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Looking Back at 8 Years of Operating ISRO's Mars Orbiter Mission: Challenges and Lessons Learned

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Abstract

The Mars Orbiter Mission (MOM) was the first interplanetary mission of the Indian Space Research Organization (ISRO). It was launched on 5th November, 2013 and its committed design mission life was 1.5 years. Presently, it has crossed more than eight years. Being the maiden interplanetary mission, planning and executing operations called for a paradigm shift in the operation philosophy. Starting right from launch, ISRO has overcome many challenges to make it possible to sustain the mission for long. The entire mission operation scenario was different and there were plenty of new situations and learning opportunities. In this paper, an effort has been made to put all the challenges faced by the MOM operation team into perspective and how each time the operation team overcame the situations. Once after Mars orbit insertion, the next challenge for the operation team was to formulate an operation plan for the upcoming blackout, with no prior experience in planning and executing such operations. The paper includes analysis of the blackout and whiteout geometries, detailed study of Sun's scintillation effect on MOM's communication frequency, effects of MOM antenna's field of view, etc. During such solar conjunction periods, the operation team planned payload operations to study the effect of solar corona on MOM's signals. Later, this data was analysed and the results were published in reputed journals. The other difficulties mentioned here are long eclipse avoidance strategies during 2017, challenges thrown by the Siding Spring comet and aerodynamic drag effect due to low Periapsis, and how the MOM operation team has faced them. The paper also explains the handling of one reaction wheel failure during 2015, and in spite of that, how payload operations were smoothly carried out with three working reaction wheels. The operation team developed a MOM power generation model by taking into consideration spacecraft attitude, solar panel to sun angle, number of available strings and illumination strength. Based on this prediction model, day-to-day operations were planned, including judiciously taking JPL station support for the initial few years. The paper also highlights dynamic link margin calculation and subsequent dynamic change of operational strategy. The MOM team also developed a ground model for mimicking on-orbit thruster performance for estimating fuel balance. This paper mentions how high disturbances during low Periapsis crossing were dealt with and how the operation team formulated a new operational strategy to predict the disturbance and configure the spacecraft in order to avoid reaction wheel saturation. The paper also brings out how day-to-day operations and orbit determination were managed with only one ground station i.e., ISDN-32, especially even on occasions when the station was under maintenance. Finally, the operations team studied various scenarios to avoid consecutive predicted long eclipses during April 2022 and since avoiding was not possible due to lack of fuel, a special operation plan was designed based on MOM's limited battery capability and stringent attitude pointing requirements. The Mars Orbiter Mission operation scenario was full of new situations and challenges. The operation team along with the subsystem design and mission teams faced all these situations and every time, came up with novel solutions. Hopefully, these experiences in operation management will be highly beneficial to any nation or any agency that is aiming for interplanetary missions in the coming years.
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Keywords: Mars Orbiter Mission, ISRO, Interplanetary Mission operations, Whiteout, Blackout, Spacecraft Attitude, Siding Spring Comet and Long Eclipse

Abbreviations:
MOM - Mars Orbiter Mission
ISRO - Indian Space Research Organisation
TM - Telemetry
TC - Telecommand
DDOR - Delta Differential One-way Ranging
AH - Ampere Hour
AU - Astronomical Unit

JPL - Jet Propulsion Laboratory
FOV - Field of View

1. **Introduction**

For many reasons, interplanetary missions are more challenging than conventional earth-orbiting missions. The main differences between conventional earth-orbiting missions and planetary missions are large signal delay, link margin issues for deep space communication, power generation issues varying with geometry, requirements for special configurations for whiteout and blackout periods, and so on. The Mars Orbiter Mission of ISRO has faced all of these challenges and it has successfully overcome all of them. The mission was initially designed for 6 months in the Martian orbit, and it has spent 8.5 years in the Martian phase. The mission operation team faced many difficult situations, and every time, in coordination with the subsystem design teams and the mission team, came up with innovative solutions. ISRO had no prior experience in managing an interplanetary mission. This mission has provided a good opportunity to learn and exercise many new concepts. In this paper, efforts have been made to summarise all the activities that the MOM operation team has undertaken to make it successful mission.

1.1 *Blackout-Whiteout*

Black-out and White-out are phenomena that occur once in every synodic period (i.e. every 780 days for the Mars-Earth System) which is nearly every 2 years. MOM has experienced blackouts on 14th June 2015, 27th July 2017, 2nd September 2019, and 8th October 2021, while it has experienced whiteouts on 21st May 2016, 27th July 2018, and 15th October 2020 till date. Typical blackout geometry has been shown in the figure below.

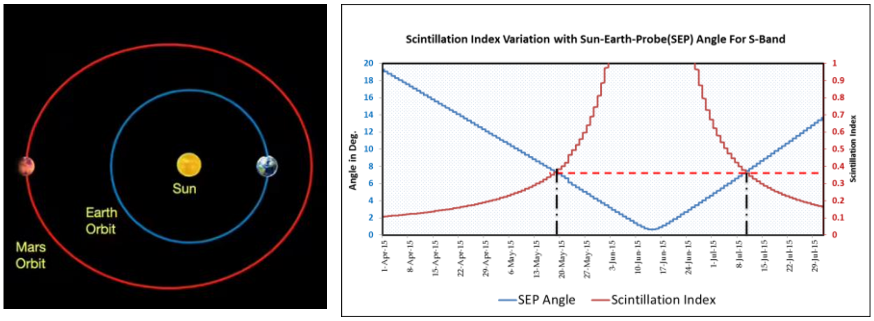

Fig. 1 : Mars-Sun-Earth Geometry in Blackout Geometry and scintillation Index Variation

