POST MISSION DISPOSAL OF CARTOSAT-2: COMPLIANCE WITH IADC GUIDELINES

Bulbul Mukherjee and A. K. Anil Kumar

Directorate of Space Situational Awareness and Management, ISRO Headquarters, Bengaluru,
Email: bulbul@isro.gov.in, ak_anilkumar@isro.gov.in

ABSTRACT

Cartosat-2 was launched in a sun-synchronous polar orbit of 635 km altitude in 2007. After 12 years of mission, its payload services were discontinued in 2019 due to system degradation. The post mission lifetime of Cartosat-2 was estimated to be more than 25 years, and there was 26 kg left-over propellant. ISRO's Directorate for Space Situational Awareness and Management (DSSAM) proposed to lower the perigee of Cartosat-2 till fuel depletion, so that its post mission orbital lifetime as well as any accidental break-up risk due to left-over propellant could be minimised. The de-orbiting operations were planned and executed through close coordination among teams from various ISRO centres. The lifetime of the satellite in the currently achieved orbit is expected to be less than 10 years. Cartosat-2 is the first Indian LEO satellite to undergo post mission disposal. This paper outlines the relevant background analyses along with an assessment on the achieved compliance of the disposal exercise with IADC space debris mitigation guidelines.

Keywords: De-orbit, lifetime, 25-year rule, Cartosat-2, Post Mission Disposal, Space Debris Mitigation.

1. INTRODUCTION

The Low Earth Orbit (LEO) is presently the most congested orbital regime. In the near future, the object population is anticipated to increase by many times due to the disruptive changes brought about by large constellations. Therefore, in order to ensure sustainable space operations in LEO, it becomes imperative to strictly adhere to internationally accepted guidelines on space debris mitigation, especially the "25-year rule" to limit the presence of an object in LEO once its mission is completed. ISRO has been a member of IADC since 1996, and follows UN and Inter-Agency Space Debris Coordination Committee (IADC) recommended guidelines on space debris mitigation to the maximum possible extent. The mitigation measures adopted by ISRO's launch vehicle and spacecraft projects include passivation of LV upper stages, limiting the release of objects during mission operations, Post Mission Disposal (PMD) of GEO objects, conjunction assessment and collision avoidance with catalogued objects. The Directorate of Space Situational Awareness and Management (DSSAM) of ISRO-HQ strives to implement space debris mitigation measures through necessary coordination with various work centres in ISRO. Until recently, there was a lack of compliance with the post mission disposal guidelines for LEO objects. Noting the alarming increase in object population in LEO, and recognising the need for greater compliance towards PMD guidelines for LEO, DSSAM has proactively initiated efforts to limit the post mission orbital lifetime of LEO spacecraft. The post mission disposal of Cartosat-2, a decade-old satellite operating around 630 km altitude, was one of the major activities proposed and pursued by DSSAM.

This paper concerns the post mission disposal of Cartosat-2 which was undertaken by ISRO recently with an aim to achieve compliance with IADC guidelines on post mission disposal of LEO objects. At the outset, the paper provides a brief description on Cartosat-2, which is followed by the potential risks arising due to the satellite at its end-of-life, and the analyses which aided in deciding the strategy for post mission de-orbiting of Cartosat-2. The resultant benefit in terms of post mission lifetime reduction, and the overall compliance with IADC guidelines along with the lessons learnt are discussed in the ensuing sections.

2. BACKGROUND

2.1. Cartosat-2 Mission

Cartosat-2 was the first among the second generation of Indian Earth Observation satellites dedicated for advanced cartography. It was launched on 10^{th} Jan 2007 by PSLV-C7 into a sun-synchronous polar orbit of 635 km altitude and 9:30am LTDN (Local Time at Descending Node) [1]. Equipped with a single Panchromatic camera payload, the satellite had body-fixed deployable solar panels, the hard body radius being of the order of 3 m.

