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DEBRIS CREATION IN GEOSTATIONARY TRANSFER ORBITS: A REVIEW OF LAUNCH PRACTICES 2004-2012

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Objects left in Geostationary Transfer Orbit (GTO) pose a threat to operational satellites in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). In addition to regularly crossing both of these belts at high relative velocities, objects in these orbits are often large in size and mass (i.e. upper stages, fuel tanks and payload adaptors). Each successful satellite launch to GEO can generate 1-4 large pieces of debris (dependent upon the launch vehicle), a significant portion of which is left in transfer orbits that do not decay.

This paper analyses the past practices of all launch vehicles that placed satellites in GEO from 2004- 2012. The orbits of the 294 pieces of debris that were identified are discussed further in depth with reference to their threat to the Low and Geostationary Earth Orbits and the likelihood of their decay in 25 years as per international guidelines. Results are grouped for each of the 17 distinct launch vehicles used, and rankings of launch vehicles with regards to the amount of mission related debris are developed.

Furthermore, the physical mechanisms with regards to orbital decay are investigated in order to ascertain the impact of various orbital parameters on re-entry time. The European Space Agency's (ESA) Debris Risk Assessment and Mitigation Analysis (DRAMA) tool specifically is used to conduct Monte-Carlo analyses on nominal upper stages in GTO.

I. INTRODUCTION

From 2004-2012, 210 launch vehicles operated by five independent nations and two international organisations placed satellites in Geostationary Earth Orbit (GEO; altitude 35,786km). In almost all cases, each successful launch left one or more pieces of debris (e.g. upper stages, payload carriers or auxiliary fuel tanks) in highly elliptical Geostationary Transfer Orbits (GTO). GTOs typically have perigees in Low Earth Orbit (altitude < 2000km) and apogees near-GEO. Inclinations for GTO vary depending upon launch site, and can be as high as 52°. Debris in GTO is particularly concerning for operational satellites as it frequently crosses both GEO and the crowded LEO.

The Inter-Agency Debris Coordination Committee (IADC) has defined two "protected regions with regard to the generation of space debris" [1]: Region A, a "spherical region that extends up from Earth to an altitude of 2000km" (i.e. LEO) and Region B, a segment of a spherical shell near GEO (shown in Figure 1) [1]. The IADC Guidelines strongly recommend disposing objects that pass through these protected regions at mission end-of-life, either by placing them in 'parking orbits' (IADC Measure 5.3.1) or by placing them in orbits that will decay with the debris re-entering within 25 years (IADC Measure 5.3.2).

The following sections of this paper will analyse the mitigation measures of launch vehicle upper stages from 2004-2012. Furthermore, the physical mechanisms with regards to orbital decay will be investigated to determine the impact of various orbital parameters on the rate of orbital decay.

The survey of GTO launches extends on work previously conducted by Johnson [2] where a similar analysis was conducted from 2000-2003.

Data for this study has been obtained from Space Track (https://www.space-track.org), and orbit propagation and re-entry calculations utilise the European Space Agency's (ESA) Debris Risk Assessment and Mitigation Analysis (DRAMA) tool.

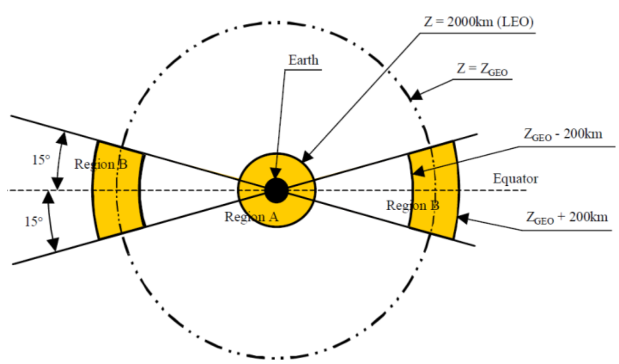

Fig. 1: IADC Protection Zones [1]

II. BACKGROUND

As mentioned in Section I, debris in GTO is a cause for concern as it crosses both the congested LEO and GEO orbits. In addition, the orbits of objects in GTO are difficult to propagate and predict due to intricacies in their orbital perturbations. This section will provide background information on both orbital perturbations and allowable debris mitigation orbits for objects in GTO.

