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Power Profiling through Orbit Tuning during Lunar Eclipses: Chandrayaan-2

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Abstract

Watching the total lunar eclipse is always an exciting event for astronomers and sky watchers, but it's a survival challenge for satellites orbiting around the moon. This is because of non-availability of the solar power for a longer duration to charge the battery, and satellites also experience a cooler environment than usual during the eclipse duration. During the total lunar eclipse on 26th May, 19th Nov 2021, 16th May, and 8thNov 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 ~47 min due to the lunar (primary body) shadow. 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 Chandrayaan-2 orbit was tuned to optimize 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 over-discharge. In the Chandrayaan-2 orbiter, the orbital parameters were tuned by conducting the orbit maneuvers to optimize power generation and efficient load management during the eclipse and protect the battery from over discharging. The paper describes the orbit tuning methodology followed for optimal power profiling strategy.

Keywords: Chandrayaan-2 Orbiter, Lunar Eclipse

Acronyms/Abbreviations

CH-2 – Chandrayaan-2
DOD – Depth of Discharge
AOP – Argument Of Perigee
OM – Orbit Maneuver

1. Introduction

Chandrayaan-2 (CH-2) is a lunar mission, designed and developed by the Indian Space Research Organization (ISRO) and was launched by GSLV MK-III from SDSC, Sriharikota on July 22, 2019. It was configured as a two-module integrated system comprising an Orbiter Craft and a Lander Craft. Orbiter Craft is the second in its series of lunar explorations and carries eight payload instruments for science data collection. Initially, CH-2 was injected into an elliptical Earth parking orbit by the launcher and later through a series of Earth and Lunar bound maneuvers the final polar 100 km circular lunar orbit was achieved. Currently, Orbiter craft is orbiting the Moon in a near polar circular orbit at an altitude of 100 km. A brief overview of the Chandryaan-2 power system is described in the next section.

The power subsystem mainly comprises of solar panel, power electronics and battery. Solar panel consists of solar cells which convert the solar energy to electrical energy and this energy is supplied to the mainframe loads and stored in battery as well. The energy stored in the battery is used to supply the loads during eclipse and peak demands during payload operations. Nominally CH-2 Orbiter experiences a maximum of 47 min of eclipse every orbit of period 120 min. The CH-2 Orbiter solar panel is designed to generate a required power of 1000 Watts at equinox, normal incidence at end of Life (EOL) at a bus voltage of 41.5 Volt. CH-2 Orbiter has one Li-ion battery of 50.4 Ah, a max cumulative Depth of Discharge (DOD) of around 20% observed during eclipse and payload.

On 26th May 2021, CH-2 Orbiter experienced the first ever total lunar eclipse since its launch. It was predicted that the CH-2 Orbiter would undergo a 2 extended eclipse and the worst-case estimate of battery DOD was more than 60%. To mitigate this situation, orbit tuning and its impact on power generation were studied. Based on the study few orbit maneuvers (OM) were carried out. The next section describes the motivation for orbit tuning.

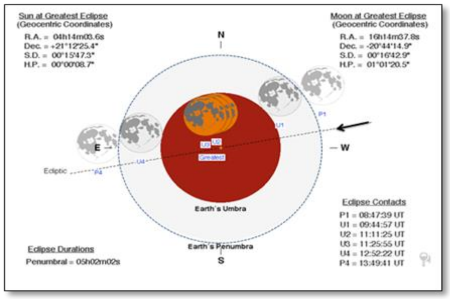


Figure 1: Lunar Eclipse on May 26, 2021 (eclipse.gsfc.nasa.gov)

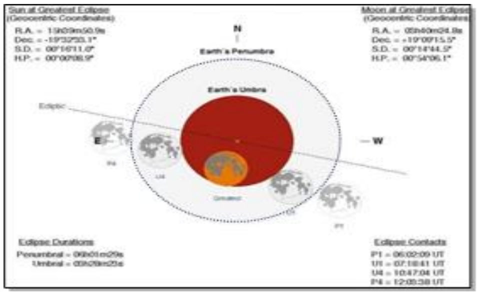


Figure 2: Lunar Eclipse on Nov 19, 2021 (eclipse.gsfc.nasa.gov)