Cartosat-2 was also a demonstrator of several key tech-

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nologies which were later incorporated in subsequent spacecraft bus design by ISRO. The planned mission life for the satellite was 5 years. Despite suffering several anomalies, loss of redundancies, and system degradation, the operation of its PAN payload were continued till mid-2019 by adopting various operational work-around. By August 2019, the payload operations were no longer feasible due to further on-board failures.

2.2. Post Mission Risks

With its payload rendered non-utilizable, the primary concern with Cartosat-2 was that its orbital lifetime at around 630 km altitude was more than 25 years. The IADC Space Debris Mitigation Guidelines for Post Mission Disposal (PMD) of objects passing through the LEO region recommends that spacecraft or orbital stages ending their mission life in orbits potentially interfering with the LEO region should be de-orbited, preferably by direct re-entry, or maneuvered into an orbit with reduced orbital life time, wherever possible [2]. While it is desirable to minimise the residual orbital lifetime after end of mission, considering the fuel penalty involved, 25 years is considered to be a reasonable and appropriate limit on the post mission orbital lifetime for LEO objects [2]. This limit is arrived at based on the studies conducted by IADC et al. and has already been adopted by several space-faring agencies in their space debris mitigation standards/requirements. Therefore, in its status quo, Cartosat-2 would have been non-compliant with the 25-year limit prescribed by IADC. Furthermore, it was estimated that the satellite had about 26 kg left-over monopropellant (hydrazine) fuel, with a potential for accidental explosion. The satellite carried two Nickel-Cadmium batteries among other energy sources, adding to post mission accidental break-up risks.

2.3. Proposal for Post Mission Disposal

Considering the aforementioned risks, it was proposed by DSSAM to lower the perigee of Cartosat-2 to limit its post mission orbital life time by depleting the left-over fuel followed by an electrical passivation. The de-orbiting would have served the dual purpose of limiting the post mission orbital lifetime and minimised the post mission accidental break-up due to stored fuel. Recognising the risk an improperly disposed object would pose in the crowded LEO region, the Project Management Council of URSC [1] agreed to the proposal for de-orbiting of Cartosat-2 by late 2019.

However, the aged satellite had lost redundancy of reaction wheels and gyros, and some of the sensor performances were also degraded. Moreover, the satellite lacked the design features for electrical passivation which requires disconnecting the batteries from solar arrays. These limitation posed major challenges for PMD of Cartosat-2. Nevertheless, considering the benefit that could be reaped in terms of first-hand operational experience for utilization in post mission disposal of future missions, it was decided to undertake the PMD exercise of Cartosat-2.

[1] U. R. Rao Satellite Centre of ISRO, Bengaluru, is responsible for spacecraft manufacturing, integration, and management of spacecraft projects

3. PRELIMINARY ESTIMATIONS

First, a preliminary estimate was made on the theoretically achievable disposal orbit with the available fuel, and the consequent advantage in lifetime reduction.

3.1. Delta-v Computation

The delta-v is found from

$$\Delta v = g_0 I_{sp} \log(1 + m_p/m_0) \qquad (1)$$

where,
I_{sp}: specific impulse
m_p: propellant mass
m_0: dry mass (assuming complete exhaustion of propellant, this is the final mass)
g_0: acceleration due to gravity at sea level.

Assuming an conservative estimate of 22 kg usable fuel, and a specific impulse $I_{sp} = 205$ s,
$\Delta v = 0.07$ km/s.

Although maximal perigee de-boost is the recommended strategy followed for post mission disposal of LEO objects, a few alternatives were also proposed and considered. Cartosat-2 was in a 622 km $\times$ 638 km orbit at the time of end of mission. In the ensuing computations, a 630 km circular orbit is assumed for the sake of simplicity as the calculations are tentative in nature.

3.2. Change in SMA for a given Delta-v for Perigee De-boost

The semi-major axis (SMA) of the initial orbit is given by:

$$a_1 = R_e + \frac{h_{a1} + h_{p1}}{2} \qquad (2)$$

where R_e, h_{p1}, h_{a1} are the mean earth radius, the perigee altitude and the apogee altitude of the initial orbit, respectively. The initial circular velocity,

$$v_{a1} = \sqrt{\frac{\mu}{a_1}} \qquad (3)$$

Let h_{p2} be the final perigee altitude achieved when an apogee firing is performed to reduce the perigee (refer Fig.1).