II. I Orbital Perturbations in GTO

Objects in GTO are very susceptible to perturbations that change their orbital parameters. This can lead to interesting and counter-intuitive effects. The primary perturbations arise from atmospheric drag, the oblateness of the Earth (i.e. the 'J2 effect') and third body effects.

A brief outline of the effects of these orbital parameters is presented here. For additional details please refer to [3], [4] and [5].

II.I.I Atmospheric Drag

The density of the Earth's atmosphere decreases exponentially with increasing altitude. It hence has the largest impact at low altitudes, i.e. near perigee. Atmospheric drag works to decrease the object's orbital velocity at perigee, which results in a lower apogee during subsequent orbits. It has negligible effect on the Argument of Perigee (AoP), Right Angle of Ascending Node (RAAN) and inclination of an orbit, instead steadily decreasing the semi-major axis and eccentricity.

The magnitude of drag is difficult to predict in advance as the atmospheric density is highly dependent upon solar activity. There are a variety of methods used in its estimation, as further outlined in [6].

II.I.II J2 Effect

The Earth is not a perfect sphere (it is closer to an oblate ellipsoid), and hence it generates a non-uniform gravitational field. The gravitational pull of the Earth on the object is hence not directly towards the centre of the Earth, but is offset slightly towards the equator. Any orbiting object is pulled preferentially towards the equator, creating a torque on the orbit. This torque does not affect inclination, and instead causes gyroscopic precession of both the RAAN and the AoP.

II.I.III Third Body Effects

Gravitational perturbations due to the Sun and the Moon directly affect the RAAN, Argument of Perigee, inclination and eccentricity of an orbit. They do not however affect the semi-major axis [3]. The Sun and the Moon apply an external torque to the orbits and cause the angular momentum vector to rotate. The effect on RAAN and argument of perigee is small compared to the J2 effect.

For objects in GTO, the effect of third body forces on eccentricity is important as a small change in eccentricity can result in a large change in perigee. The effect of the sun is much larger than the effect of the moon [4].

Depending on the relative position of the sun, the eccentricity of the orbit will either increase or decrease. As the semi-major axis is unaffected by third body effects, an increase in eccentricity will lead to a decrease in perigee. This is illustrated in Figure 2.

II.I.IV Sun Synchronous Resonance

For certain combinations of semi-major axis, eccentricity and inclination, the J2 effect can result in a solar angle α (itself dependent upon the RAAN and AoP; shown in Figure 2) remaining approximately constant over an extended period of time. Third body effects can then result in significant increases or decreases in the orbit's eccentricity, and therefore its perigee, over time. This effect can be exploited to

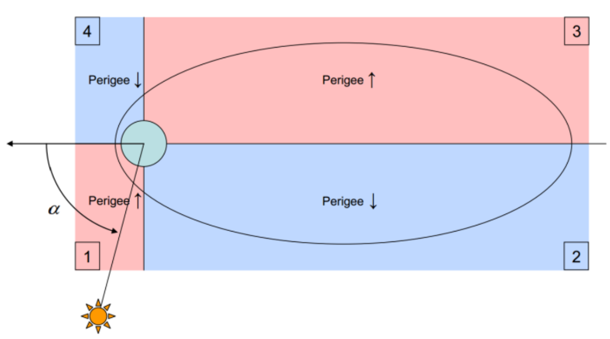

Fig. 2: Dependence of perigee increase/decrease on location of the Sun [3]

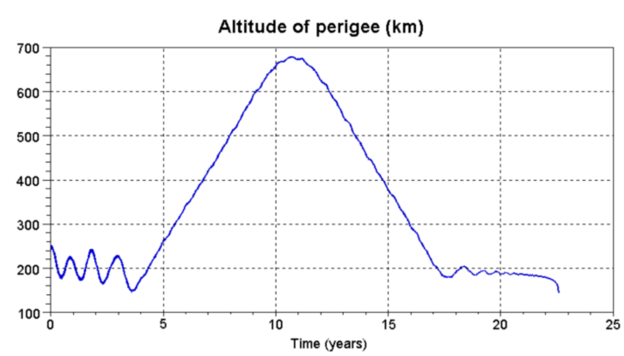

Fig 3: Example of sun-synchronous resonance [4]