2. Motivation

Careful observation of eclipse geometry in Figures 1 and 2 shows that the Moon passes over along the boundary (the edges of the red boundary in Figure-1 & 2) of Earth's umbra and penumbra for quite a significant time during the total lunar eclipse. Taking the advantage of orbital altitude of the CH-2 Orbiter (~100 km), it can be placed in the penumbral region during Earth's umbra crossing, resulting in a significant power generation during the total eclipse. This can be done by appropriately tuning orbital elements through orbit maneuvers. The next section describes the analysis methodology of orbit tuning and its impact on power generation. To keep the satellite battery within the specified DOD, suitable planning was done by load shading and thermal management alongside orbit tuning. However, the mainframe management aspects are outside the scope of this paper

3. Analysis Method

CH-2 orbital elements with April, 24 2021 11:00 UT Epoch was taken as the initial state and propagated till May 26, 2021. Figure-3 shows the default power generation considering the nominal maintained (100 ± 25 km) orbit. If allowed, the same satellite battery would have discharged beyond its permissible limit. A study was carried out by varying selected orbital parameters within its allowable limit. In each case, power generation was estimated for three successive orbits keeping umbra affected orbit at the center. Three successive orbits were chosen for analysis, as average power generation required to be optimized considering pre and post-eclipse. Out of all the cases optimal and operationally feasible orbital elements were chosen and targeted through a sequence of orbit maneuvers. While planning the orbit maneuver the natural variation of orbital parameters was also considered. This further optimized the fuel required for orbit maneuver. Solar power generation was estimated through an indigenous lunar eclipse model. However, it was also validated with Satellite Tool Kit (STK) and with GMAT tool. The remaining part of this section describes CH-2 nominal orbit characteristics and maneuver planning philosophy.

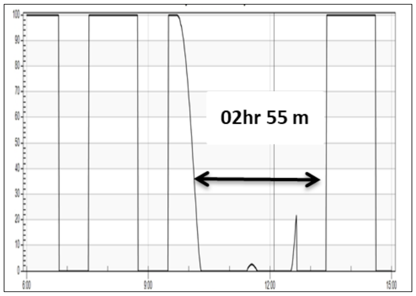


Fig-3: Default Solar Intensity (without OM) on 26-05-21

4.1 Nominal CH-2 Orbiter Station Keeping strategy & Argument of Perigee (AOP) Variation

Lunar orbits can be characterized by the evolution of their argument of periapsis and eccentricity over time. The non-uniform gravitational field of the Moon causes significant perturbations to these two parameters. Figure 4 and 5 illustrates the variation of these parameters, overtime for CH-2 orbiter. This orbit shows significant development in eccentricity and argument of periapsis (AOP) from month to month. In Figure 4, this is clearly seen in the increasing eccentricity as the orbit evolves. If left uncorrected, these perturbations would cause CH-2 orbiter to hit the lunar surface in approximately 70-80 days. The orbiter is maintained at 100km x 100 Km mapping orbit. The mission specified limits for the orbit are 75 to 125 Km.

