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Posthumous Analysis of the Indian Anti-Satellite Experiment: Puzzles and Answers

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Abstract

The Indian anti-satellite (ASAT) experiment of 27 March 2019 created some unexpected results. The destruction of the target satellite Microsat-R was planned by a head-on collision with a kinetic kill vehicle (KKV) such that most of the fragments produced by the backward impulse would deorbit rapidly and pose no threat to the space environment. Actually however, several hundreds of fragments spread in the forward direction, many into higher orbits. This unexpected puzzle has been solved in this study by analyzing the collision via orbital mechanics. The results show that whereas collision alone was not responsible for the debris production, explosions resulting from the collision explain the fragments formation in the forward direction. Careful examination of the 'Gabbard diagram' suggests that there were at three secondary explosions following the primary explosion which took place after the target satellite was knocked into an elliptical orbit as a result of the collision with the ASAT.

1. INTRODUCTION

On 27 March 2019, ***India became the fourth nation in history to attain anti-satellite (ASAT) capability*** when its ***Microsat-R*** satellite was destroyed in Sun-synchronous orbit. The ASAT weapon was a ***kinetic kill vehicle*** (KKV) atop a third-stage rocket launched from Abdul Kalam Island [1]. The impact occurred at 11:13 IST or 05:43 UT on Julian day 2019086 which translates to epoch 2019086.23819444. The location of the event was over Bay of Bengal at latitude 18.715°N and longitude 87.450°E [2]. The mass of the target satellite was 740 kg whereas the third-stage rocket including the KKV weighed 1,800 kg [3].

