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Chandrayaan-2 Orbiter Operations: Challenges and Learnings

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Abstract

Chandrayaan-2, the second lunar mission by the Indian Space Research Organization was successfully launched on 22nd Jul 2019 from Satish Dhawan Space Centre, Sriharikota. After a series of Earth-bound and lunar-bound maneuvers, the spacecraft entered into the designated 100 km science orbit around Moon on 24th -Sep 2019. The major science objectives of the Chandrayaan-2 (CH-2) Orbiter mission are, to map and study the variations in lunar surface and atmospheric composition with its eight diversified indigenously developed payloads, operating in Optical, Microwave, X-Ray and Infrared (IR) band along with in-situ measurements. This paper focuses on the long-term operation management strategies learnt from handling the challenges faced in the Chandrayaan-2 (CH2) Orbiter mission. It describes the characteristics of the lunar polar orbit and its strong correlation with payload operations strategy and the need for different attitude referencing during different seasons. The mainframe bus management during non-nominal geometries, orbit determination (OD) and orbit maintenance strategies are also discussed. The goal of this paper is to share the experience gained in CH-2 Orbiter flight operation management in all the above aspects and should be useful for all research operation agencies involved in future lunar remote sensing explorations.

Keywords: Orbit characteristic, Sun Aspect Angle, Total Lunar eclipse, Orbit Determination, Orbit Maneuver

1. Introduction

The polar lunar orbit exhibits few distinct characteristics compared to Low Earth Remote Sensing (LEO) Orbits. This is due to the Earth's motion around the Sun, and also its inertially fixed nature. Over a year the angle between the Sun and the orbital plane (Sun-aspect angle) varies widely and thereby provides a variable sun illumination condition for lunar imaging, this is termed as Dawn-Dusk (DD) and Noon-Midnight (NM) seasons. The Tracking Telemetry Tele-command (TTC) view period of an inertially fixed CH2 polar orbit varies with a period of 14 days. When the view axis from Earth is perpendicular to the orbital plane for ~3 days, continuous visibility for ~11hrs/day is available, and this is termed as Face ON orbit. On the other hand, when the view axis is occulted by the moon for the remaining ~11 days, the view period is variable, and this is termed an Edge ON orbit. The Optical and Microwave payload imaging strategy is tightly coupled with the different seasons (DD and NM) and mentioned view periods. Payload operation which is comprised of imaging feasibility checks, science data recording and download duration check and energy balance estimation need optimal planning for global lunar coverage. The 100 km polar lunar orbit is a non-sun synchronous orbit, and this has a major impact on solar power generation. Hence, CH2-orbiter requires a different attitude configuration to meet power and thermal constraints. Optical High-Resolution Camera (OHRC) which provides the world's best lunar resolution (0.32m) imagery, has a specific altitude and sun illumination requirement for imaging and calls for systematic and rigorous operation planning.

Bus management during the total lunar eclipse is extremely challenging as the spacecraft experiences a hostile cold environment without power generation for an extended duration, which is four times more than the regular eclipses. A complex mission strategy was adopted through orbit tuning and bus management to overcome the adverse situation created during total lunar eclipse. CH-2 orbiter successfully overcame four such total lunar eclipses.

A precise knowledge of orbital parameters is mandatory for the determination of the position of a spacecraft at any given time. Initially, tracking data was available from JPL-DSN and IDSN stations. Later, only IDSN data was available and it was challenging for the orbit determination (OD) process to meet the mission requirements. Orbit prediction accuracy is particularly challenging during periods when CH2-Orbiter is in the Noon-Midnight season with the dominant force being lunar gravity for the low altitude orbit in combination with momentum de-saturations maneuvers. To account for the impact of momentum dumps, post-OD activities are being carried out, wherein the post-fracto knowledge of momentum dumps are used to refine the trajectory. Lunar orbits are characterized by the evolution of their eccentricity and argument of perilune over time. Without periodic orbit maintenance, CH2-Orbiter will have a lifetime of only about ~220 days. Periodic orbit maintenance maneuvers are required to keep apolune & perilune within ±25 km over the nominal altitude of 100 kms. So far more than 50 orbit maneuvers were successfully carried out for science orbit maintenance successfully.