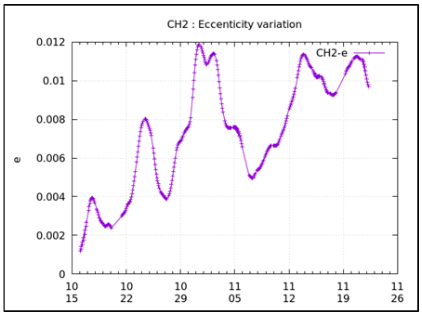


Figure-4: Typical variation of Eccentricity

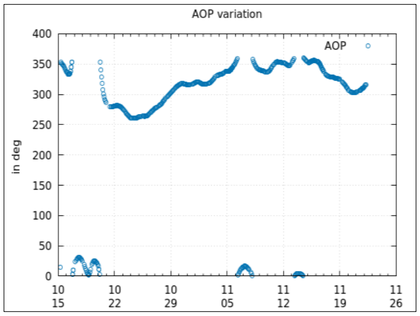


Figure 5: Typical Variation of AOP

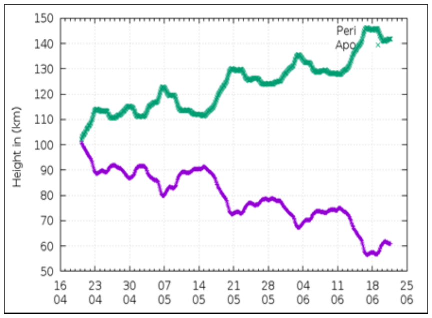


Figure 4: Typical variation of Apolune & Perilune

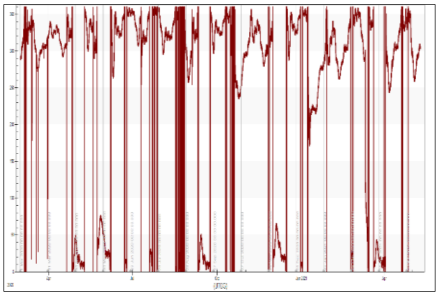


Figure 5: Natural AOP Variation over a year (with OM)

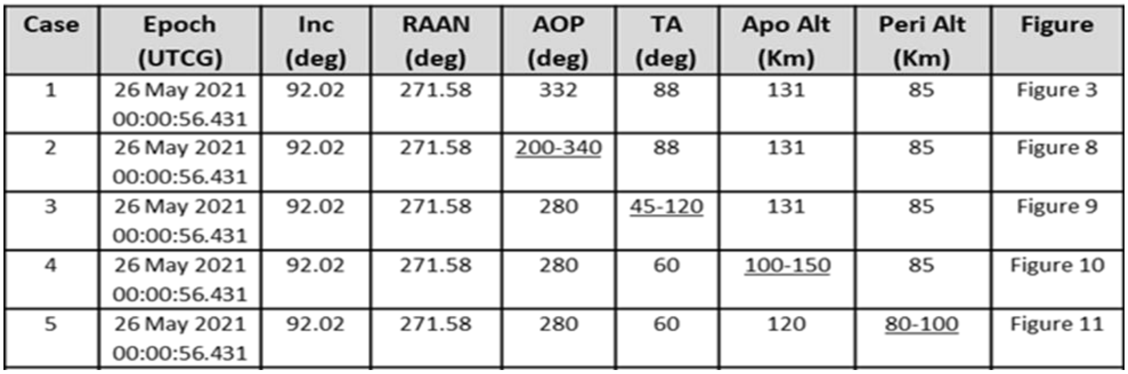
The variation in apolune and perilune resembles a butterfly pattern as shown in Figure 6. The station keeping strategy makes use of the repeating pattern of Apolune-perilune parameters. For orbit maintenance, the aim is to circularize the orbit with a 2-burn sequence. From the above Figure 7, it is observed that the Argument of perilune varies from 300° to 30° for most of the days. When the AOP is 250°, it starts increasing to around 290° in about 7 to 8 days. This is observed in October, 2020 and March-2021 period. With the orbit as on May 10, 2021 the argument of perilune would be 332° by May 26, 2021 and the solar intensity would be as in Figure 3. A study was made towards impact on target orbit AOP with different burn times. A few combinations of maneuver plans were simulated to obtain a favorable orbit towards optimum power generation on May 26, 2021. The subsequent section describes the maneuver plan towards optimum power generation.