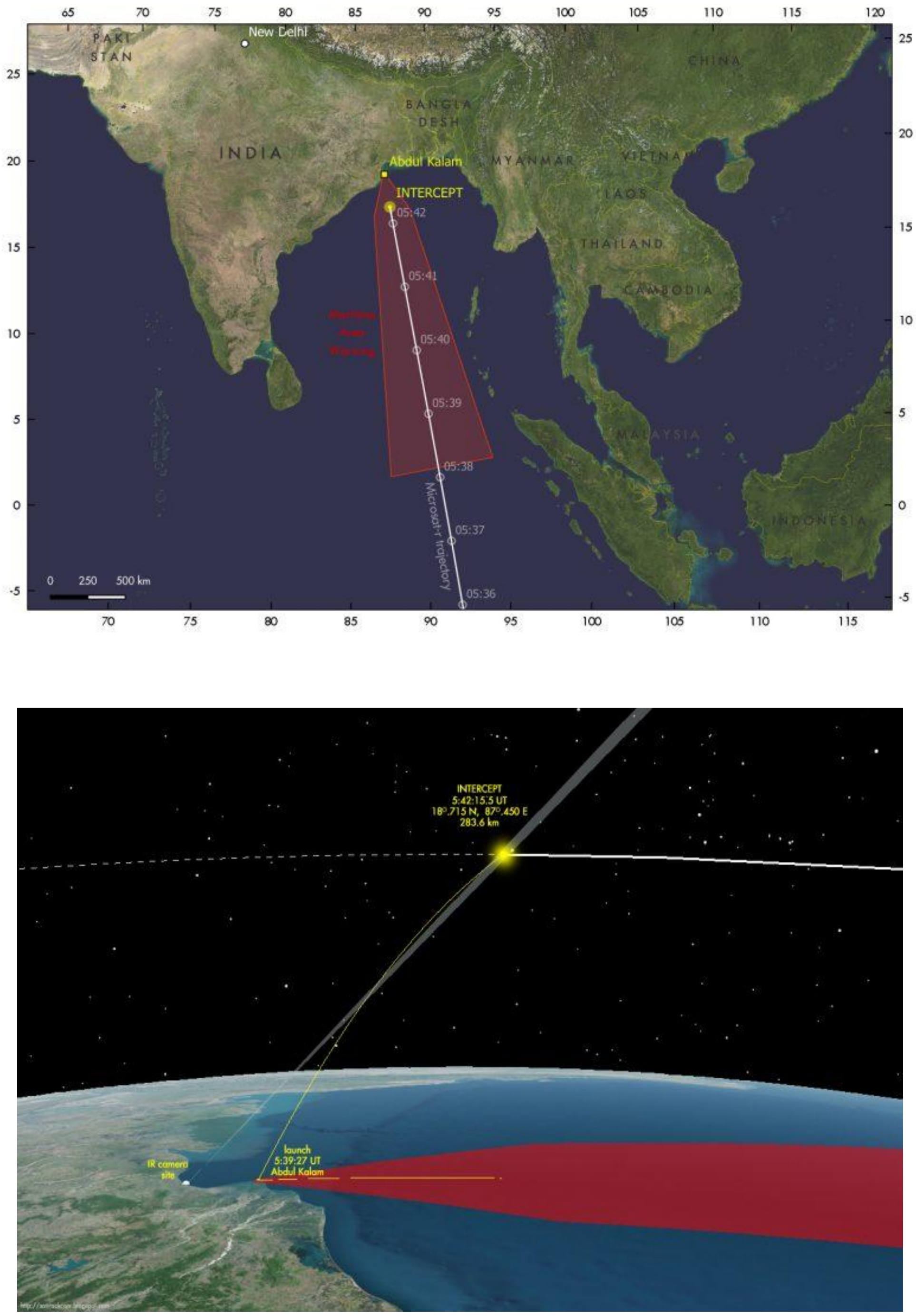

Fig 1

Figure 1 (from [2]) shows the geometrical perspective of the ASAT test. The collision was almost head-on in a horizontal plane (upper panel). However, the ASAT was still ascending in the vertical plane when the collision occurred (lower panel). This ASAT experiment was planned such that most of the fragments produced by the backward impulse would deorbit rapidly and pose no threat to the space environment. Actually however, several hundreds of fragments spread in the forward direction, many of them into higher orbits. This unexpected puzzle is analyzed in this study. The results show that whereas collision alone was not responsible for the debris production, explosions resulting from the collision do explain the fragments formation in the forward direction. Careful examination of the '***Gabbard diagram***' will suggest that at three secondary explosions following the primary explosion took place after the target satellite was knocked into an elliptical orbit as a result of the collision with the ASAT.

2. TARGET SATELLITE

Microsat-R (International Designator 2019-006A; USSTRATCOM Catalog Number 43947) was launched on 24 January 2019 to presumably serve as the target satellite for the forthcoming ASAT test [1]. The orbital elements of the satellite prior to its fragmentation (as well as those of the resulting fragments) are found from Ref. [4]. In accordance to the latter, the orbit of Microsat-R was nearly circular having ***eccentricity*** e = .0015984; ***semi-major-axis*** a = 6649.0615 km; ***apogee height*** h_a = 281.5443 km; and ***perigee height*** h_p = 260.2886 km. The ***true anomaly*** at fragmentation θ is obtained by subtracting the ***argument of perigee*** ω from the ***argument of latitude*** u: $\theta = u - \omega$. The argument of latitude is calculated from the right ***spherical triangle*** bounded by the ***ground track*** of the satellite, event meridian and the equator:

$$u = sin^{-1}\left(\frac{sin\lambda}{sini}\right) \quad (1)$$

where i is the ***inclination*** and λ the ***latitude*** of the event location, giving u = 18.84602°, whence θ = 160.0326°. The ***altitude*** of the event location h is obtained by subtracting the ***reference radius of the Earth*** r_0 (6,378.145 km) from the ***radial distance from the center of the Earth*** r. The last quantity is calculated from the ***equation of the orbit***:

$$r = \frac{a(1-e^2)}{1+ecos\theta} \quad (2)$$

giving h = 280.9014 km.

The ***orbital speed*** of the satellite v is calculated from the ***vis-viva equation***:

$$v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)} \quad (3)$$

where μ is the ***gravitational parameter***. In the fragmenting satellite's local inertial frame of reference, the ***down-range component of the velocity*** is given by

$$v_d = \frac{\sqrt{\mu a(1-e^2)}}{r} \quad (4)$$

whereas the ***radial component of the velocity*** is expressed (for north-bound motion) as

$$v_r = \frac{\sqrt{\mu}}{r}\sqrt{ae^2 - \frac{(r-a)^2}{a}} \qquad (5)$$

We obtain: v = 7.731024267 km/s; v_d = 7.731023106 km/s; and v_r = 4.23808 m/s. Thus Microsat-R was virtually horizontal with a ***slope angle*** of $\alpha = \tan^{-1}(v_r/v_d) = .0314^o$.