The Sun is in the middle, and Earth and Mars are in opposite directions. The signal, which is coming from the ground antenna and supposed to reach the spacecraft, has to travel through the Sun's environment. In a similar way, the signal, which is coming out from the spacecraft, has to also experience the same environment. Due to its position in the middle, the Sun will introduce noise in the signal of Earth ground station antenna as well as the MOM on-board antenna creating corruption in telemetry (TM) as well as in telecomm and (TC). That is why it is referred to as a black-out. The 2nd picture shows the scintillation index variation with the Sun-Earth-Probe (MOM) angle variation. MOM is communicating in S-band, so for S-band only, scintillation variation has been shown. ISRO has decided to stop real-time commanding when the scintillation index is more than 0.35. All blackout operations were planned based on these dates. Typically, blackout operations are planned for 50 days. As there would be no commanding to the spacecraft and ensuring spacecraft health is essential, the spacecraft would be configured in such a way that every day it would send some signal to the ground station at a specific time and its health would be determined based on the signal carrier frequency. If there is some problem, it will be indicated by no carrier or a different carrier signal. The spacecraft is also configured in such a way that if some anomaly occurs, then it should be able to normalise on its own, or it would point to a safe orientation and wait for the blackout period to be over for ground intervention. All the four blackouts till date were configured in the same way. Taking advantage of the geometric orientation during blackout, some payloads like DDOR (Delta Differential One-way Ranging) transmitter was made ON and 2-way Doppler data was collected for some specific time intervals to study the Sun's corona. The difficulty for the operation team was to generate (in advance time tag mode), validate and uplink all correct command sequences. If any command is not correctly sent, it may be catastrophic for the mission as ground intervention during a black-out is not possible.

The term white-out refers to the phenomenon of solar conjunction in which Earth and Mars align in a straight line with the Sun at one end and Earth in the middle. It is clear from Fig.2 that only commanding is an issue in this geometry, as the spacecraft would be receiving signals simultaneously from the ground station as well as the Sun. The Sun's signal would corrupt the commands sent from the ground station, and thus based on the angle clearance of 8 degree in Sun-Mars-Earth, white-out operations were planned. The Sun-Mars-Earth angle variation during a typical white-out is shown in below figure.

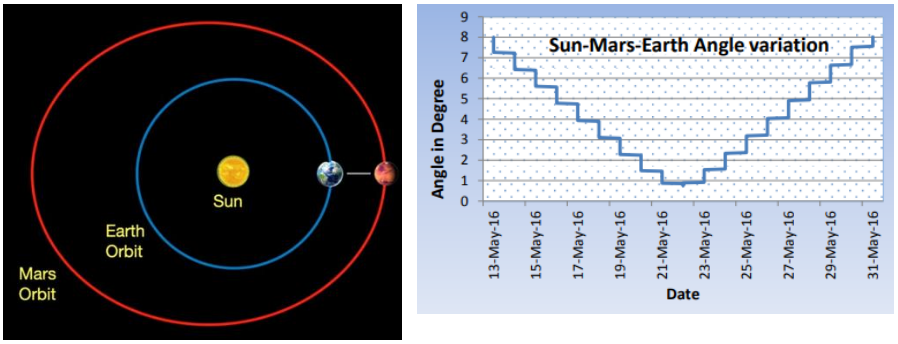

Fig. 2: Sun-Earth-Mars Geometry and Sun-Mars-Earth Angle Variation in Whiteout Period

During this period, the Deep Space Network (DSN) communication antennas receive TM signals from the satellite without any problem since the Sun does not come into the field of view of the antennas. But as for commanding, there is a high chance that commands get corrupted and wrongly decoded on-board due to the Sun's radiation effect. This is because the MOM antenna receives signal from the DSN antenna along with the Sun's strong radiation. As a result, commanding is avoided during a whiteout period, and an operational strategy is formulated in advance such that the spacecraft is pre-programmed to send signals at regular intervals. In the event of any problem, the spacecraft is programmed to orient itself in a safe attitude and wait for ground commands once the whiteout phase is over.

1.2. Long Eclipse Avoidance Manoeuver in 2017

The battery capacity of the Mars Orbiter Mission is 36 AH. And it is designed to support around 100 minutes of eclipse duration. MOM was designed for 6 months in Martian orbit, but in late 2016, a long eclipse of 480 minutes was predicted from January 21st, 2017 to February 6th, 2017. As per design specifications, the battery would not be able to sustain the entire eclipse duration. Hence, a decision was taken to perform an orbit manoeuvre on January 17th such that the eclipse duration would be brought down within the limit of 100 minutes. In this orbit maneuver 97 m/sec velocity was imparted by spending 20 kg of fuel. The actual spacecraft attitude during this maneuver as well as pre-manoeuver and post-manoeuver orbits are shown below.

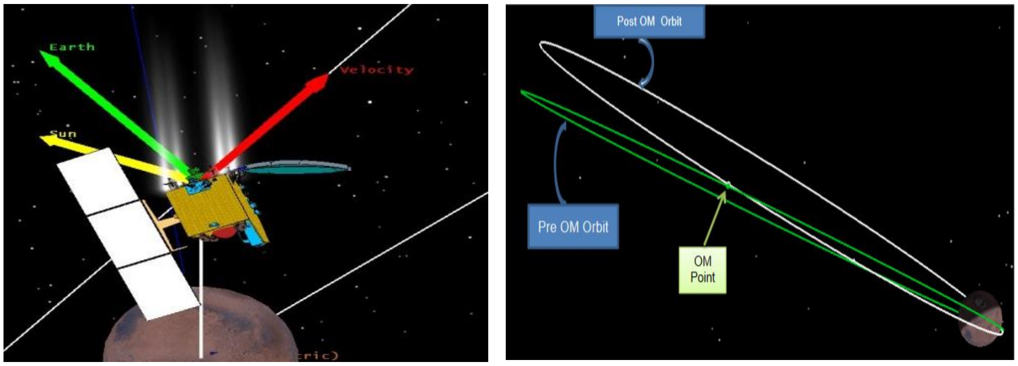

Fig. 3: Spacecraft Attitude during Maneuver Pre and Post Orbit manoeuver MOM Orbit

The predicted eclipse pattern and the post maneuver eclipse pattern have been shown in the figure below.