Operation strategies were evolved and implemented in critical mission operations, payload planning, and orbit determination. This has enabled successful global lunar coverage and imaging of the special areas of interest by Chandrayaan-2 Orbiter with improved accuracy. The following sections provide further details on all these areas.

2. Challenges *in Operation Management*

This section discusses about challenges faced during long term mission and operation management with CH-2 orbiter. It starts with describing lunar orbit characteristic followed by its impact on payload scheduling. Protecting the battery from deep discharge during total lunar eclipse and orbit determination with limited tracking data and efficient orbit maintenance strategies are the major challenges encountered in CH2-orbiter mission operations management.

2.1 ***Orbit Characteristic***

100 km CH2 orbit around Moon is a non-sun synchronous and inertially fixed, due to this the sun-aspect angle i.e. angle between the CH2 orbit-plane and Sun varies in full range (0 to 360˚) over the year (refer Figure-1). This results in two extreme cases of illumination, defined as Dawn-Dusk (DD Season) orbit, where the sun vector is perpendicular to the orbit plane and Noon-Midnight (NM Season) Orbit, where the sun vector is parallel to the orbit plane.

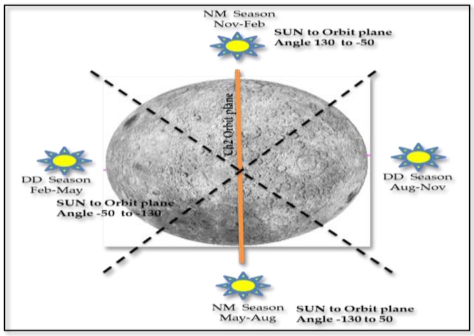


Figure-1: Sun Aspect angle over a year

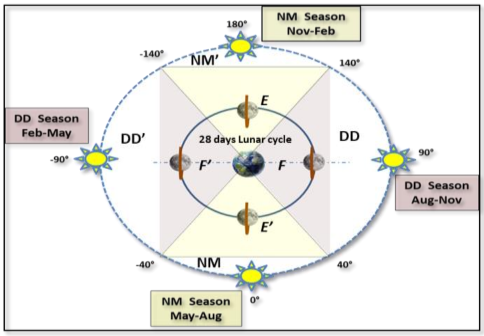


Figure-2: Earth, Moon and Sun Geometry considering earth is Fixed

Figure-2 shows Sun, Earth and Moon geometrical position during different seasons i.e. Dawn-Dusk/Noon-Midnight season along with CH-2 orbit. The geometry is drawn assuming that the Earth's position is fixed. The sun incidence angle w.r.t. the CH2 orbit plane changes ~1 deg/day. The outer circle in figure-2 represents 365 days Sun's movement around Earth considering Earth fixed. The sections DD and DD' correspond to Dawn-Dusk (DD) season while the Sun vector and orbit plane are around 40 to 140 deg cantering ±90 deg indication of the peak DD days. The section NM and NM' correspond to the peak Noon-Midnight (NM) season while Sun vector and orbit plane are around -40 to 40 deg cantering 0/180 deg indicating peak NM day.

In Figure-2, the inner circle represents the position of CH2 orbit w.r.t the Earth in 28 days lunar cycle. Section *F* and *F'* in Figure-2 are termed Face On geometry, where Earth and orbit normal are in the same plane. While sections *E* and *E'* are termed as Edge On geometry, where Orbit Normal to Earth is perpendicular. The Face ON and Edge ON geometries are significant in terms of the view period or the access interval. During the Face on day, CH2-Orbiter is visible continuously from a ground station; while on the Edge ON days, the CH2-Orbiter view period is occulted due to Moon.

The variation of sun angle w.r.t orbit plane causes non-uniform power generation in different seasons if a single attitude referencing is followed. To overcome the same two different attitude referencing schemes have been defined. Although the orbit-reference attitude is desirable in view of payload operations, it is not possible to generate enough power during DD season (in orbit-reference attitude) as the Sun rays will be parallel with Orbit Normal. Hence, a different attitude referencing sun-pointing referencing scheme is followed in DD season. Figure-3.a and 3.b pictorially shows the two different attitude schemes followed in two different seasons.