3. ANTI-SATELLITE

The ASAT was a KKV atop the third stage of a ***direct-ascent three-stage rocket*** [1]. It was launched on 27 March 2019 at 5:40 UT to collide head-on with its target within 3 mins [1]. The ***angular distance*** δ (at the center of the Earth) between the take-off point (Abdul Kalam Island) and breakup point of the ASAT is calculated from ***spherical trigonometry*** in accordance with the formula

$$cos\delta = sin\lambda_1 sin\lambda_2 + cos\lambda_1 cos\lambda_2 cos(\phi_2 - \phi_1) \qquad (6)$$

where (λ_1 = 20.75804°N, ϕ_1 = 87.085533°E) and (λ_2 = 18.715°N, ϕ_2 = 87.4550°E) are the coordinates (***latitudes*** and ***longitudes***) of the take-off and breakup points, respectively. Upon substituting the values, we get δ = 0.999346482°. The ***horizontal distance traversed*** by the ASAT is then $\ell = \delta r_0$ = 230.60146 km. Thus, the ASAT climbed 280.9014 km as it covered 230.60146 km horizontally.

Like most other ***sub-orbital space flights***, the ASAT vehicle is assumed to have taken a ***least-energy trajectory*** which is characterized by the ***angular parameter*** ϕ between the take-off and apogee points at the center of the Earth such that the take-off point lies on the ***semi-latus rectum at the empty focus*** [5] (Fig. 2). All the relevant quantities of the sub-orbital trajectory for this "***economy flight***" are expressed in terms of this parameter ϕ [5]. For example, the ***semi-major axis*** a, ***eccentricity*** e, ***initial velocity*** v_0 and the ***angle of elevation*** α of v_0 are given, respectively, as follows:

$$a = \frac{1+sin\phi}{2} r_0 \qquad (7)$$

$$e = \frac{cos\phi}{1+sin\phi} \qquad (8)$$

$$v_0 = \sqrt{\frac{\mu}{r}}\sqrt{\frac{2sin\phi}{1+sin\phi}} \qquad (9)$$

and

$$\alpha = \frac{\pi}{4} - \frac{\phi}{2} \qquad (10)$$

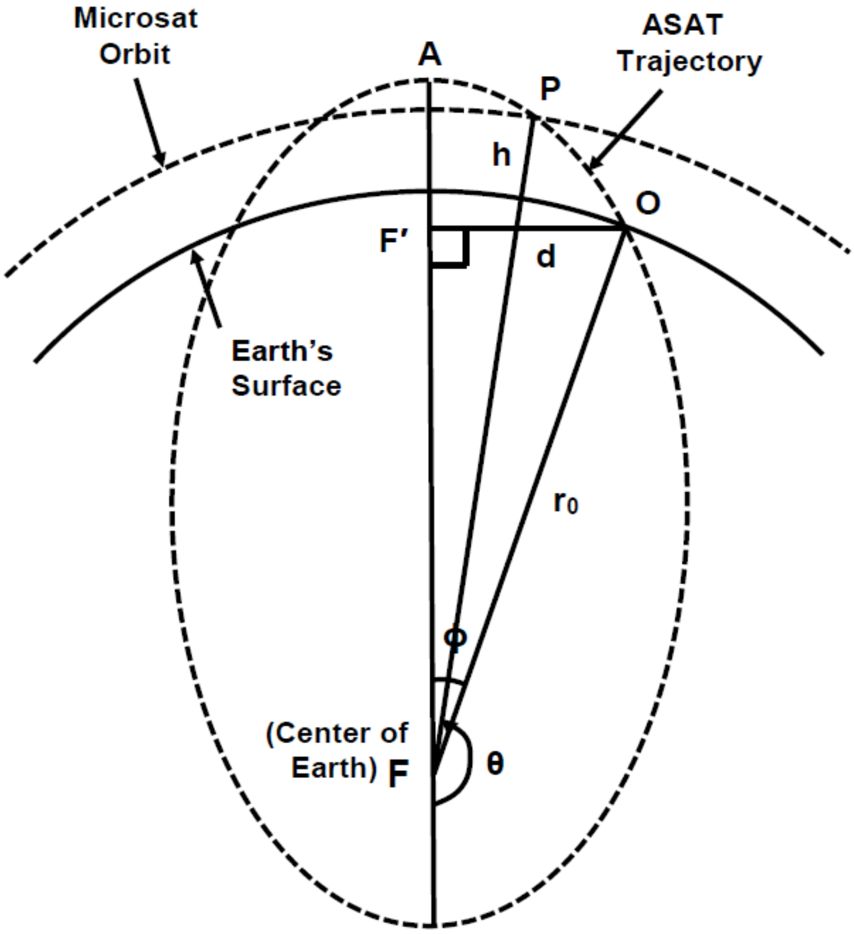

Fig 2

Further, the ***height of apogee*** h_a and the ***speed at apogee*** v_a are given by [5]

$$h_a = \frac{r_0}{2}\left[\sqrt{2}sin\left(\phi + \frac{\pi}{4}\right)\right] \quad (11)$$

and

$$v_a = v_0\sqrt{\frac{2}{1+sin\phi}}\sqrt{\frac{1-e}{1+e}} \quad (12)$$

The parameter $\boldsymbol{\phi}$ for the ASAT trajectory is determined as follows. First, the semi-major axis is calculated by inverting Eq. (3), giving:

$$a = \frac{\mu r}{2\mu - rv^2} \quad (13)$$

Given the fact that the event occurred at r = 280.9 km and the ***velocity of the ASAT*** was reportedly to be 3 km/s [2], we get from Eq. (13): a = 3,600.17327 km. ϕ can then be computed from the inversion of Eq. (7):

$$\phi = sin^{-1}\left[\frac{2a}{r_0} - 1\right] \quad (14)$$

giving ϕ = 7.40656°; whence from Eq. (8): e = .87842. The ***true anomaly of the ASAT*** at fragmentation is expressed from Eq. (2) as

$$\theta = cos^{-1}\left[\frac{a(1-e^2)-r}{er}\right] \quad (15)$$

giving θ = 174.6913°. The ***slope angle of the ASAT*** at fragmentation α is given by [6]:

$$\alpha = tan^{-1}\frac{v_r}{v_d} = tan^{-1}\left[\frac{esin\theta}{1+ecos\theta}\right] \quad (16)$$

giving α = 32.96455°. The ***angular distance covered by the ASAT*** is given by d$\theta = \theta -$ (π-ϕ) = 2.09786°, which translates to a ***linear distance*** of ℓ = d$\theta.r_0$ = 233.533 km (cf. our previous value of ℓ = 230.60146 km).

The ***velocity of the ASAT relative to the target satellite*** is

$$v_{21}^2 = v_1^2 + v_2^2 + 2v_1v_2cos\alpha \quad (17)$$

where v_1 is the velocity of the target satellite, v_2 that of the ASAT and α is the angle given by Eq. (16). On substituting the values, we get v_{21} = 10.375 km/s, well in the hyper-velocity range. This compares with the figure of 10 km/s quoted in the literature [1 – 3].

4. ORIGIN OF THE FRAGMENT CLOUD

Collision phenomenology involving two large objects in space was first revealed in the ***Delta-180 collision experiment*** [6 – 9] and subsequently confirmed in the ***accidental collision of Cosmos 2251 and Iridium 33 satellites*** [10 – 13]. It is now an established wisdom that ***when two large objects collide in orbital space, each object produces its own fragment cloud which is spread around the original direction of that object***. In the case of the Microsat-R fragmentation, the target satellite (740 kg) and the KKV (1,800 kg) were expected to have produced their own debris cloud. But since the KKV was on a sub-orbital trajectory, its debris cloud was expected to have de-orbited immediately afterwards. Hence the observed debris cloud almost certainly originated from the target satellite.