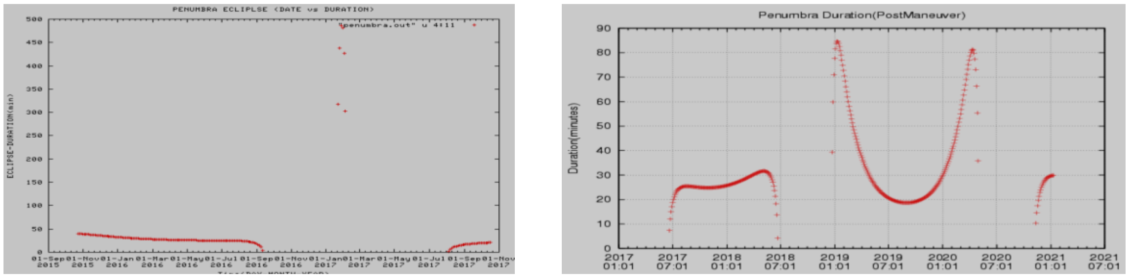

Fig. 4: Predicted eclipse Duration before and after Orbit maneuver

The figure shows that the predicted eclipse duration was ~480 minutes(8 hours) and once after the orbit maneuver it has come down less than 90 minutes while petecting upto July 2021.

1.3. Dynamic Link Margin Calculation and Data Rate Adjustment

The Earth and MOM spacecraft orbit follows a synodic period of 780 days. In one synodic period, the variation of the distance between the spacecraft and the Earth as well as path loss due to this distance variation have been shown in the figure below.

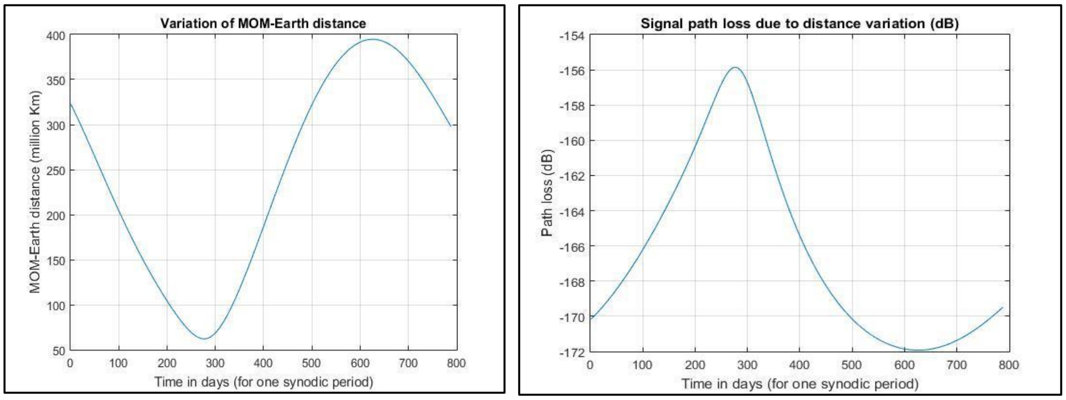

Fig. 5: In one synodic period typical variation of MOM to Earth Distance and due to that the path loss variation

The strength of the signal received from on-board to the Earth station is dependent on the distance between them. It can be seen from Fig.5 that there is a variation of 16 dB in path loss over one synodic period. Hence, there is a need for dynamically tuning the data rate for successful reception of signals from MOM. Many times with short notice it was informed that the 32 meter antenna support would not be available due to other mission support or due to maintenance activity. As a result, the operations team devised a dynamic link margin computation utility. It accounts for the Earth-Mars distance variation, antenna available for support like 32 meter or 18 meter etc. and serves as a guide for adjusting payload and telemetry data rates. For smooth operation, both ground stations and the payload team must be apriori informed about the change in the payload data rate. IDSN D18 antenna can support nominal TM TC upto 180 Million Km as it has G/T of 30 dB/K (in S-band) and it can uplink maximum 2 Kilo Watts of power while D32 meter can support more than 400 Million Km with G/T of 37.5 dB/K and maximum power transmission capability of 20 Kilo Watts. In case of pass clash with other mission , operation team used to analysed the pass clash and used to proposed and take pass support when there is no pass clash with available station.

1.4. Power generation prediction and Dynamically tune TM ON/OFF

The eccentricity of the Martian orbit is 0.093 compared to Earth's 0.017. The mean distance from the Sun to Mars is 1.52 AU, as a result of which the mean solar intensity on Mars is 43.1 % of the Earth's mean solar intensity and, due to its large eccentricity variation; solar intensity varies between 36.0 % to 52.0 % of the Earth. This variation is observed over a Martian year (i.e., 688 days). The variation of the distance of MOM from the Sun over a period of one revolution (i.e., 688 days) as well as due to this distance variation what is the maximum power generation capability has been shown in the figure below.

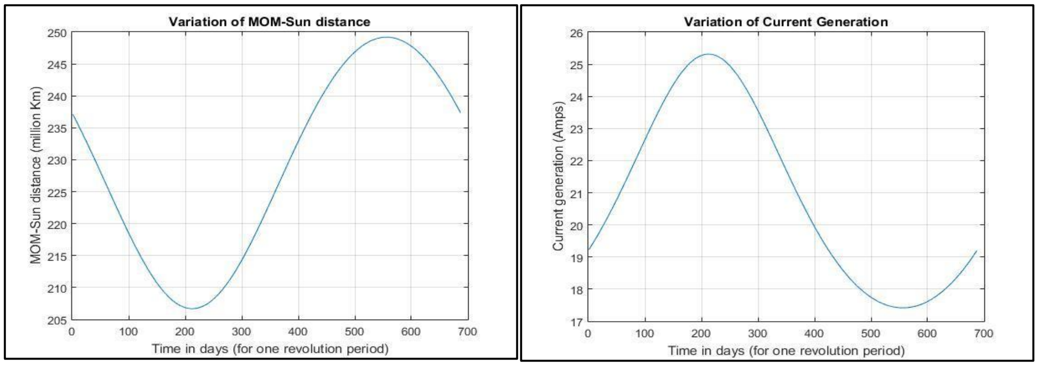

Fig. 6 . MOM to Sun Distance and the maximum power generation capability

With normal incidence, the MOM solar panel can generate around 50 amps of current in Earth's orbit. Many factors influence on-board current generation, including MOM-Sun distance, solar panel normal to sun angle variation (i.e., right ascension variation), sun declination variation, and solar panel design, among others. The operation team initially studied the MOM power generation in Martian Phase and based on the study generated MOM's power generation model, which considers several variables, including the spacecraft's attitude, and can accurately predict the power generation. Spacecraft attitude play a major role in MOM maximum power generation. If sun is in the Roll Yaw plane then proper solar panel can make the sun perpendicular to panel but if it is not there then it will generate less current. MOM's maximum current generation can be written as

$$I_{Capacity} = (I_{earth})(\alpha_{due\_2\_distance})(\cos(\theta_{sun\_az}))\cos(\phi_{sun\_ele})(\eta_{ageingEffect})..(1)$$