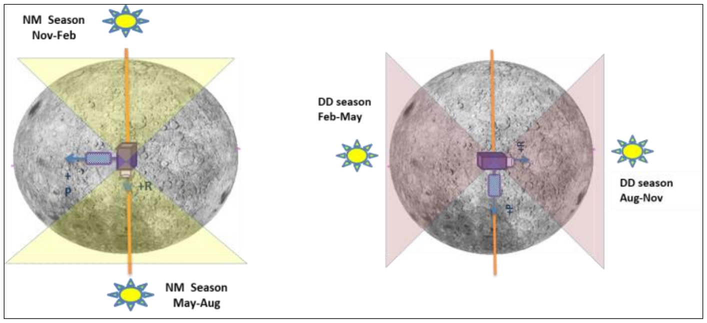


Figure-3.a: Orbit Ref. Attitude during NM Season   Figure-3.b: Sun Ref. Attitude during DD season

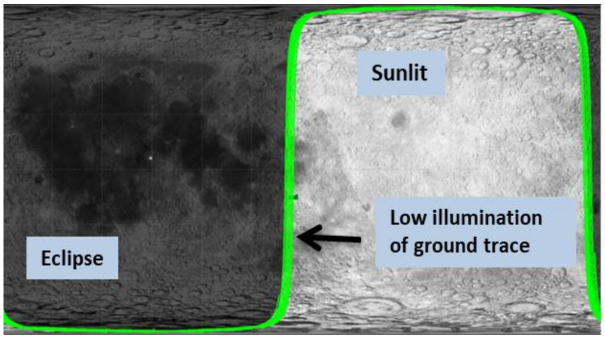
2.2 Payload Operation Strategy based on Season:

This section highlights the payload operation strategy and its strong correlation with orbit characteristics such as ground trace illumination, energy balance and attitude. A brief introduction to the objective of all the payloads is explained; subsequently, payload scheduling strategy is described.

Chandrayaan-2 Large Area Soft X-ray Spectrometer (**CLASS**) payload makes use of X-ray fluorescence spectra to determine the elemental composition of the lunar surface. Solar X-ray monitor (**XSM**) is for mapping major elements present on the lunar surface. Dual Frequency L and S band Synthetic Aperture Radar (**DFSAR**) is used for probing the few meters of the lunar surface for the presence of different constituents, including water ice. DFSAR is expected to provide further evidence confirming the presence of water ice, and its distribution below the shadowed regions of the Moon. Imaging IR Spectrometer (**IIRS**) is for mapping of lunar surface over a wide wavelength range for the study of minerals, water molecules and hydroxyl present. It features an extended spectral range (0.8 μm to 5 μm) which is an improvement over previous lunar missions whose payloads worked up to 3 μm. Chandrayaan-2 Atmospheric Compositional Explorer 2 (**ChACE-2**) Quadrupole Mass Analyzer has been included to carry out a detailed study of the lunar exosphere. Terrain Mapping Camera-2 (**TMC-2**) is for preparing a three-dimensional map essential for studying the lunar mineralogy and geology. For Radio Anatomy of Moon Bound Hypersensitive Ionosphere and Atmosphere, a dual Frequency (S and X Band) Radio Science experiment (**DFRS**) is flown to study the electron density in the Lunar ionosphere. Orbiter High Resolution Camera (**OHRC**) is for scouting a hazard-free spot prior to landing. It will later help prepare high-resolution topographic maps and digital elevation models of the lunar surface. OHRC has a spatial resolution of 0.32 m from 100 km polar orbit, which is the best resolution among any lunar orbiter mission to date.

The remaining part in this section describes imaging strategy and its correlation with orbit characteristic was explained.

As a result of the Sun’s apparent motion over the CH2-orbit, illumination of lunar sub-satellite point varies across the year, i.e. the ground traces are poorly illuminated (Figure-4.a) during DD season and well illuminated (Figure-4.b) during the NM season. Due to this NM-season is also termed as Optical imaging session, where the illumination-dependent payloads like TMC-2 and IIRS are operated. Typically, Noon-Midnight (NM) season holds for around 80 days centering on peak NM day, around January and July. On the other hand, Dawn-Dusk (DD) season holds around 100 days centering on peak DD day, around September and March and is termed as radar imaging (non-illumination dependent payload) season. DFSAR payloads are getting operated during DD season.