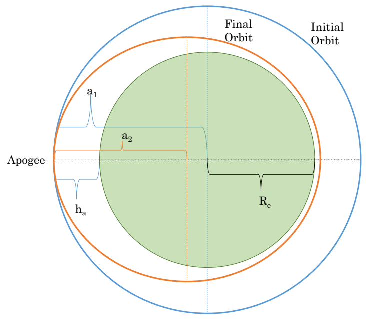

Figure 1. Reduction of perigee altitude by apogee burn

Let v_{a2} denote the velocity at the apogee of the final orbit after de-boost with Δv to lower the perigee. Then,

$$v_{a2} = v_{a1} - \Delta v \tag{4}$$

Assuming an impulsive burn at the apogee, post-burn apogee velocity v_{a2} from vis-viva equation is:

$$\frac{v_{a2}^2}{2} - \frac{\mu}{r_{a1}} = -\frac{\mu}{2a_2} \tag{5}$$

where, the apogee radius $r_{a1} = a_1$ for an initially circular orbit. From

$$v_{a1}^2 - v_{a2}^2 = \frac{\mu \Delta a}{a_1(a_1 - \Delta a)}$$

the change in SMA , $\Delta a = a_1 - a_2$ is found as:

$$\Delta a = a_1 \left[1 + \frac{\mu}{a_1 \Delta v (2v_{a1} - \Delta v)}\right]^{-1} \tag{6}$$

3.3. Finally Achieved De-boosted Perigee

For a given Δa, where the perigee is de-boosted without changing the apogee, let the corresponding change in perigee height be given by Δh_{pe}. Since, $h_{p1} = h_{a1} = h_{a2}$, it follows that

$$\begin{aligned} a_1 &= R_e + h_{p1} \\ a_2 = a_1 - \Delta a &= R_e - \frac{h_{p1} + h_{p2}}{2} \\ \Delta h_{pe} &= h_{p1} - h_{p2} = 2\Delta a \end{aligned} \tag{7}$$

Thus, the reduction in the perigee altitude is double the reduction in SMA for a perigee de-boost though an apogee burn.

With 70 m/s delta-v, from (6), the change in SMA $\Delta a =$ 127 km, and the corresponding reduction in the perigee is 254 km. Hence the finally achievable perigee altitude is 376 km.

3.4. De-boost to Co-planer Circular Orbit at Lower Altitude

To compute the finally achievable limit on a lower circular disposal orbit, we assumed the transfer via the standard Hohmann transfer scheme [3] as it is the most fuel optimal two-impulse transfer between co-planer orbits. First de-boosting to an intermediate elliptical orbit with its apogee at the original orbital altitude (or with a SMA of a_1) and the perigee at the final orbit (SMA of a_2) requires a delta-v for an apogee-burn:

$$\Delta v_1 = \sqrt{\frac{\mu}{a_1}} \left[1 - \sqrt{\frac{2a_2}{a_1 + a_2}}\right] \tag{8}$$

Next, de-boosting and circularizing requires a second burn at the perigee:

$$\Delta v_2 = \sqrt{\frac{\mu}{a_2}} \left[\sqrt{\frac{2a_1}{a_1 + a_2}} - 1\right] \tag{9}$$

Now, for a given $\Delta v = \Delta v_1 + \Delta v_2$, we need to find $a_2 = a_1 - \Delta a$, and hence Δa. Let

$$a_2 = \eta a_1 \tag{10}$$

where, η is positive scalar, and $\eta < 1$. Defining

$$f(\eta) = \sqrt{\frac{\mu}{a_1}} \left[1 - \sqrt{\frac{2\eta}{1+\eta}} + \frac{1}{\sqrt{\eta}} \left(\sqrt{\frac{2}{1+\eta}} - 1\right)\right] \tag{11}$$

The non-linear equation in terms of η is solved numerically:

$$f(\eta) - \Delta v = 0 \tag{12}$$

where Δv is found from (1).