Where, $\mathbf{I_{capacity}}$ is the maximum current generation capability in Mars, $\mathbf{I_{earth}}$ is the maximum current generation capability of MOM panel if it is kept Earth distance (i.e 1 AU) from the Sun. $\boldsymbol{\alpha_{due\_2\_distance}}$ is the scale factor due to distance variation from Sun to MOM , $\mathbf{cos(\theta_{sun\_az})}$ is due to solar panel offset i.e in the spacecraft body frame where sun vector is falling and where the solar panel is tracking . $\mathbf{cos(\theta_{sun\_ele})}$ Is the sun elevation angle in the body frame. It is measured by taking the sun vector and the spacecraft reference attitude. $\boldsymbol{\eta_{ageingEffect}}$ is the ageing effect combined with efficiency from design team. One typical simulation scenario where $\mathbf{cos(\theta_{sun\_az})}$ and $\mathbf{cos(\theta_{sun\_ele})}$ angles have been shown below.

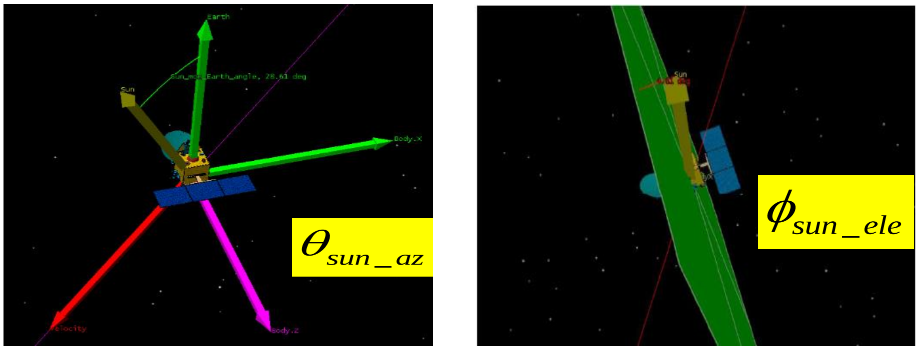

Fig. 7: Solar Panel Normal to sun and angle sun elevation angle in body has been shown

The value predicted by the model was used for operational planning. With normal incidence, the power generation varies from 17.5 Amps to 25.5 Amps. Getting telemetry data from MOM requires 22 amps of current. One typical profile has been shown below.

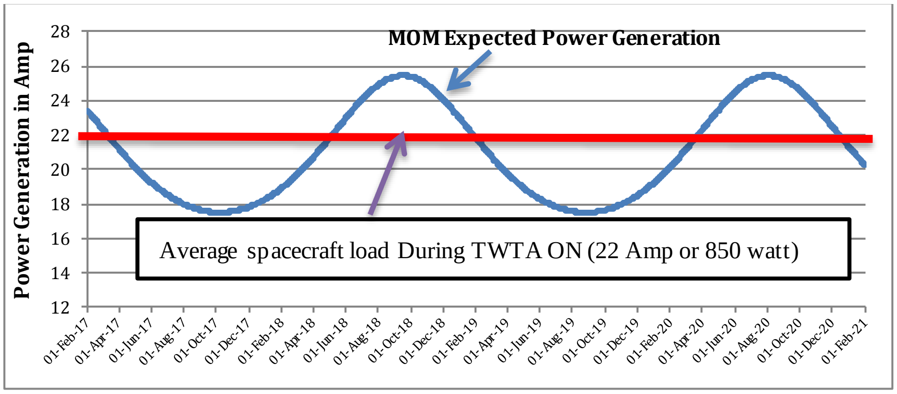

Fig. 8 : Power Generation Capability and Real Time Power Requirement

So, based on on-board generation and the allowable depth of discharge in the battery, there is a requirement for a duty cycle of telemetry data during station visibility periods. This was the guiding factor for judiciously using JPL station's support. The model based power generation predictions and operation planning have assisted in reducing unnecessary long passes from JPL, resulting in a reduction in the JPL support cost.

1.5. Solar Panel Offset Tuning

MOM solar panel is not in continuous Sun-tracking mode. As described in the above equation number 1, the total power generation depends on $\boldsymbol{\theta}_{\mathbf{sun\_az}}$. If the solar panel offset is not corrected regularly then the angle will increase as the MOM attitude definition has been attached to the geometry of the Earth-Sun-Mars and that geometry is always changing, resulting in a change in spacecraft attitude. With continuous change in attitude, the angle between the solar panel normal vector to the Sun keeps on changing. This brings the requirement to manually orient the solar panel at 90 degrees with the Sun vector. The operation team needs to simulate the required panel offset before uplink. One such typical simulation scenario has been shown in Fig.9.