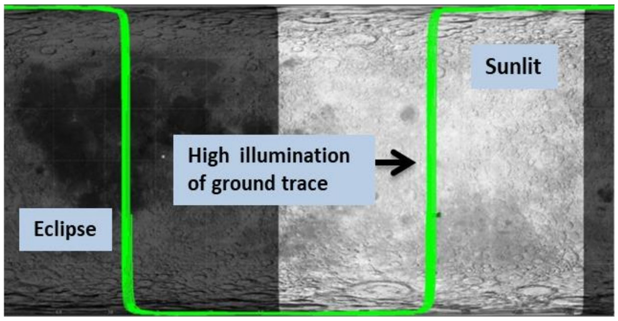
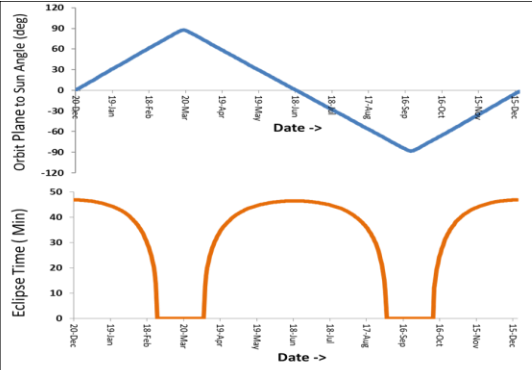


Figure-4.a: Ground Trace illumination during DD season   Figure-4.b: Ground Trace illumination during NM season

Generally, CH2-orbiter encounters an eclipse of around 47 min per orbit due to its primary body (Moon) shadow. However, during DD season when the sun angle with respect to the orbit plane is more than ±70° CH2-orbiter does not have any eclipse. Gradual decrease and increase in eclipse duration was observed while approaching DD day and moving away from DD day, refer Figure-5 for the eclipse duration plot over the year. In a year around 80 days, 40 days each during two DD seasons; there will be no eclipse zone. The duration of the eclipse is a major factor in payload planning, as energy balance needs to be considered for imaging and science data download. As discussed in the previous paragraph in this season the DFSAR payload is getting operated as ground trace illumination is less. The frequency of payload operation is more during no-eclipse zone compared to the zone with eclipse, due to higher energy balance. The other factor that determines payload session frequency is Near/Far side imaging and explained subsequently.

The moon's revolution around the earth exactly matches with its rotation; as a result, any location on the earth sees only one face of the moon. Because of these longitudes around 0° to ± 90 ° are always viewed from Earth and is termed as the near side. Longitude between ±90° to ±180° is not viewed from the earth and termed as the far side of the moon. The Orbit period of CH2-Orbiter is around 2 hr. and is visible from Indian Deep Space Network (IDSN) for around ~11.5 hours, i.e. 5-6 orbits per day.

In a 28 days lunar cycle, lunar shadow (lunar night) moves completely from near side to the far side in 14 days. While the near side is in eclipse, imaging can be done on the far side and dumped during ground station visibility. Cycle-A in figure-5 shows the above geometry and imaging in every orbit followed by the download in the same orbit is feasible during these days. However, during the other half cycle, i.e. while the near side is sunlit, imaging and data dump need to be scheduled in alternate orbit. As simultaneous imaging and dumping may degrade science data quality. Cycle-B in figure-5 shows the geometry for the same and this restricts the imaging sessions.



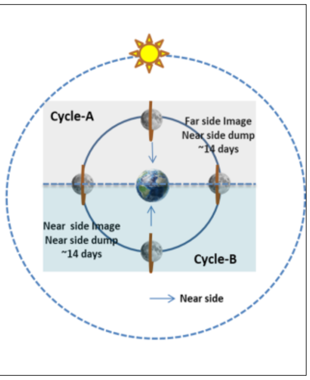


Figure-5: Sun Angle w.r.t Orbit plane and Eclipse duration
Figure-6: Near/Far side imaging and dump geometry

OHRC is a very high spatial resolution camera operating in a visible panchromatic (PAN) band and designed to image low sun elevation condition [1]. To image an intended Area Of Interest (AOI), very precise planning is required, which satisfies many conditions; such as sun elevation (illumination) at AOI needs to be within 5 to 12°, orbiter altitude needs to be maintained within 85 to 100 km, along and across track bias to be maintained within ±

26° for better image quality, and two imaging sessions with different attitude bias for DEM generation. This requires a precise selection of imaging days for illumination conditions and orbit control to meet altitude restrictions for every imaging AOI. This makes the OHRC imaging session more challenging as compared to other payloads.