Launch System	Stages left in GTO per launch	Other mission-related debris left in GTO per launch	GTO Perigee Range (km)	GTO Apogee Range (km)	Number of launches
Ariane 5	1	0-1	222-658	33,476-38,467	43
Atlas 2AS	1	0	207-236	35,262-35,534	2
Atlas 3A[a]	1	0	191	35,080	1
Atlas V	1	0	110-6,231	34,644-85,173	6
Long March 3A	1	0	134-405	35,794-42,062	8
Long March 3B	1	0	156-197	30,472-49,260	4
Long March 3B/E	1	0	105-268	14,886-49,902	11
Long March 3C	1	0	161-295	34,272-42,402	9
Delta 4M+(4,2)	1	0	6,595-6,604	35,127-35,173	3
GSLV	1	0	172-192	31,659-35,486	2
H-IIA	1	0	180-263	34,048-34,899	4
Proton-K/DM	0-1	0-2	240-361	35,699-36,180	9
Proton-M/Briz-M	0-1	1	310-14,676	12,092-42,470	54
PSLV-XL[a]	1	0	282	21,342	1
Soyuz-FG Fregat[a]	1	0	311	66,081	1
Zenit-3F[a, b]	0	0	N/A	N/A	1
Zenit-3SL[c]	1	0	132-11,250	35,710-39,378	26
TOTAL					**185**

Table 1:2004-2012 launch systems examined

[a]Only one mission was flown during 2004-2012

[b]Upper stage was left in GEO; specific GTO unknown

[c]Includes both Zenit-3SL and Zenit-3SLB

expedite re-entry of debris in GTO. Conversely, if it occurs unexpectedly (e.g. due to changing solar conditions over several years), it can result in a much longer decay time.

Figure 3 shows an example of how this effect, termed sun-synchronous resonance, can result in a dramatic increase in perigee radius from 200km to 700km over the course of 7 years.

II.II Acceptable Orbits for Debris Mitigation

As previously mentioned, the IADC Guidelines recommend that at end of life, spacecraft be disposed of by either placing them in orbits that will decay within 25 years, or relocating them to orbits that do not cross the LEO or GEO protected regions.

For the purposes of this paper, three IADC-compliant mitigatory orbits are therefore defined.

- Mitigatory Orbit 1: Low perigee (<200km). Low perigee orbits will ensure that objects re-enter Earth's atmosphere within 25 years.[†]
- Mitigatory Orbit 2: Between LEO and GEO. A perigee above LEO and an apogee below GEO will ensure that the debris does not enter either protected orbits. Specifically:
    a. Perigees of more than 2000km and apogees less than 35,351km, or
    b. Perigees of more than 2000km with inclinations of more than 15 degrees.
- Mitigatory Orbit 3: Super-synchronous orbit. Perigee and apogee of greater than 36,221km will ensure that debris does not cross either LEO or GEO orbits

If an upper stage or associated piece of debris is located within either of these three orbits, then it is compliant with the IADC Guidelines.

III. REVIEW OF PAST PRACTICES 2004-2012

From 2004-2012, 210 launch vehicles operated by five independent nations (China, Japan, Russia, India and the United States) and two international organisations (Sea Launch and Arianespace) placed satellites in GEO. In order to analyse the debris generated by each launch, Two Line Element (TLE) data was obtained from Space Track.

[†] Although the amount of time required orbital decay depends heavily on solar activity and debris characteristics, upper stages with a perigee of less than 200km have an 80% probability of decaying in less than 25 years. This is discussed further in Section IV.