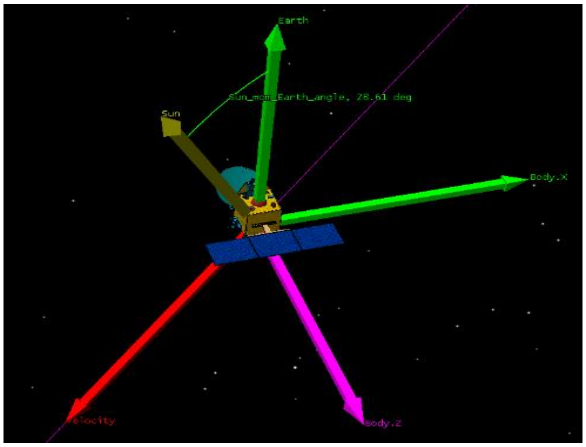

Fig. 9 : Simulation Result for Panel Offset Checking

1.6. Hiding from shower of Siding Spring Comet in 2014

Comet C/2013 A1 Siding Spring travelled from the most distant region of our solar system, called the Oort cloud, and made a close approach within about 139,500 kilometres of the Red Planet during October 2014. This is less than half the distance between Earth and our moon and less than one-tenth the distance of any known comet flyby of Earth. The spacecraft orbit was changed such that when the comet was closest to Mars, MOM was on the other side of the planet, thus hiding from its shower. This further enabled MOM to take its tail’s picture from other side as shown in the figure below.

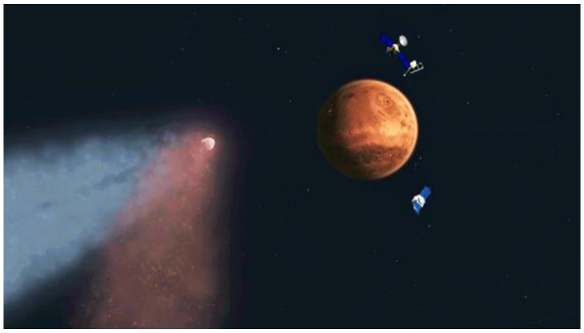

Fig. 10 : The MOM hiding from the Siding Spring Comet

1.7. Bias Momentum Tuning in 2015

There was a failure in one of the reaction wheels of the spacecraft in 2015. So the spacecraft was required to be in three-wheel mode. In spacecraft the wheels are mounted along a particular axis and it has some capacity. If all wheels are rotating then there will be angular momentum in each mounting axis. One typical wheel mounting has been shown below. In the figure red colour axis is Yaw, green is Roll, blue is pitch and all black colour are wheel mounting axis.

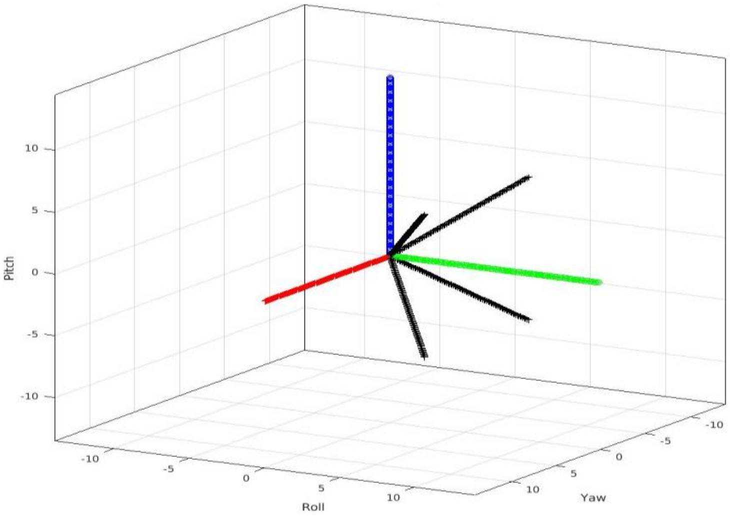

Fig. 11: One typical wheel mounting with respect to spacecraft body frame

Depending upon the capacity of the mounted wheel and the wheel speed and direction it will impart the angular momentum in its mounting axis. One typical case the equation has been shown below.

$$\begin{bmatrix} H_{w1} \\ H_{w2} \\ H_{w3} \\ H_{w4} \end{bmatrix} = \eta \begin{bmatrix} R_{w1speed} \\ R_{w2speed} \\ R_{w3speed} \\ R_{w4speed} \end{bmatrix}$$

.As the wheel mounting angles are known it will impart angular momentum in each axis. In a typical tetrahedral configuration the imparted angular momentum in the spacecraft body has been shown below.

$$\begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} = \begin{bmatrix} \sin(\alpha)\cos(\beta) & \cos(\alpha)\cos(\beta) & -\sin(\alpha)\cos(\beta) & -\cos(\alpha)\cos(\beta) \\ \sin(\beta) & \sin(\beta) & \sin(\beta) & \sin(\beta) \\ \cos(\alpha)\cos(\beta) & -\sin(\alpha)\cos(\beta) & -\cos(\alpha)\cos(\beta) & \sin(\alpha)\cos(\beta) \end{bmatrix} \begin{bmatrix} H_{w1} \\ H_{w2} \\ H_{w3} \\ H_{w4} \end{bmatrix}$$

In this case α and β are mounting angles and its developed angular momentum along each mounted axis are H_{w1}, H_{w2}, H_{w3} **and** H_{w4} are the momentum developed by wheels along the spacecraft body axes are H_X H_Y H_Z . As per the mounting angles and the configuration of MOM, the momentum distribution with four reaction wheels and Once the reaction wheel-2 failed then the resultant, the momentum envelope has reduced and has been shown as in the figure below.

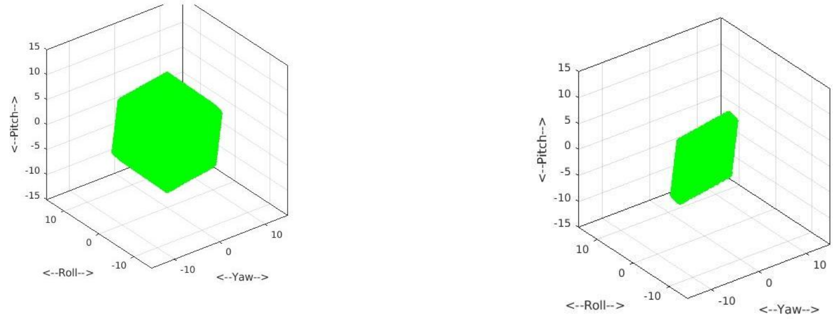

Fig. 12 : MOM Momentum imparting Capability with 4-RW and 3 RW in Spacecraft body axis

From the graph, it is clear that in a three-reaction wheel configuration, the angular momentum cannot be distributed equally in all three axes, and thus, it is not possible to put the spacecraft in a zero momentum system because at zero cross-over time, three active reaction wheels have more friction. This led to the decision to put the spacecraft in a bias momentum system, where all the reaction wheels would rotate with some non-zero value, and from that attitude, when it manoeuvres to attain imaging attitude, the wheels should not encounter zero crossover. Because spacecraft attitude was linked with the geometry of Mars-Earth-Sun and it was changing, it was necessary to change this bias momentum value at regular intervals by remote memory programming. As the two-way delay is high, every time it would take more than two hours to carry out the operation as verification was involved. Operation team used to monitor daily reaction wheel profile and if any of the reaction wheel's speed is coming towards zero then existing bias momentum value operation team used to update.