Hence, $\Delta a = a_1 - a_2 = a_1(1 - \eta)$. In this case, or the reduction in perigee (and apogee) altitude to the final circular disposal orbit is the same as SMA reduction, i.e., $\Delta h_{pc} = \Delta a$.

For an initial circular orbit of 630 km and a delta-v $\approx$ 70 m/s, the SMA change Δa = 128 km, and final circular orbital altitude h_{p2}= 502 km.

4. LIFETIME REDUCTION DUE TO DE-ORBITING

Based on the physical dimensions and the mass of the satellite, an area to mass ratio of 0.0137 m^2/kg was considered, assuming that the fuel is completely depleted. The orbital lifetime was computed with STK's [4] Lifetime tool for various combinations of perigee and apogee altitudes using NRLMSISE-00 density model, HPOP propagator and predicted space weather data (solar flux, geomagnetic indices) [5]. Fig. 3 shows the dependence of lifetime on the final disposal orbit.

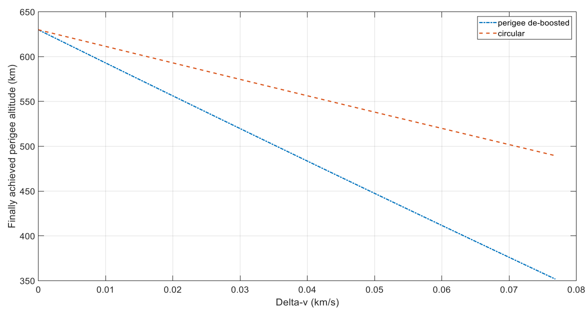

Figure 2. The final achievable perigee/ circular orbital altitude for the same delta-v for ideal, impulsive burn(s)

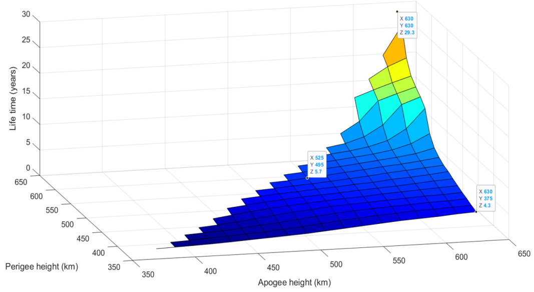

Figure 3. Orbital life-time dependence on orbital apogee and perigee altitude

It is found that de-boosting the perigee altitude to 610 km is sufficient for being compliant with the 25-year rule prescribed by IADC. The post mission lifetime at a 630 km × 380 km orbit is expected to be 4.4 years, while the expected lifetime at a circular orbit of 502 km altitude is 5.5 years.

5. DE-ORBITING STRATEGY SELECTION

In addition to maximal perigee de-boost and minimum lower circular orbits, an alternative strategy for disposal to a less eccentric, intermediate orbit was also proposed. Compared to the maximal perigee de-boosted orbit which would also have the maximum eccentricity, a final circular/less eccentric disposal orbit has the following advantages

(i) Less eccentric orbit will have less transit through different orbital regimes, posing potentially less close approach threats to other operational space assets.

(ii) Circular orbits offer an advantage from an operational point of view in terms of more extended visibility, convenience for orbit determination, and benign tracking rate for the ground antenna, compared to more eccentric orbits. This advantage is substantial only when the perigee is below 300 km.

However, this less eccentric orbit disposal scheme has the following shortfalls compared to the maximum perigee de-boost scheme:

(i) For the same delta-v, orbital life time differs by 1-2 years in circular orbit compared to an eccentric orbit, as a lower perigee offers more advantage in terms of atmospheric drag induced decay.

(ii) Bringing the satellite to a less eccentric/circular orbit essentially involves burn at perigee and apogee, calling for more careful planning and execution.