Note that this analysis does not include payloads placed in highly inclined Geosynchronous Earth Orbits (e.g. the Chinese Beidou constellation), failed launches (including partial failures), and accidental debris generation (e.g. tank explosions). Classified launchers, apogee-kick motors and other satellite-specific debris (i.e. not generated by launch vehicles) are also not included.

Of the 210 GTO launches during 2004-2012, data was obtained for the analysis of 185. Seventeen different basic expendable launch vehicle types were subsequently identified, and are summarised in Table 1.

III.I Country Analysis

III.I.I China

The Chinese Long March 3 (Chang Zheng 3) rocket family has performed 33 GEO missions from 2004-2012. Four different configurations have been utilised; Long March 3A, a small three-stage launch vehicle (8 GEO launches); Long March 3B, a heavy lift variant of the Long March 3A with four additional strap on liquid boosters (4 GEO launches); Long March 3B/E, an enhanced Long March 3B with enlarged first stage and boosters (11 GEO launches) and Long March 3C, a medium lift variant with two instead of four strap on liquid boosters (10 GEO launches).

All variants of the Long March 3 family utilised a similar upper stage which was left in GTO. The perigees observed for all launches were between 105km and 405km. Two different GTO apogees have been observed; near-GEO (16 launches, 30,471-36,253km), and above GEO (17 launches, 40,349-49,901km).

To date, the orbits of sixteen of the upper stages (4xLM-3A, 3xLM-3B, 5xLM-3B/E, 4x LM-3C) have decayed on timeframes ranging from three months to two years. These stages had perigees of 105-215km, which represented 16 of the lowest 20 perigees.

III.I.II Arianespace (Europe)

The European multinational organisation Arianespace operated three different variations of the Ariane 5 Launch Vehicle for GEO insertion from 2004-2012; the Ariane 5G+ (1 GEO launch), Ariane 5GS (5 GEO launches) and Ariane 5ECA (37 GEO launches). The 5G+, used for one GEO launch during early 2004, featured an improved hypergolic upper stage Aestus over the original Ariane 5G. It was capable of launching one payload to GTO. The Ariane 5G+ was due to be replaced by the Ariane 5ECA, a dual-launch capable vehicle featuring an improved Vulcain 2 Main Engine first stage and a new cryogenic upper stage named ESC-A (Etage Supérieur Cryogénique-A). The failure of the first Ariane 5ECA launch led to an intermediate configuration, the Ariane 5GS, being used between 2005 and 2007. It was of similar design to the Ariane 5ECA, and was capable of delivering dual payloads, however it utilised the original Vulcain 1b Main Engine and the hypergolic upper stage Aestus.

For all three versions, a nominal launch left the hypergolic (Ariane 5G+, Ariane 5GS) or cryogenic (Ariane 5ECA) upper stage in GTO. For dual launch configurations (40 of the 43 launches), the SYLDA payload adaptor was also released into GTO. The GTO nominally had a perigee of 250km and an apogee in GEO [7], however perigees of 222-658km and apogees of 33,476-38,467km have been achieved in practice.

To date the orbits of five SYLDAs have decayed, with re-entry occurring between one and seven years after launch. They have all had low initial perigees (229-268km). None of the upper stages have decayed.

III.I.III India

The Indian Space Research Organisation (ISRO) currently has two launch vehicles capable of GEO insertion. In the period 2004-2012, one launch of the PSLV-XL (Polar Satellite Launch Vehicle) and two launches of the GSLV (Geosynchronous Satellite Launch Vehicle) placed payloads into GEO. The PSLX-XL utilised a small hypergolic fourth upper stage, which placed the payload in a sub-synchronous orbit (287x21,342km). The payload subsequently used its own on-board propulsion systems to reach GEO. The GSLV utilised a Russian-built cryogenic third upper stage, which was left in GTO. The observed orbits for the GSLV upper stage were 192x31,659km and 172x35,486km. **Both GSLV upper stages decayed within 3-4 years after launch, with the PSLV upper stage still in GTO as of 2013.**

III.I.IV Japan

Four missions by the Japanese H-IIA launch vehicle fit the conditions of this study. The H-IIA launch vehicle is built around a common core stage, with four different strap-on motor configurations.