1.8. Disturbance During Low Periapsis passing in 2018

MOM was facing several disturbances during late 2018 when the spacecraft periapsis altitude approached 160 km, and it was predicted that periapsis would come further down to 25 km by March 2019. The predicted Periapsis variation has been shown in the following graph.

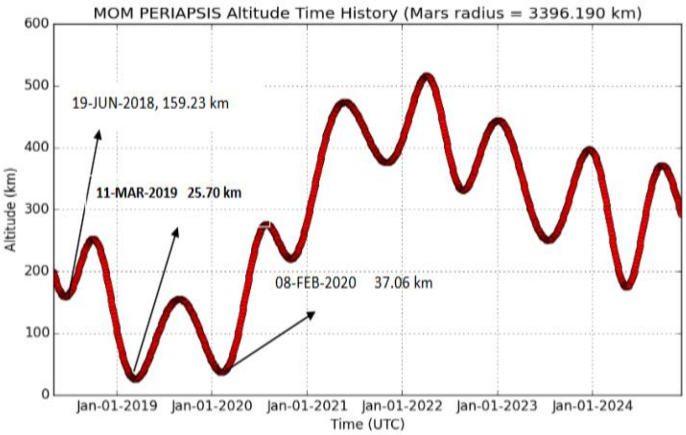

Fig. 13 : Predicted Periapsis Variation

The spacecraft was not designed to sustain the disturbance of such periapsis variation. Additionally, the spacecraft was in three reaction wheel mode and was unable to control the disturbance. To overcome the disturbance, the spacecraft was firing its thrusters, and the orbit was being continually changed. The orbit was not converging by the next periapsis. The challenge was thus with the operation team to predict the next periapsis crossing by seeing telemetry data and configure the spacecraft in thruster control mode during periapsis crossing to avoid wheel saturation. To solve this problem, an orbit manoeuvre was carried out in November 2018 to increase the periapsis altitude. Subsequently, the disturbance came down and orbit was no more changing due to unwanted thruster firings.

1.9. On board Autonomy & Regular Autonomy Parameter updating

The variation of two-way delay of signal arrival from Mars to Earth has been shown in Fig.14 below.

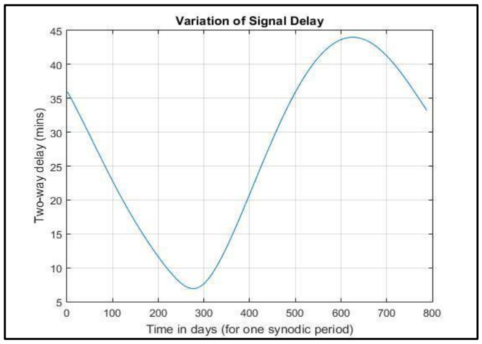

Fig. 14: MOM Two way Signal Delay for a Synodic Period

From the figure, it is seen that the two-way maximum delay is 44.5 minutes, i.e., once a command is issued from ground to the spacecraft, it will take 44.5 minutes to see its effect. So in the MOM mission, there is no scope for real-time operations, as in the case of Earth-orbiting satellites. All the operations need to be planned well in advance. The spacecraft pointing requirements are stringent at +/- 2 degrees. So if anything happens related to attitude, then no ground command would be able to operate. Keeping this in mind, the spacecraft would need to assess and identify anomalies by itself, take corrective actions and should point towards the Earth. To be able to carry out these activities, the spacecraft needs some data to be given from the ground. This data should be updated periodically as the geometry of Earth, Mars, and the Sun is dynamically changing. Throughout all these years, the autonomy related commands were generated and up-linked at regular intervals. Also, a utility was developed by the operations team which ensured that ground station could operate smoothly without the need to account for dynamic two-way delay variations.

1.10. Roll Biasing to make Star Sensor FOV Clear

The Star sensor field of view (FOV) should be clear to get continuous attitude information. The spacecraft attitude changes as the Sun-Mars-Earth geometry changes dynamically. In some cases, the star sensor FOV is obstructed by Mars' albedo, so it was necessary to simulate the scenario and compute new roll bias if required so that the star sensor FOV was cleared. below figure depicts a simulation scenario in which the Star sensor FOV clearance is being tested.

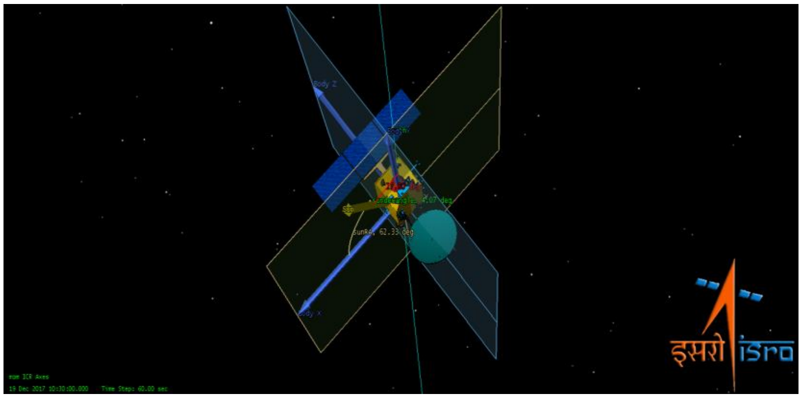

Fig. 15 : Simulation scenario depicting SS FOV clearance

1.11 Radio Occultation Experiment in MOM

RO Experiment opportunity study was carried out and based on the outcome the radio Occultation experiment using 2-way Doppler signal as well as on-board Delta-DOR transmitter was planned and executed. The RO experiment opportunity simulation of one the orotundity has been shown below.