Since it is now established that the ASAT of mass m was travelling at a speed of v = 3 km/s at a slope angle of α = 32.96455°, the target satellite received an ***impulse*** of $-mv\cos\alpha$ in the downrange direction and $mv\sin\alpha$ in the vertical direction. Generally, the effect of the former is to ***diminish the semi-major axes of the fragments***, whereas that of the latter is to ***render the orbits more elliptical***. Given the relatively low altitude of the target satellite, the effect of the negative impulse in the down-range direction would have been to de-orbit the fragments rapidly. But since the fragment cloud was unexpectedly significant, there must have been ***other factors at play***.

5. GABBARD DIAGRAM OF THE FRAGMENT CLOUD

The ***Gabbard diagram*** plots the apogee and perigee heights of the fragments against their periods. In this study, Gabbard diagram of 348 fragments of Microsat-R catalogued through 31 December 2019 in Ref. [4] was constructed and plotted in Fig. 3. As stated earlier, if the fragments were created by collision alone, most of them would have deorbited, having received negative impulses in the backward direction and the Gabbard diagram would be largely empty. But surprisingly, Fig. 3 is full of fragments, many of them in very high energy orbits. Also, Fig. 3 is a ***unique diagram with full of apsidal points within the angle formed by the two major arms – the first of its king ever recorded***. A careful scrutiny reveals that these points actually comprise three individual Gabbard diagrams belonging to separate clusters of fragments within the main Gabbard diagram of the primary cluster. These clusters are marked 2, 3 and 4 within the main Cluster 1 in Fig. 3. Further examination shows that the ***Cluster 1 diagram is consistent with an explosion of the target from a circular orbit*** since its perigee arm is horizontal at the same altitude of the target at impact [14]; whereas the diagrams for ***Clusters 2, 3 and 4 resemble those of explosions from elliptical orbits*** [15]. The Cluster 2 diagram is an interesting case where the ***apogee and perigee lines were nearly parallel*** [15].

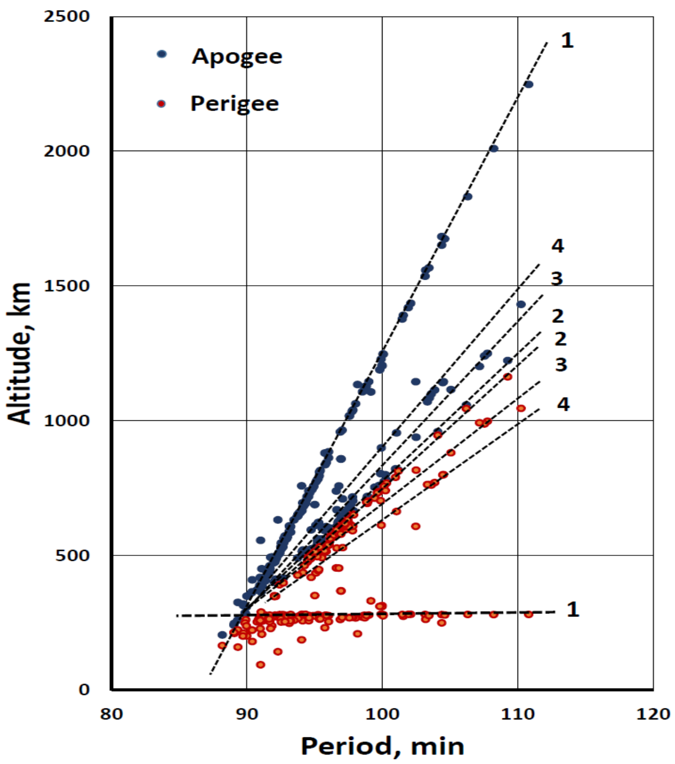

Fig 3

6. ANSWERS TO THE PUZZLES

All these puzzles can be answered if one assumes the following: (1) ***The collision was immediately followed by an explosion in the target satellite, which then produced Cluster 1 fragments***; and (2) ***This explosion was then followed by three secondary***

explosions, which produced the fragments of Clusters 2, 3 and 4. The universal times when the fragments were first cataloged [4] suggest that the primary explosion was most likely followed by the secondary explosions which produced fragments of Clusters 2, 3 and 4 in sequential order.