(iii) There is non-trivial variation in the osculating altitude primarily caused by Earth's non uniform geopotential, which can go up to 13 km. In case of improper disposal due to premature fuel depletion or any further failure in subsystems that may impair maneuverability, the satellite may be stuck in a circular orbit in the vicinity of another operational constellation, and pose conjunctions due to altitude variation. Such conjunctions will continue till the orbit decays well below the operational orbital shell of constellations. In the worst case, it could happen in the altitude range 530-570 km, which is likely to be crowded by Starlink constellation.

(iv) On the other hand, even though an object in an eccentric orbit passes through several orbital regimes, it poses collision risk to another space object only at the vicinity of the two orbit intersection points, which is less likely to lead to frequent close approaches.

Considering the aforementioned factors and the advantage of lifetime reduction, the maximum perigee deboosting scheme was finalized for Cartosat-2.

6. EXECUTION OF POST MISSION DISPOSAL

The de-orbiting operations were planned and executed by ISRO Telemetry Tracking and Command Network (ISTRAC) team [2] in close coordination with Mission and subsystem designers from various ISRO centres, namely URSC, LPSC[3] and VSSC [4]. First, a test burn was conducted on 6th March, 2020 to evaluate thrust performance. This was followed by a series of apogee burns to de-boost the perigee till 19th March, 2020. There was a temporary interruption in de-orbiting activities due to COVID-19 lock-down (during the months of April and May, 2020), when only essential operations were being managed by a very limited nuber of staff. The de-orbiting maneuvers resumed in 19th May, 2020. By 3rd September 2020, 26 perigee reduction burns were carried out which

[2]As per communications and internal notes received from Ankita Agarwal, Flight Dynamics Group, ISTRAC, and Nihil Arora, Spacecraft Operations Manager, Cartosat-2, ISTRAC

[3]Liquid Propulsion Systems Centre

[4]Vikram Sarabhai Space Centre

lowered the perigee to 390 km. With orbital lifetime reduced below 10 years and only about 2 to 3 kg fuel left on-board, the satellite was utilised for a few proof-of-concept exercises for ground automation. On 5th December, 2020, another de-boost maneuver was performed to avoid close approach within 10 km of International Space Station, which would have taken place on 6th December, 2020. This was followed by two more burns in the month of January, 2021. The final burn was conducted on 25th February, 2021. It was inferred from telemetry that the fuel was depleted, and further maneuvers were not feasible. The satellite has been declared as non-maneuverable in the Space-Track portal.

The initial apogee-burns were executed in non-visibility or partial visibility, with typically 9 to 10-minute burn duration. However, as the fuel was being depleted, all burns at the final stages were performed over visibility to ensure close monitoring of subsystem performance, and shorter burns were planned. In total, 23 kg fuel has been expended in 30 maneuvers. The the corresponding cumulative delta-v is 69 m/s, and is in good agreement with the initially estimated delta-v.

7. COMPLIANCE WITH IADC SPACE DEBRIS MITIGATION GUIDELINES

The compliance with the applicable IADC guidelines for Cartosat-2 is now discussed.

7.1. Limiting presence of an object in LEO at end of mission

The orbit achieved at the end of de-orbiting was 621 km $\times$ 380 km, this corresponds to a perigee reduction of about 242 km. Considering variability due to solar flux and geomagnetic index, the expected life-time of the satellite in the currently achieved orbit is expected to be less than 7 years (see Fig. 4). Even with very benign solar activities, the lifetime in the currently achieved orbit will be in excellent compliance with the 25-year rule. Furthermore, we have been able to reduce the lifetime to the best possible extent with the available fuel and resources, which is again in compliance with the guideline that at end of mission, the presence of the LEO object should be minimised as much as possible.

Throughout the de-orbiting phase, care was taken to ensure the satellite does not pose conjunction risk to any other object. Apart from regular conjunction analysis, all maneuver plans were subjected to conjunction analysis through Space Object Proximity Analysis (SOPA) to ensure that the post maneuver trajectory does not result in any close approach with any catalogued space objects within a period of 7 days from the burn end epoch.