All variants utilised a similar cryogenic upper stage. The upper stages of all launchers were left in GTO, with perigees of 180-263km and near-GEO apogees of 34,048-34,899km. **One upper stage decayed three years after its launch. It had a low perigee of 180km.**

III.I.V Russia

Russia's Proton launch vehicle was used for GEO insertion for 63 missions during 2004-2012. During this time two primary configurations were used; the Proton-K/Blok-DM-2 (9 missions) and the newer Proton-M/Briz-M (54 launches).

The Proton-K/Blok-DM-2 is a three-stage launch vehicle, with the Blok-DM-2 forming the fourth stage for GTO insertion. The Blok-DM-2 leave two small auxiliary propulsion units in GTO (240-361km perigee, 35,704-35,956km apogee) as well as the upper stage motor in GEO (35699-36180km near circular orbit). One launch anomalously left no propulsion units in GTO, only the upper stage motor in near-GEO. **To date, twelve out of the total sixteen auxiliary propulsion units have decayed, taking 0.5-1.5 years. Undecayed propulsion units either had relatively high perigees (309km, 344km, 348km) or were only recently launched (2008). None of the upper stages have decayed.**

The Proton-M/Briz-M launch vehicle uses two perigee burns in order to achieve GTO. The first of these increases the apogee to approximately 15,000km, with the second further increasing the apogee to achieve GTO. A toroidal propellant tank is separated from the upper stage after either the first or second burn; this leaves both the propellant tank and the upper stage motor itself in orbit.

The specific orbits however depend upon the size of the payload. For less massive (normally domestic) payloads, the tank is left in GTO with a perigee of 338-533km and an apogee of 25,251-37,654km. The upper stage motor performs the GEO insertion burn and hence remains near GEO with perigee of 28,206-37,928km and apogee of 33,679-42,470km. For larger (normally international commercial) payloads, the upper stage is unable to perform GEO insertion, and hence both the tank and the motor are left in different GTOs. In these instances the tank has a perigee of 310-900km and an apogee of 12,092-35,778km, whereas the motor has a perigee of 1,344-14,883km and an apogee of 33,227-35,958km.

Four anomalies were observed during the analysis; one launch deposited the upper stage in a 2370x63,301km super-synchronous transfer orbit, which provided a reduction in the amount of energy required by the payload's on-board propulsion system to reach GEO; one launch carried multiple satellites, and discarded a payload adaptor in a 5157x34,006km orbit; and two launchers did not release their propellant tanks. **To date, only the orbits of two of the propellant tanks have decayed, taking between one and five years. None of the upper stages have decayed.**

During the specified period the Russian Federation also launched two GEO payloads using the Soyuz-FG and the Zenit-3F. Both of these launchers utilised the Fregat upper stage for GTO insertion. The Zenit-3F used the upper stage for both GTO and GEO insertion burns, leaving it in an orbit of 35,707x34,495km. The smaller Soyuz-FG was only able to use the Fregat upper stage for the GTO insertion burn, which left it in an orbit of 311x66,081km. **The Soyuz's upper stage decayed after five months, whereas the Zenit's upper stage remained in near-GEO.**

III.I.VI Sea Launch

Sea Launch's Zenit-3SL was launched 22 times from 2004-2012. The Zenit-3SL used a two-stage Zenit-2S with an upper stage modified Blok DM-SL. The upper stage was designed to eliminate the release of the small auxiliary propulsion units seen on some Proton-K/Blok-DM-2 flights. It was left in a GTO with perigee 132-8529km and apogee 33,926-36,357km. **To date two upper stages' orbits have decayed; these had very low initial apogees of 132 and 134km.**

As of 2008, Sea Launch also conducts commercial launches from the Baikonur Cosmodrone under their subsidiary Land Launch. These launches utilise a reconfigured Zenit-3SL, known as the Zenit-3SLB with a Blok DM-SLB upper stage. Five GTO launches were undertaken from 2004-2012. The launches left the upper stage in GTO with perigees of 1360-11,250km and apogees of 35,623-39,378km. **One upper stage was re-orbited after its mission to a 39,378x34,975km orbit. No upper stages have decayed.**