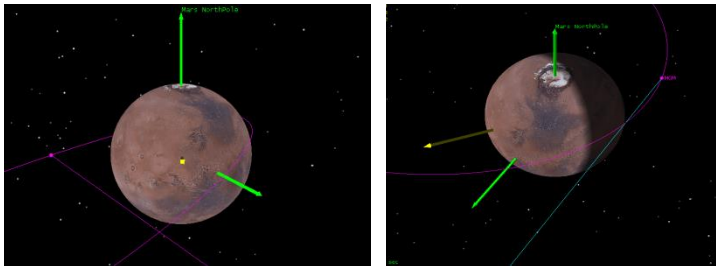

Fig. 16. Simulation of occult start and end geometry

Based on the simulation results operation team used to generate the plan and would execute the plan with the help of other entity like ground station, flight dynamics, mission and scheduling team etc.

1.12 PHOBOS Imaging

During July 2020 MOM had a close conjunction with Phobos. Once it was realized that collision is not there operation team started planning to take its image from very close distance. It was a challenge to take image of Phobos as reaction wheels are not sufficient to do attitude maneuver and thrusters were used secondly the opportunity of capturing image is around two minutes. Finally it was executed the simulation scenario has been shown below.

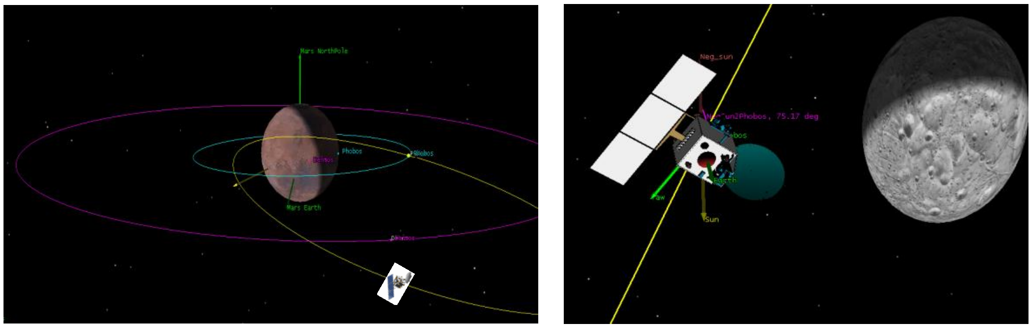

Fig. 17. Simulation for Phobos imaging geometry and spacecraft attitude requirements

1.13. Long Eclipse Prediction in 2022

In April 2022, MOM was predicted to face six long eclipses. The MOM battery was designed to withstand a maximum solar eclipse for 100 minutes, but this time the maximum eclipse duration was 450 minutes. There were many challenges as the spacecraft was not designed to face this type of eclipse. Power would not be sufficient to keep the spacecraft's thermal environment stable. The operation team investigated all possible scenarios for avoiding or shortening the duration of the eclipses. Unfortunately, the current fuel balance was not sufficient to carry out any manoeuvre. So finally, it was decided to face it.

The predicted eclipse was in the apoapsis region. As a result, the duration of the eclipse was prolonged. The predicted eclipse geometry as well as the duration has been shown in below figure.

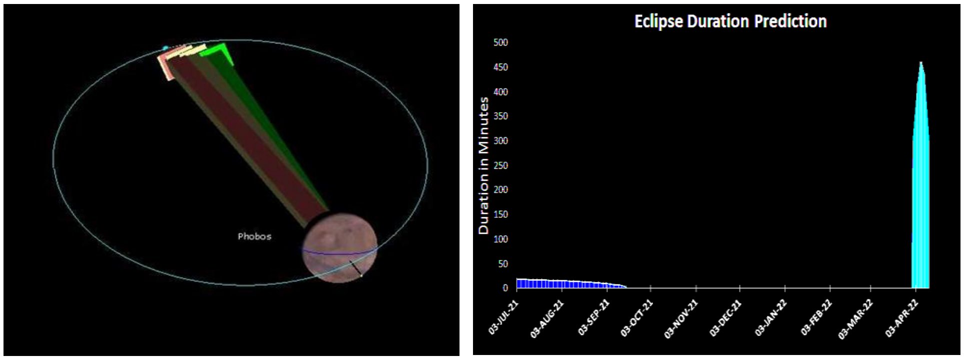

Fig. 18. Predicted eclipse in the part of the Orbit and durations

1.11. Long Eclipse Surviving Strategy Formulation in 2022

As part of the survival strategy, the bias momentum requirements were closely studied. Based on the present attitude, the disturbance vector was calculated and the bias momentum vector was proposed in the direction as shown in the figure below.

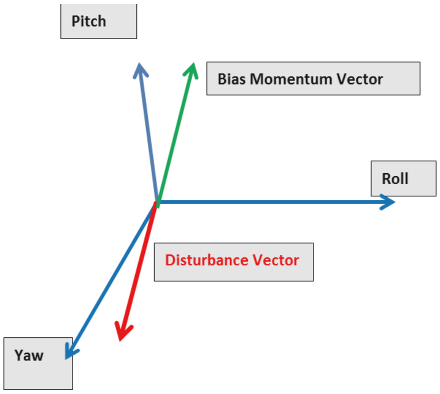

Fig. 19. Predicted Disturbance Vector direction and proposed Bias momentum Direction

Based on the spacecraft's inertia matrix and considering rotation only about the roll axis to maintain earth-pointing direction, a detailed roll rotation requirement was formulated.