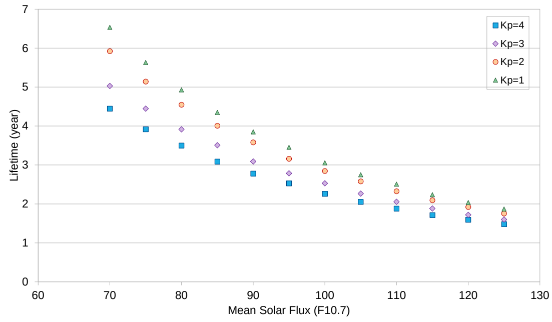

Figure 4. Variation of lifetime at post mission orbit of Cartosat-2 for various geomagnetic index and solar flux

7.2. Minimising Post Mission Break-up

Presently the left-over fuel of Cartosat-2 has been depleted to the maximum possible extent as the on-board telemetry indicated that all the fuel tanks have been emptied through the process of de-orbiting. Therefore, the post mission break-up risk due to stored propellant has been minimised.

There is no provision to disconnect the battery from the solar array at present for Cartosat-2. Hence, strategies to avoid overcharging of the battery is being worked out by draining the battery. As per an earlier study conducted by URSC, the uncontrolled satellite under tumbling condition is unlikely to generate sufficient power to overcharge the battery. The decommissioning process of Cartosat-2 will involve switching off the rotating mechanisms (reaction wheels, dynamically tuned gyros) for passivation.

8. RECOMMENDATIONS FOR FUTURE LEO MISSIONS

Based on the experience gained from the disposal exercise of Cartosat-2, a few design changes have been recommended for future missions to facilitate post mission disposal.

(a) A provision for safely disconnecting the batteries from the charging circuit, which should not be inadvertently triggered except during the disposal phase, is recommended. The feasibility of implementation of such schemes are presently being studied by the subsystem designers with consideration of the associated failure modes.

(b) Exploring options to incorporate provisions for venting fuel without orbit change, similar to ISRO launch vehicle upper stages, is also recommended. This option will be particularly beneficial if the satellite's attitude sensing and control capabilities are degraded at its end of life, which may prevent orbit maneuvering.

(c) In line of GEO missions, where fuel required for post mission re-orbiting is apportioned in the fuel budget, it is recommended to ear-mark sufficient fuel at the design level for post mission de-orbiting to minimise orbital lifetime at end of mission, wherever feasible.

(d) The extra fuel at end of life of Cartosat-2 was mainly reserved for contingency and initial orbit acquisition after injection in case of launch vehicle performance deviation. Considering the current reliability of ISRO launch vehicles and on-board subsystems, excessive fuel loading is not desirable. If unused, it not only leads to post mission break-up risk, but also adds to lift-off mass unnecessarily.

(e) Extending mission life of a satellite should be based on the consideration on system health, fuel availability, and redundancy aspects to ensure that the capability of successful post mission disposal is not compromised.

9. CONCLUSION

Cartosat-2 is the first ever Indian LEO satellite to have undergone a well-planned post mission disposal process with an aim to be compliant with the UN/IADC space debris mitigation guidelines. In view of the continual congestion of LEO regime, the de-orbiting strategy was chosen to minimise post mission orbital life time to limit the presence of Cartosat-2. The finally achieved orbit is in close agreement with preliminary, representative estimations of perigee de-boost. The compliance with post mission life time reduction is perfect, while compliance with post mission accidental break up risk reduction is not yet achieved fully owing to the present design limitations for electrical passivation. The efforts are still on to work out a scheme that can meet this goal.

The disposal exercise, executed in synergy among different teams across centres, helped ISRO to gain invaluable experience, and better insights on subtler operational aspects and challenges of disposing of an aging satellite. This experience will be suitably leveraged in subsequent de-orbiting exercises. It also aided in deriving design requirements to facilitate end-of-life disposal process of future LEO missions, such as provision for electrical passivation and fuel allocation for de-orbiting.

Despite the existing design limitations and on-board constraints, the post mission disposal of Cartosat-2 marks an important milestone in ISRO's continual efforts towards space sustainability and paves the way for better compliance with IADC/UN guidelines by ISRO in future.

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