III.I.VII United Sates

From 2004-2012, the United States government launched GEO payloads utilising the Atlas, Delta and Titan launch families. Information on twelve of the launches during this period was available; 2xAtlas 2AS, 1xAtlas 3A, 6xAtlas V and 3xDelta 4M+(4,2). Each of these missions left a single upper stage in GTO. The Atlas 2AS/3A Centaur Motors had perigees of 191-236km and apogees of 35,080-35,534km. The Atlas V Centaur Motor conversely had widely varying perigees and apogees of 110-6,231km and 34,644-85,173km respectively. The Delta 4M had a much higher perigee of 6,595-6,604km, with a near-GEO apogee of 35,127-35,173km. **Three of these upper stages (1xAtlas 3A and 2xAtlas V) decayed from low perigee orbits (110-191km) during periods of between three months and seven years after launch.**

Launcher	Number of Launches	Number of total debris (Upper stages, payload adaptors and fuel tanks); Mission-Related (Including Upper Stages)	Re-entered (inc. both controlled and uncontrolled)	Compliant			Non-Compliant		
				Orbit 1 (low perigee)	Orbit 2 (between LEO and GEO)	Orbit 3 (super-synchronous)	LEO crossing only	GEO crossing only	LEO and GEO crossing
Atlas 3A	**1**	**1**	1	0	0	0	0	0	0
GSLV	**2**	**2**	2	0	0	0	0	0	0
Soyuz-FG Fregat	**1**	**1**	1	0	0	0	0	0	0
Chang Zheng 3B	**4**	**4**	2	2	0	0	0	0	0
Chang Zheng 3A	**8**	**8**	4	0	0	0	4	0	0
Chang Zheng 3B/E	**11**	**11**	5	2	0	0	4	0	0
Chang Zheng 3C	**9**	**9**	4	0	0	0	5	0	0
H-IIA	**4**	**4**	1	0	0	0	3	0	0
Atlas 2AS	**2**	**2**	0	0	0	0	1	0	1
PSLV-XL	**1**	**1**	0	0	0	0	1	0	0
Delta 4M+(4,2)	**3**	**3**	0	0	3	0	0	0	0
Ariane 5	**43**	**83**	5	0	0	0	3	0	75
Atlas V	**6**	**6**	2	0	3	0	0	0	1
Proton-M/Briz-M	**54**	**107**	2	0	34	2	52	17	0
Proton-K/DM	**9**	**25**	12	0	0	0	4	9	0
Zenit-3SL	**26**	**26**	2	0	1	0	2	9	12
Zenit-3F	**1**	**1**	0	0	0	0	0	1	0
TOTAL	**185**	**294**	**43**	**4**	**41**	**2**	**79**	**36**	**89**

Table 2: Orbits of upper stages and mission related debris from GEO launches 2004-2012

III.II Threat to LEO and GEO

The orbits of the generated debris were analysed to determine the threat that they offered to satellites in LEO and GEO based on their apogee and perigee values. Orbits were classified depending upon their apogee and perigee values, as discussed in Section II.II previously. The results are summarised in Table 2 and Figure 4.

Of the seven launch operators, it can be seen that the United States, India and China mitigate the majority of debris generated by their launch vehicles, with 75%, 67% and 59% of all debris generated by their GTO launch vehicles placed in disposal orbits or directly deorbited.

Russia and Japan mitigate a reasonable amount of the debris generated by their launch vehicles (38% and 25%).

Arianespace and Sea Launch performed poorly with regards to upper stage debris mitigation, placing only 11% and 6% of the debris generated by their launch vehicles in disposal orbits.

It should be noted that this analysis does not take into account use of sun-synchronous resonance in launch planning. Some launch providers (specifically the United States and Russia) select the time of day for launches to either capitalise on or avoid these effects, which can result in potentially faster decay times for higher perigee orbits [2].