4. Orbit Tuning for Power Profiling

This section describes the orbit tuning strategy and its effect on power generation. Different cases were generated by varying selected orbital elements and studied the impact of solar array current generation. A nominally maintained 100 ± 25 Km orbit without any orbit maneuver shows the worst-case power generation as in Figure 3. The power generation study was done for three consecutive orbits. This was done to optimize cumulative power generation for the entire eclipse duration.

Out of six Keplerian elements, four elements namely, Apolune altitude, Perilune altitude, Argument of Periapsis (AOP), and True Anomaly (TA) were considered for the study. RAAN and inclination adjustment were not considered as it requires fuel expensive orbit maneuvers. While doing the study, the parameters are varied within mission operational limits.

To study the orbit impact on power generation, out of the four elements chosen, three orbit elements were taken constant and the other orbit parameter was varied as tabulated in Fig-7 (Table-1) below and power generation were estimated for three successive orbits. For Example, the AOP was varied from 200 to 340 in steps of 20° for constant Apolune altitude, Perilune altitude; TA and Solar power generation was estimated for each of the AOP. Later, from the estimated power generation, the AOP was identified which gives maximum power generation. The same strategy was adopted for the other three orbit parameters and arrived at the final orbit elements. Subsequently, from all the identified orbit parameters that produce maximum solar power generation, a suitable orbit was chosen for optimal power and mission management. Accordingly, an orbit maneuver was carried out before entering the eclipse. The next section provides the details about different cases studied.



Case	Epoch (UTCG)	Inc (deg)	RAAN (deg)	AOP (deg)	TA (deg)	Apo Alt (Km)	Peri Alt (Km)	Figure
1	26 May 2021 00:00:56.431	92.02	271.58	332	88	131	85	Figure 3
2	26 May 2021 00:00:56.431	92.02	271.58	200-340	88	131	85	Figure 8
3	26 May 2021 00:00:56.431	92.02	271.58	280	45-120	131	85	Figure 9
4	26 May 2021 00:00:56.431	92.02	271.58	280	60	100-150	85	Figure 10
5	26 May 2021 00:00:56.431	92.02	271.58	280	60	120	80-100	Figure 11

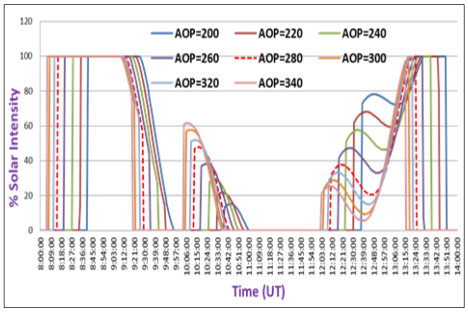
Fig-7: Table of Case Study

4.1 *Case Study 1*

The Solar intensity pattern is shown in Figure-3 for nominal-maintained orbit considering no maneuver condition. CH2 orbital elements with April, 24 2021 11:00 UT Epoch was taken as the initial state and propagated till May 26, 2021. This shows the average 80% power generation in orbit-2 but poor generation in orbit-3. And effective eclipse duration increased up to nearly 170 min.

4.2 *Case Study 2 & 3*

The Effect of solar intensity was studied with an AOP variation 200 to 340°, keeping other orbital parameters fixed in case 2. In case study 3, TA was varied 45-120°, keeping other orbital elements constant. Refer Table 1 for the epoch parameter used for the cases. AOP and TA were varied in steps of 20° for a case study. It was observed that with increasing AOP and TA the peak power in orbit 2 increases but the average power in orbit 3 reduces (Refer Figure 8 and Figure 9).



