realize the targeted parameters defined by ISRO. The effective thrust and mass flow rates varied for all maneuvers and were provided by ISRO in the MPDF. This targeting scheme was the same as was done for the EBNs. A summary of the Lunar Phase maneuvers is shown in Table 10.

LBN-5 had a significant under burn. ISRO reported that the burn had to be cut off due to exceeding the burn duration time limit of 41 seconds. The predicted duration was 38 seconds. This prediction was off due to the low propellant on the composite spacecraft and limited experience with these thrusters. The only other use of the small ACS thrusters was on TCM-1, when the spacecraft was carrying significantly more propellant. Because of this under burn, ISRO decided to perform a make-up maneuver that was not part of the nominal plan. This burn was called LBN-5A. This burn was used to re-establish the nominal spacecraft trajectory, and to achieve the orbital track accurately over the desired landing site using the propulsion module propellant. [11] LBN-5A also underperformed, but ISRO reported that its performance was within the 3-sigma expectations.

Separation of the Propulsion Module and the Lander Module occurred on August 17. The separation occurred via a spring mechanism that imparted a ΔV of 0.20 m/s on the Lander and 0.72 m/s on the Propulsion Module.

Since the Lander Module thrusters had not been used yet, the goal of the first burns after separation, Deorbit-1 and Deorbit-2, was both to calibrate the four 800 N engines on the Lander, and to target the powered descent start conditions (30 km altitude, latitude -44.8°, longitude 32.4°) [11]. Deorbit-1 was a relatively small burn, 9.7 m/s, and split into two parts. This burn checked the rise and fall time characteristics of the 800 N engines. Deorbit-2 completed the targeting to the Powered Descent start conditions, while also checking the throttling regime of the 800 N engines.

Burn	Date (2023) Time (UTC)	Post Burn SMA (km)	Post Burn Perilune Alt. (km)	Post Burn Period (hr:min)	Planned ΔV (m/s)	Executed ΔV (m/s)	Mag-nitude Error (%)
LBN-1	05-AUG 13:42:28	1078 0	172.6	28:12	272.54	272.54	~0.0
LBN-2	06-AUG 17:37:08	3980	169.5	06:15	191.73	192.07	0.2
LBN-3	09-AUG 08:09:02	2543	172.7	03:12	186.83	186.54	-0.16
LBN-4	14-AUG 06:26:44	1901	149.4	2:04	193.73	193.63	-0.05
LBN-5	16-AUG 03:14:01	1896	152.8	2:03	2.51	2.12	-15.55
LBN-5A	16-AUG 15:29:14	1895	153.8	2:03	0.62	0.57	-8.03
Separa-tion	17-AUG 07:45:00	1895	154.6	2:03	0.20	0.20	-0.35
Deorbit-1	18-AUG 10:30:18	1872	112.9	2:01	9.68	9.90	2.3
Deorbit-2	19-AUG 20:15:42	1817	26.0	1:56	24.55	24.60	0.2

Table 10: Lunar Orbit Phase Maneuvers

After Deorbit-2 and prior to the Powered Descent (PDSC) Burn, the JPL Navigation Team began using a 300x300 parameter Grail 900C Lunar gravity field. Prior to this, the Team had employed a 150x150 gravity field. Also, during this period, there was an opportunity or placeholder for an additional targeting maneuver, TCM-3, to fine-tune the start conditions of the PDSC Burn. Because the deviation from the nominal trajectory was small, ISRO canceled this maneuver.

XV. Powered Descent

At 6 hours prior to the Powered Descent Burn, the JPL Navigation Team delivered their final OD solution upon which the PDSC final design was based. The predicted state uncertainty, mapped to the start of the PDSC was 27.22 meters in position, and 1.47 cm/sec in velocity (3 sigma). The Lander was in an orbit of approximately 129 x 30 km.

The Powered Descent Burn was broken into 3 phases, as shown in Fig. 11. The powered descent phases included Rough Braking, Attitude Hold, and Fine Braking. In the Rough Braking phase, the objective is to achieve the required altitude and attitude for the navigation sensor operation. In the Attitude Hold phase, the thrust and attitude of the lander has to be held for 10 sec to get an absolute state information. Once the precise state information is known, the objective of the Fine Braking phase is to reach the desired site at a safe height with a vertical orientation. [11] From this point, the spacecraft descends to the surface using an on-board, closed loop system.

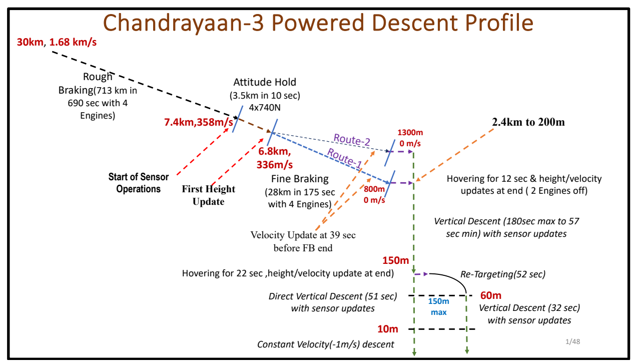

Fig. 11. CH-3 Powered Descent Profile (taken from ISRO slide at CH-3 TIM, Oct. 2022)