DFRS sessions are planned only during DD season. A specific orbit segment in sun pointing attitude allows S-band (2240 Mhz) and X-Band (8496 Mhz) transmitter signal to receive simultaneously in the IDSN ground station due to its payload mounting and its designed Field-of-View (FOV)[2]. In addition to this, a fixed roll-bias is also imparted to overcome on-board mechanical restrictions in the X-band antenna. This additional roll bias brings down the available power margin, due to all the above factors DFRS sessions are limited and conducted in campaign mode. DFRS payload is operated around pole crossing during Edge ON orbits so that signal passes through dense and depth lunar atmosphere. Other payloads e.g. XSM, CLASS and CHACE-2 do not have any specific orbit, illumination or satellite orientation requirement and are planned considering positive energy balance. Table-1 shows the nominal payload operation duration along with the season:

Table-1: Nominal payload operation duration

P/L	Nominal Operation Duration	Season
OHRC	10 sec	Dawn-Dusk
XSM	Continuously ON	Dawn-Dusk & Noon-Midnight
CLASS	Nominally during sunlit period. 10 days continuously ON around Full Moon day.	Dawn-Dusk & Noon-Midnight
CHACE-2	260 min. (Twice a day 6 orbits apart)	Dawn-Dusk & Noon-Midnight
DF-SAR	2 min	Dawn-Dusk
TMC-2	10 to 30 min	Noon-Midnight
IIRS	Pre-CAL & post CAL : 1 min (Eclipse) Imaging: 10 min – 60 min	Noon-Midnight
DFRS	9 min ± 2 days around Edge ON day, once in lunar cycle	Dawn-Dusk

2.3 The Total Lunar Eclipse:

CH-2 Orbiter experienced four total lunar eclipses since its launch. It's a survival challenge for any satellite orbiting around the moon. This is because of non-availability of the solar power for a longer duration than usual. This affects the battery charging and the satellite also experiences a cooler environment than usual during the total eclipse. During the total lunar eclipse on 26th May 2021, 19th Nov 2021, 16th May 2022, and 8th Nov 2022, Chandrayaan-2 Orbiter went into the lunar shadow (due to the primary body) followed by the Earth's shadow and thereby experienced an extended eclipse for nearly three hours, which is otherwise nominally around 47 min due to lunar (primary body) shadow.

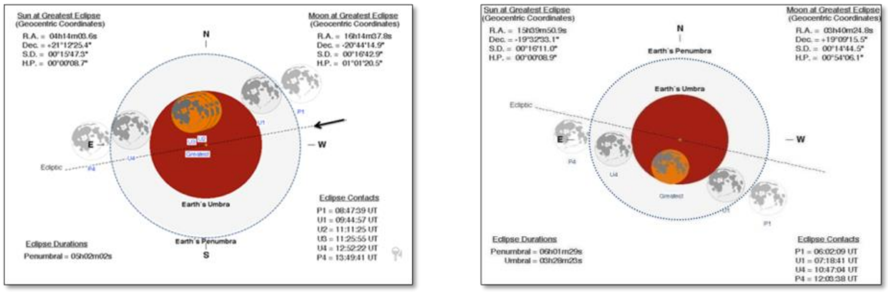


Figure-7: Total lunar eclipse geometry on 26th May & 19th Nov-2021 (eclipse.gsfc.nasa.gov)

An extended eclipse of a similar duration will discharge the battery beyond its safe limit and may lead to mission contingency. To circumvent the same, the orbit can be tuned to optimize the power requirement by profiling power generation. Power profiling is the method of controlling power generation based on the power consumption requirement. A suitable satellite load management was also carried out to protect the battery from deep or over-discharge. In the Chandrayaan-2 orbiter, the orbital parameters were tuned through the orbit maneuvers to optimize power generation and an efficient load management during the eclipse and protected the battery from over-discharging.