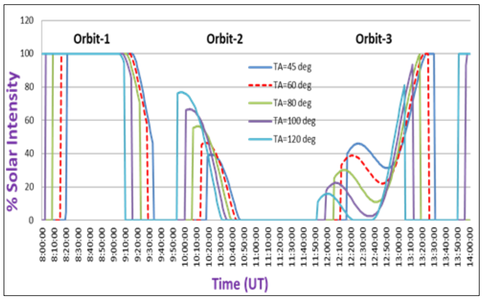


Fig-8: Solar intensity for various AOP

Fig-9: Solar intensity for various True Anomaly

4.3 Case Study 4 & 5

The effect of solar intensity was studied with an Apolune variation of 100 to 150 Km, keeping other orbital parameters fixed in case 4. In case study 5, Perilune was varied 80-100 Km to examine the impact of power generation based on altitude. Refer to Table 1 for the epoch parameter used for the case. Variation of power generation observed based on altitude is shown in Figure 10 and Figure 11. Power generation based on altitude variation was less sensitive compared to TA and AOP variation. Extreme variation of altitude not studied as achieving the desired altitude and normalization will call for fuel extensive maneuvers and the orbit might not be suitable for payload operations, as maneuvers need to be planned couple of days in advance.

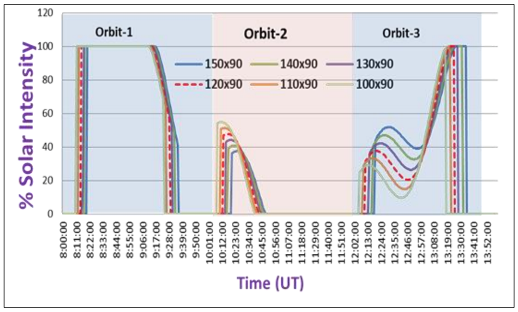


Fig-10: Solar intensity for various Apolune Altitude

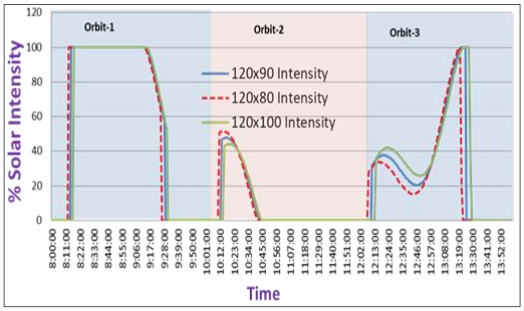


Fig-9: Solar intensity for various Perilune Altitude

5. Optimal Maneuver Planning

A study of orbit parameters was carried out towards optimization of the maneuver planning to maximize power generation during the Eclipse period. The natural variation of AOP and Apolune-Perilune was considered for maneuver planning. Rest of this section focuses on nominal AOP variation and maneuver planning strategy.

Case-A: An increasing maneuver on May 20, 2021 to get a target orbit of 112 x 127 Km, followed by a reduction maneuver on May 23, 2021 @ 14:48 UT. With this, the archived orbit would be 95 x 110 Km. But AOP was < 250° on May 26, 2021.

Case-A: An increasing maneuver on May 20, 2021 to get a target orbit of 112 x 127 Km, followed by a reduction maneuver on May 23, 2021 @ 14:48 UT. With this, the archived orbit would be 95 x 110 Km. But AOP was < 250° on May 26, 2021.

Case-B: From above Case-A, it was observed that the AOP changes substantially within 4-5 days of maneuver. Hence it is desirable to execute the maneuver about 8 to 10 days before the Eclipse. This would result in smaller variation of AOP. A maneuver with ΔV of 5 m/s was planned on May 18, 2021 to obtain a target orbit of 109 x 130 km. This had to be followed by another maneuver to meet the target orbit requirements. Following table summarizes the result of few cases which were simulated:

Maneuver -date	**Target Peri-Apo (Km)**	**AOP on May 26, 2021**	**Remarks**
20-05-2021 @ 12:13 UT	112 x 127	NA	Increasing maneuver
23-05-2021 @ 14:48 UT	95 x 110	Less than 250°	After Perilune-cross, Reduction maneuvera
20-05-2021 @ 12:05 UT	81 x 133	More than 300°	After ascending node cross
20-05-2021 @ 10:55 UT	96 x 118	~ 13°	Before ascending-node cross
20-05-2021 @ 11:29 UT	89 x 117	246°	At ascending-node cross

Case-C: An orbit raising maneuver was planned such that the burn would take place between Descending-node cross and south-pole. This increased the SMA by 15.9 km and changed the AOP from 333 deg to 261 deg. The time of burn was chosen such that both perilune & apolune altitude are maintained within the mission specified limits.