The JPL Navigation Team validated the ISRO Powered Descent Burn by replicating the models sent by ISRO in the PDSC file. This file contained position, velocity, and acceleration data at 0.096 second intervals. This process began by first converting the ISRO PDSC file from cartesian EME2000 coordinates to ME (Mean Earth) Moon Fixed Frame latitude, longitude and altitude. ISRO requested the PDSC to begin at -44.8094 deg latitude. The JPL and ISRO simulations agreed very well. The start time of the JPL simulation differed by only ~0.1 second at this latitude. Results of the final validation are shown in Fig. 12. The ISRO model is shown in red in Fig. 12 and the JPL model is shown in blue, which is extended one hour after landing. The red points are on top of the blue points until landing. The differences between JPL and ISRO in altitude, longitude, latitude, and position are extremely small.

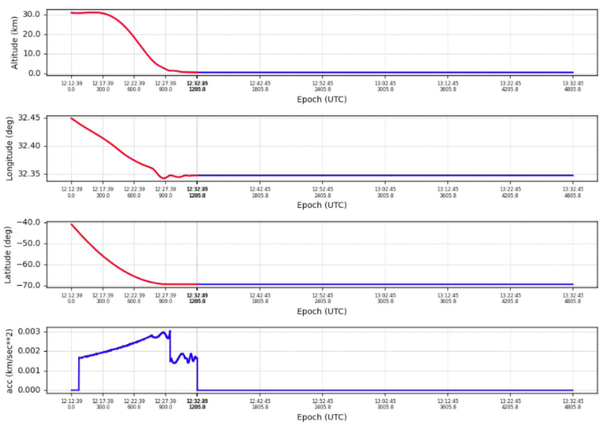

Fig. 12. Powered Descent Time History Models (red points are reported by ISRO, blue points computed by JPL)

Fig. 13 shows the real-time residual plot of the Powered Descent Burn. The solid green line is the predicted Doppler shift during the burn, and the magenta dots are the real-time Doppler residuals that were observed. The actual Doppler tracking data residuals lined up very well with the predicted Doppler residual line.

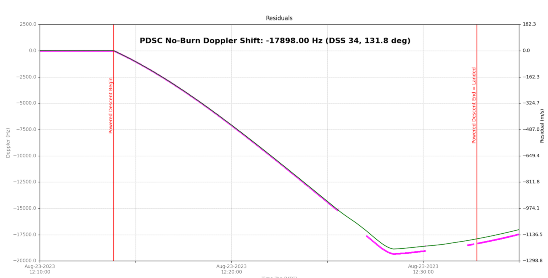

Fig. 13. Doppler Residuals for PDSC Burn

Table 11 shows a comparison of the pre-launch targeted landing site and the actual landing site, as confirmed by a picture from the CH-2 Orbiter shown in Fig. 14. The distance between these two points in Table 11 is approximately 345 meters. This confirms an extremely accurate landing by CH-3.

	Pre-Launch Targeted Landing Site [12]	Actual Landing Site [13]
Latitude	69.368° S	69.373° S
Longitude	32.348° E	32.319° E

Table 11. Pre-Launch vs. Actual Landing Site Comparison

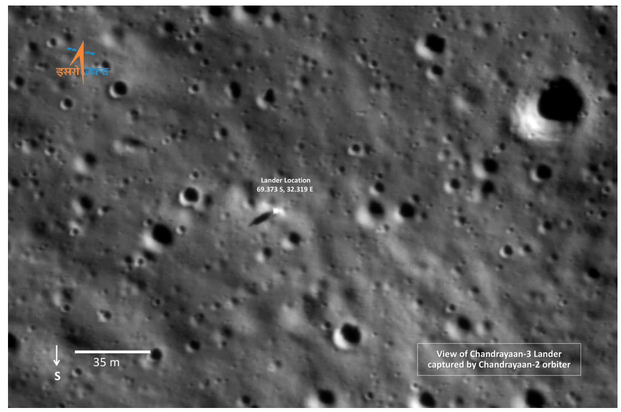

Fig. 14. View of CH-3 Lander Captured by CH-2 Orbiter [13]

XVI. Conclusion

CH-3's success strengthens India's experience and reputation in space research and space operations by becoming the first nation to successfully land a spacecraft near the Moon's South Pole.

The ISRO/NASA collaboration on CH-3 was mutually beneficial and a learning experience for both organizations. It is a collaboration that we hope will continue in future deep space missions. It is anticipated that the success of the CH-3 mission could lead to future international collaboration on space missions between NASA and ISRO.

XVII. Acknowledgments

CH-3's success is a direct result of the contributions of many people. The authors would like to express their appreciation and deep respect for the members of the ISRO navigation team. Special thanks are due to our System Administrator, Kevin Stanchfield, and the JPL Navigation Advisory Group (NAG) review board, including Tim McElrath, Tung-Han You, Brent Buffington, Dimitrios Gerasimatos, Eric Gustafson, Shyam Bhaskaran, Bill Taber, and Try Lam. The authors would also like to thank Sami Asmar, the JPL Project Manager for CH-3.

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