In order to validate our conclusions, we now turn to Fig. 4 which is a plot of the apogee and perigee heights of Microsat-R and their mean values against time during the entire life of the satellite in orbit. First, the satellite was launched on Day 24 (24 January) of 2019. Orbital maneuvers in the early days and orbital rounding from Day 50 until impact by the ASAT on Day 86 (27 March) suggest that the satellite ***contained propellants*** in it; and it is the ***ignition of this propellant by impact which must have produced the explosive fragmentations***. Of course, how much did the KKV's own fuel contributed to the target's explosions cannot be inferred in this study.

There was a ***9-day interval*** from Day 86 until Day 95 (marked in yellow) when the episode was sorted out and no orbital elements were cataloged. ***It is within this interval that the primary and secondary explosions must have occurred***, since the altitudinal data points thereafter were smooth and showed no abrupt discontinuities.

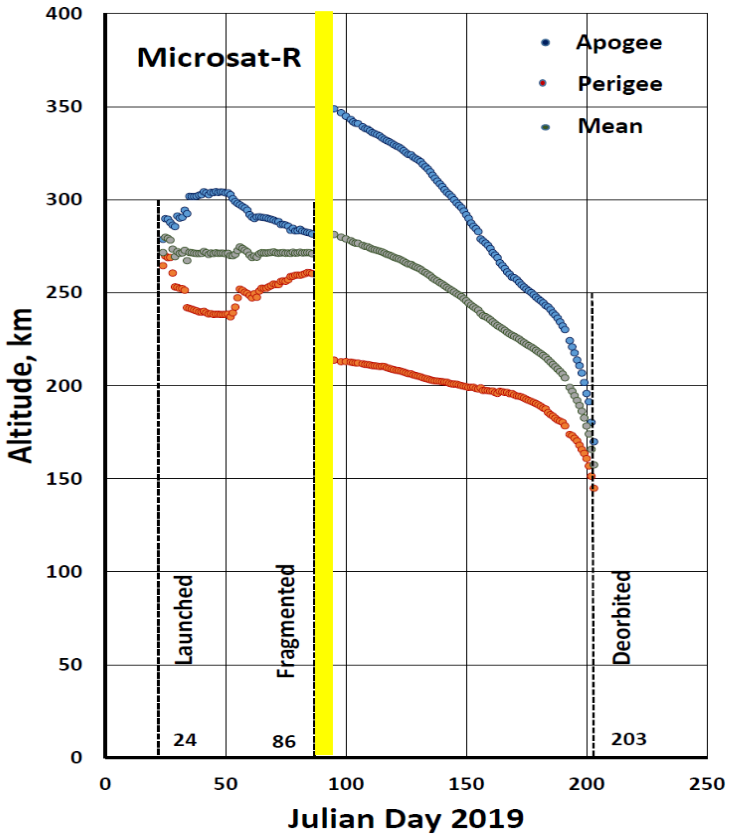

Fig 4

In Fig. 4, the data points from Day 95 are those of the main remnant of Microsat-R which inherited the Catalog Number of the parent satellite. The figure clearly shows that ***the orbit of the remnant became significantly elliptical*** (e = .0101419 as opposed to e = .0015984 of the parent at last observation) with its apogee soaring to 348.815 km and perigee dropping down to 213.737 km on Day 95. Interestingly, the mean apsidal height $h_{av} = (h_a + h_p)/2$ actually increased from 270.917 km to 281.276 km. ***This dramatic increase is due to the positive radial impulse imparted by the ASAT which could not have happened from simple explosion alone***. Since $h_{av} = a - r_0$ is a measure of the semi-major axis, period and energy of the orbit, ***the target satellite was knocked into a higher energy orbit***. This also explains the fact that the ***fragments of the secondary explosions exhibited signatures of fragmentation from elliptical orbits with slant perigee arms***.

In summary, the Indian Anti-Satellite Experiment of 27 March 2019 was a unique event – the first of its kind ever conducted. Although it was planned to avoid creation of hazardous orbital debris, this actually happened due to the ignition of propellant remaining in the target.

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