Maneuver: on 18-05-2021 @ 10:50 UT with Delta-V of 7 m/s & 2.3 kg fuel.

- Orbit shall change from: 94 x 123 km to 112 x 136 km
- AOP shall change by 72 deg (260)

After maneuver execution as in case-B, the AOP variation and solar intensity pattern was as shown in Figure-12 & Figure-13

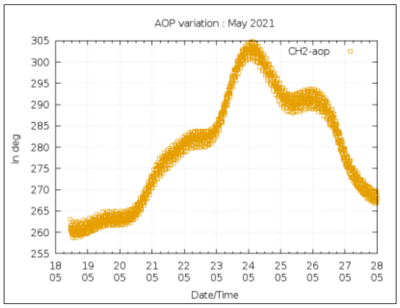


Fig- 12: AOP variation after OM

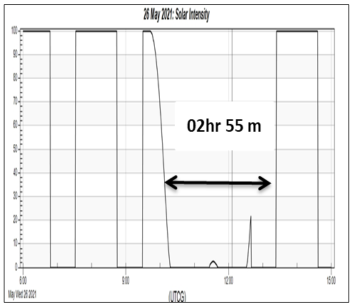


Fig-13: Case-A Power generation in nominally maintained orbit without Orbit Maneuver

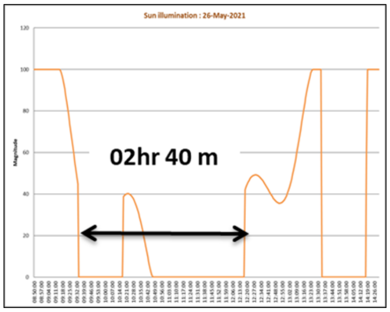


Fig-14: CASE-B Power generation in Tuned orbit with AOP 280 TA 60

6. *Result & Discussion*

Case studies with different combinations of orbital elements showed that AOP and TA variation were more sensitive for power profiling rather than Apolune and Perilune altitude. Out of many cases studied, two cases compared nominal-maintained orbit (Case-A: figure-13) power generation with targeted orbit i.e., AOP=280°, TA=60°, Apo=120 Km Peri=80 Km as shown in Case-B (Figure-14). The challenge here is not only to maximize power generation during eclipse duration but also to control the generation profile. A power generation profile can be defined as generation of power based on the load requirement. For example, if power generation is maximum while the satellite battery is fully charged, then generation is non-utilized and generally bypassed electronically. Typically, the power generation curve should follow the power requirement curve. The rationale behind choosing Case-B is described next by comparing orbit wise power generation.

Even though Orbit-1 in case-A shows full power generation, Orbit-1 of Case-B is preferred as the satellite does not require full power at eclipse entry as the battery gets fully charged much before that, and lead to higher cumulative DOD.

Based on the above analysis case -B was finalized and targeted through orbit maneuver. Figure-15 shows the actual CH-2 power generation during the orbit, time vs. actual solar array current generation has been plotted. A similar study was carried out to handle the lunar eclipse on November 19, 2021. However, a different AOP and TA combination was targeted as eclipse entry geometry was different. The Next section briefly describes the analysis.