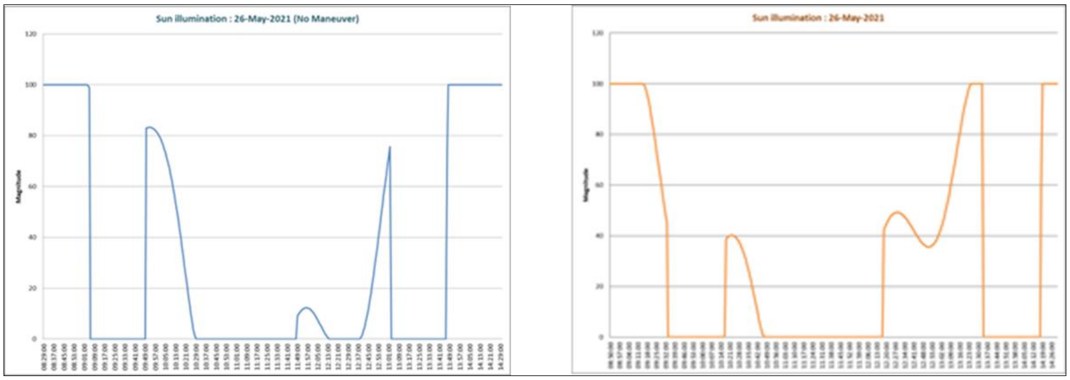


Figure-8.a & 8.b: Power generation without orbit tuning and after orbit tuning

To get an orbit that optimizes power generation during the eclipse, orbital parameters are required to be tuned in a way that they are maintained within the mission bounds. Tuning of Argument of Perigee (AOP) and True Anomaly (TA) provides better control of power profiling than any other orbit (Keplerian) elements like Apolune or Perilune. For a specific Epoch, AOP and TA are directly affecting the eclipse entry and exit condition and are more sensitive to energy/power optimization. Moreover, a maintained polar orbit around the moon shows a natural variation of AOP of ~140 deg due to lunar gravity field distribution and provides additional flexibility for tuning AOP. To generate optimal power during the total lunar eclipse a typical AOP and TA combination was targeted at the eclipse entry epoch and achieved through orbit maneuvers. Figure-8.a shows the percentage of power generation for a non-tuned orbit and Figure-8.b shows power generation for the same tuned orbit. In Figure-8.b the eclipse entry and exit conditions were tuned to maximize the power margin.

2.4 Orbit Determination:

A precise knowledge of orbital parameters is mandatory for the determination of the position of a satellite at any given time. Orbit Determination (OD) is a process in which model parameters are adjusted to converge to best fit trajectory i.e. trajectory for which the measurement residuals (difference between actual and model predicted value) are least. OD program uses the weighted least squares method. Tracking data consists of Range and Doppler measurements from the ground station tracking system. The Range and Doppler measurements are processed prior to orbit determination (OD) as below.

- The raw range and Doppler measurements are compared with the predicted measurements obtained from the predicted Ephemeris and the differences are calculated. If the difference exceeds a threshold limit, then the measurement is not considered for OD.
- The Range and Doppler data are further adjusted for atmospheric and delay corrections and the measurement data selected by this procedure is finally used for the orbit determination process.

Tracking requirements were met nearly 100% of the time with the combination of NASA JPL/DSN and ISRO/IDSN stations, during the initial phase of the Chandryaan-2 mission. Subsequently, the availability of tracking data was reduced by ~ 50 % as TTC visibility was restricted only to ISRO-IDSN. This posed a great challenge for Flight Dynamics Operations (FDO) team to derive the OD solutions using 11 – 11.5 hours of tracking data collected over IDSN.

Various analysis/studies were carried-out to evolve the OD declaration criteria and improve OD accuracies.

It was observed that:

- The orbital geometry and attitude definition of the orbiter has impact on OD process.
- The momentum dumps (desat) have more impact on orbit during Noon-Midnight season.

Sun pointing attitude referencing during Dawn-Dusk season is dominated by negative roll dumps which perturbs the orbit to an extent of 500 m per day whereas orbit reference attitude in Noon-Midnight season with major dumps observed in negative Yaw, Positive Roll and Negative Pitch axis perturbs the orbit to an extent of 1km per day.

The difference between two trajectories, one without desat inclusion and another one with desat inclusion is shown in Figure-9 and Figure-10.