If we rotate roll axis by a rad/sec, then considering MOM's inertia matrix, one momentum vector B_m is generated.

$$B_m = 2.1a\vec{i} + 548.9a\vec{j} + 2.9a\vec{k}$$

Considering a disturbance momentum vector, where D_m

$$D_m = d_1\vec{i} + d_2\vec{j} + d_3\vec{k}$$

the resultant momentum vector in the body frame will be:

$$B_{m\_total} = D_m + B_m = (d_1 + 2.1a)\vec{i} + (d_2 + 548.9a)\vec{j} + (2.9a + d_3)\vec{k}$$

This momentum vector would make a cone about roll axis with θ, where

$$\theta = \cos^{-1}\left(\frac{(d_2 + 548.9a)}{\left((d_1 + 2.1a)^2 + (d_2 + 548.9a)^2 + (2.9a + d_3)^2\right)^{0.5}}\right)$$

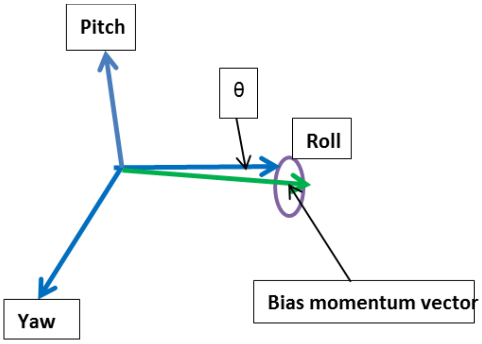

Fig. 20. Figure showing the resultant angular vector precession about the Roll vector

Based on the analysis, the angular rate, thus formulated about the roll axis, would ensure MOM's earth-pointing attitude and also help in generating power with the solar panel after eclipse exit. Implementation of this plan during a typical eclipse session has been shown in the figure below.

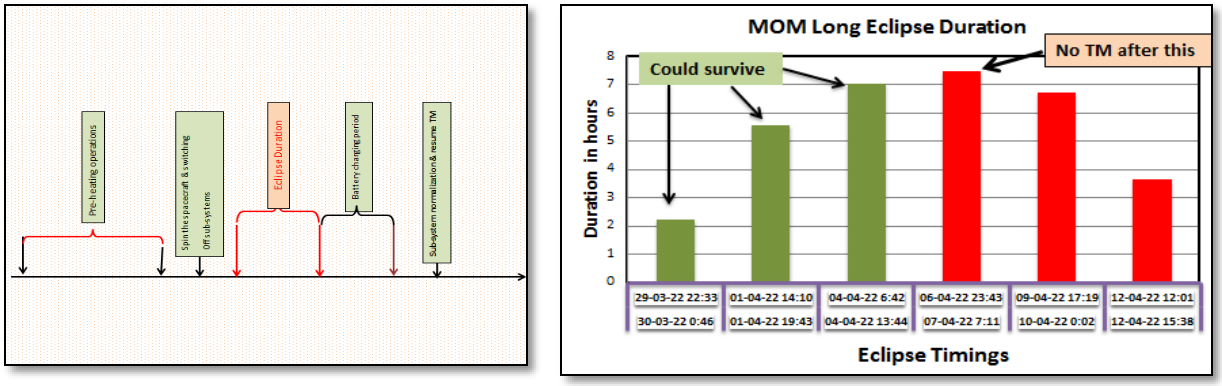

Fig. 21.The Eclipse Survival Strategy and the result

MOM was originally designed to sustain eclipse duration of maximum 100 minutes, and with the above strategy in place, it could survive the first three long eclipses up to 7.1 hours. But, after the longest predicted eclipse of 7.45 hours, ground contact was lost with the spacecraft. On further analysis, probable reasons were cited to be complete exhaustion of on-board fuel, resulting not able to do attitude maneuver to point towards the Earth or battery has fully got discharge, thus switching off all the pre-planned commands and subsequent loss of control and attitude.

2. Conclusions

The Mars Orbiter Mission was a learning tool for the entire operations team. The team gained experience in situations such as how to take care of large round-trip delays and, accordingly, how to plan on-board operations; how to programme the spacecraft to autonomously take care of long-duration command outages like whiteout and blackout; how to manage all operations with only one ground station with minimum support, etc. Though the mission was initially designed for 1.5 years, it carried out its operations successfully for more than 8.5 years. One of the main contributing factors would be flawless operation and monitoring. After this MOM operation, ISRO is now confident in handling any future interplanetary mission.

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References

[1] Kiran Kumar A.S. et al; Scientific exploration of Mars by first Indian interplanetary space probe: Mars Orbiter Mission, Current Science, 107, 1096 (2014).

[2] Ritu Karidhal, et al; Mission automation and autonomy for the Mars Orbiter Mission, Current Science, 109, 1070 (2015)

[3]Arunan. S, et al; Mars Orbiter Mission spacecraft and its challenges, Current Science, 109, 1061 (2015)

[4]Adimurthy, V., Prasad, M. Y. S., \& Shivakumar, S. K.; Space mission planning and operations, Current Science, 93(12),1791–1811 (2007)

[5] Choukroun, P., Denis, M., Schmitz, P. and Shaw, M.; Evolving ESA Mars express mission capability with on-board control procedures, Space Ops, Huntsville, Alabama, USA, 2010.

[6] Delta-DOR Correlator Development at ISTRAC/ISRO" in the Journal of Spacecraft Technology} by Dr.R.Manikantan ,Bijoy Kumar Dai, Dr.P.D.Mishra , B.N.Ramakrishna, Vol. 32, No. 2, pp.41-51, July –December 2021.

[7] Gyro Sensor Calibration of ISRO's Remote Sensing Satellites" by Pooja Prasad, Bijoy Kumar Dai & B.N Ramakrishna, in the Aerospace System Journal of Springer, https://doi.org/10.1007/s42401-021-00118-6.

[8] "A study on the solar coronal dynamics during the post-maxima phase of the solar cycle 24 using S-band radio signals from the Indian Mars Orbiter Mission" in the Monthly Notices of the Royal Astronomical Society} by Richa N Jain, RK Choudhary, Anil Bhardwaj, Umang Parikh, Bijoy K Dai, MV Roopa, Vol. 511, No. 2, pp.1750-1756, Feb-2022.