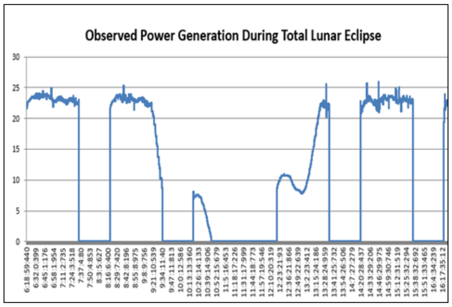


Fig-15: Observed Power Generation on 26-05-21

The ACE module represents ground breaking advancement in automated command execution for space missions. By integrating automated scheduling, real-time feedback updating, and telemetry-driven decision-making, it significantly enhances mission efficiency, accuracy, and adaptability. The research findings confirm that automation-

7. Analysis for 2nd Total Lunar Eclipse during 19-Nov-2021.

The same strategy explained in previous sections was adopted and successfully executed for total lunar eclipse (Umbral Magnitude: 0.974) encountered on November 19, 2021. The following figure 16 and figure 17 show the solar Intensity pattern for non-tuned and tuned orbits respectively a study of orbit parameters was carried-out towards planning maneuver for optimum power generation during Eclipse on 19-Nov 2021. An AOP ~ 320 deg & True anomaly ~178 deg would suffice the power requirement during this eclipse.

Hence an orbit reduction maneuver, at Peri-crossing time was planned to reduce the Apolune. Subsequently, an increasing maneuver at Apo-cross time was planned to achieve the target True anomaly of 178 deg. However a minor modification in the second maneuver was needed to ensure that the Close-Aproach distance with Lunar Reconnaissance Orbiter (LRO-NASA) has sufficient radial separation. Hence the target True-Anomaly was ~ 174 deg.

Maneuver-1: on 13-11-2021 @ 11:24 UT with Delta-V of -5.5 m/s & 1.8 kg fuel.

- Orbit shall change from: 95 x 98 km to 112 x 136 km

Maneuver-2: on **15-11-2021 @ 13:15 UT** with Delta-V of 3.2 m/s & 1.03 kg fuel.

- Orbit shall change from: 88 x 105 km to 102 x 105 km

After both the maneuvers, the orbit on 19-Nov-2021 was 95.3 x 112.6km, AOP=318.93 and TA = 173.96.

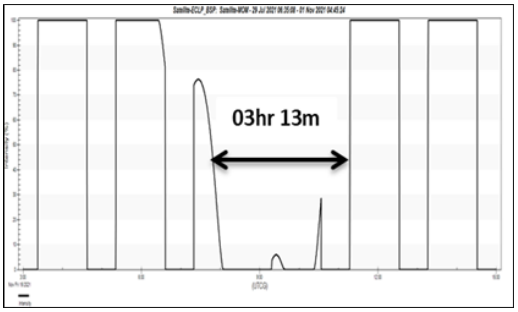


Fig-16: Pre-Maneuver Solar Intensity Pattern

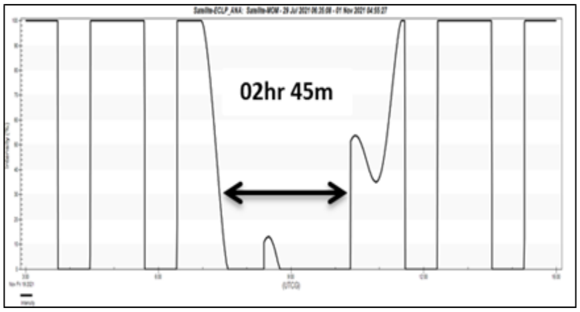


Fig-17: Post-Maneuver Solar Intensity pattern

8. Conclusion:

Chandrayaan-2 Orbiter experienced the first ever total lunar eclipse on May 26, 2021, after its launch on July 22, 2019. The Orbiter first went into the lunar shadow followed by the Earth's shadow and thereby experienced an extended eclipse for nearly three hours. An extended eclipse of a similar duration can discharge the battery beyond its safe limit and may lead to mission contingency. To mitigate the same, CH-2 orbital parameters were tuned to optimize the power requirement through power profiling. The paper describes the orbit tuning method, optimal strategies for orbit maneuver towards achieving the targeted orbit and finally the observed power generation during the eclipse.

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