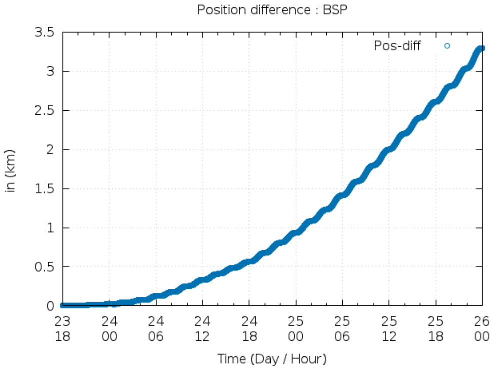


Figure-9 : Trajectory Difference in Position

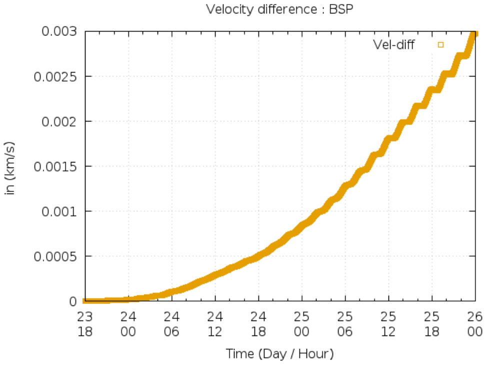


Figure-10 : Trajectory Difference in Velocity

It is observed that Position-difference is 3.29 km & Velocity-difference : 2.9 m/sec for a period of 54hrs. Based on a several case studies it was observed that inclusion of momentum desaturations (desat) information in trajectory, significantly improves the orbit knowledge.

Information about the momentum desaturation: Due to the onboard telemetry sampling, timing information of desat is available for a window period rather than a fixed time. An analysis was carried-out to time-tag desat (small force) at window start-time, mid-time and end-time and its impact over trajectory was studied.

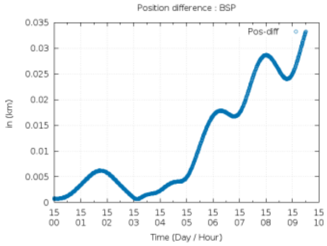
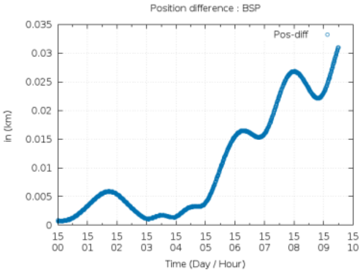
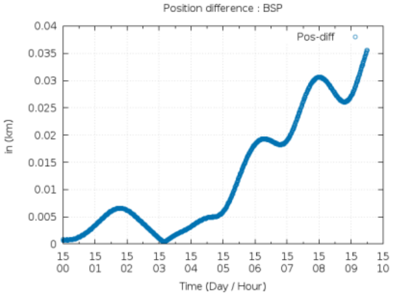
@ MidTime of window period :	@ StartTime of window period :	@ EndTime of window period :
		
Position-difference = 33m	Position-difference = 31m	Position-difference = 35m

Figure-11 : Time stamping comparison for desat

It was observed that time-tagging of Delta-Vs at mid-time of window period provided better trajectory. The process of re-generating the trajectory using desat (small force) information was incorporated in regular flight dynamics operations.

2.5 Orbit Maintenance

Lunar orbits are characterized by the evolution of their eccentricity and argument of perilune over time[3]. Without periodic orbit maintenance, CH2-Orbiter will have a lifetime of only about ~220 days. The Moon’s non-uniform gravitational field causes significant perturbations to these two parameters. Periodic orbit maintenance maneuvers are required to keep apolune & perilune within ±25 km over the nominal altitude. To maintain science orbit, a pair of orbit maneuvers (station-keeping orbit maneuvers) is being carried out periodically and also for conjunction mitigation with other lunar-orbiting spacecraft, as and when required. The frequency of this orbit maintenance is around 35 to 40 days. Typical Apolune & Perilune variation follows a butterfly pattern shown below (Figure-12 & 13).

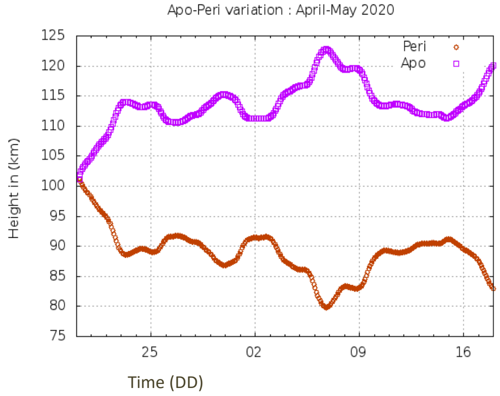


Figure-12 Typical variation of Apolune & Perilune

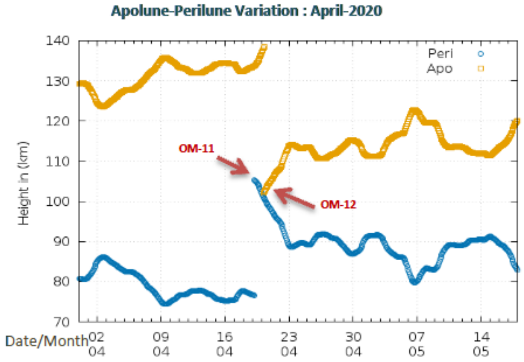


Figure-13 Apolune –Perilune variation during maneuver

The altitude of CH2 is monitored and when it crosses the specified limits, the orbit is circularized with a two burn sequence. The first is the raising maneuver, executed at Apolune cross-time to increase the Semi-Major-Axis (SMA) and the Perilune; the second is the reduction maneuver, executed at Perilune cross-time to decrease the SMA and the Apolune. As shown in Figure-12, Perilune-Raise Maneuver OM-1 was executed on Day-1 with a Delta-V of 6.4 m/s. The orbit was changed from 76.6 x 134 km to 105.4 x 134 km. Subsequently, Apolune-Reduction Maneuver OM-2 was executed on Day-2 to circularize the orbit with a Delta-V of -7.9 m/s.

2.6 Optimization of Orbit Maneuver period

Based on the variation of Perilune & Apolune values during maneuvers, an analysis was carried-out towards interval between subsequent maneuvers and fuel-consumption towards the same.

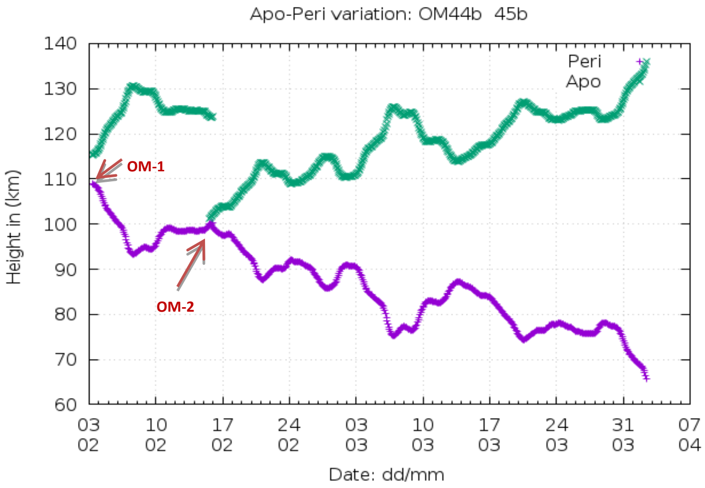


Figure-14 Apolune –Perilune variation OM-1 on day-1 and OM-2 on day-12

If the first maneuver is planned such that the perilune would "raise back" to 100 km or above in 12 - 15 days, the subsequent circularization maneuver (apolune reduction) can be done. As shown in Figure-13, OM-1 was executed on Day-1 with Delta-V of 5.3 m/s to increase perilune to 108km. It is observed that after 12 days, perilune is 100km and hence a reduction maneuver was planned on Day-12 with a Delta-v of 5.0 m/s to circularize the orbit. The period between orbit maintenance activities is increased to around 50 to 55 days; this has benefits in terms of number of maneuvers per unit-period (planning and operations work) and fuel consumption in the long-term.

This strategy has optimized the orbit-maintenance process by saving fuel and helps with mission operations life.

3. Conclusions

The paper summarizes the operation management strategies learned from the Chandrayaan-2 Orbiter mission launched by ISRO in July 2023. A detail description of lunar polar orbit characteristics and its impact on payload operation and power generation has been discussed. The paper also brings out the challenges faced by orbiter during the total lunar eclipses, and the mitigation strategies adopted; this can be useful for space agencies involved in lunar missions to handle upcoming lunar eclipses in 2025 and 2028. It also emphasizes orbit determination confronted with limited tracking data and the inclusion of momentum dumping the information to achieve better acquires in orbit determination and propagation.

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