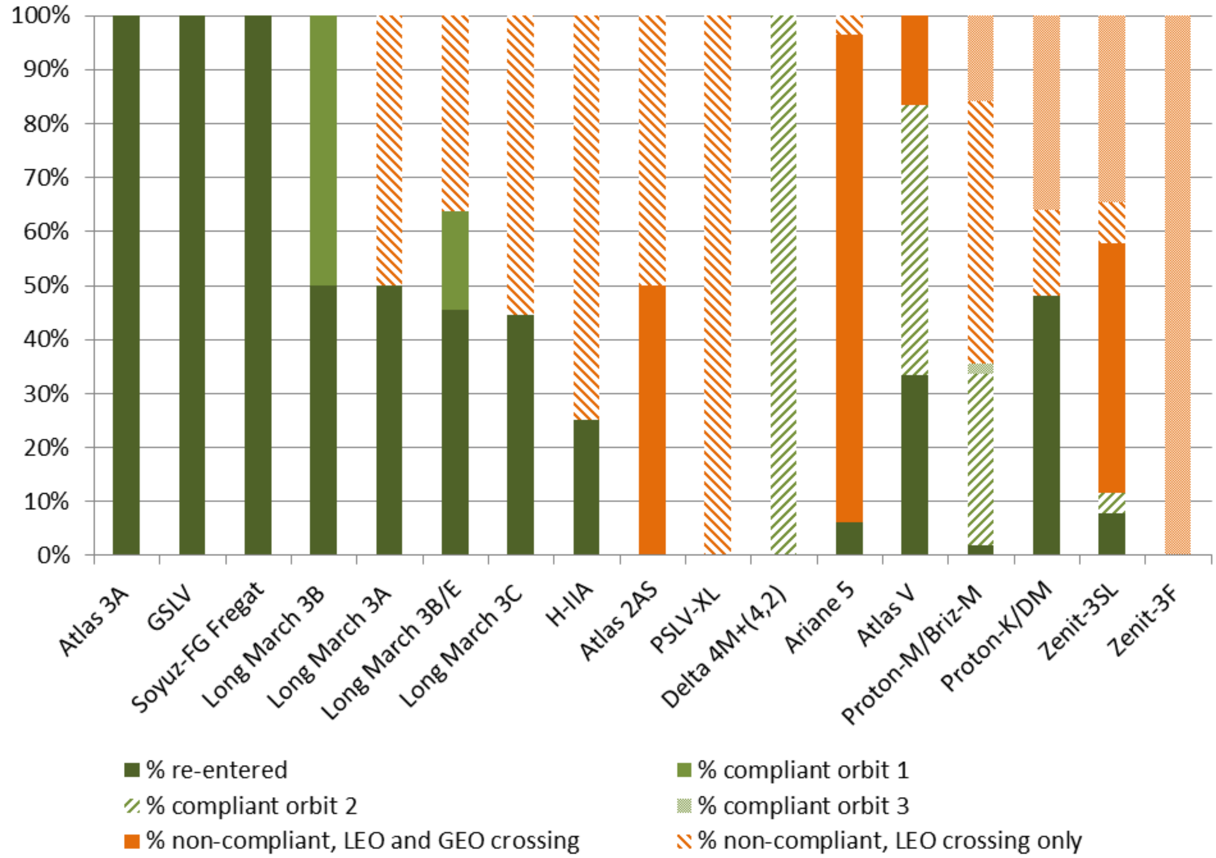

Fig 4: Orbits of upper stages and mission related debris from GEO launches 2004-2012: Launcher breakdown

IV. ORBITAL DECAY MONTE-CARLO

To verify the assumptions in section II.II regarding minimum orbital perigee required to ensure de-orbit within 25 years, a Monte-Carlo analysis with 100,000 samples was run utilising the European Space Agency's Debris Risk Assessment and Mitigation Analysis (DRAMA) tool [8]. Specifically the OSCAR (Orbital Space Craft Active Removal) module was utilised. OSCAR propagates orbits accounting for:

- J2 and J3 zonal harmonics and J22 tesseral harmonics (i.e. the oblateness of the Earth)
- Stationary, oblate, exponential atmospheric drag, with predictions of solar flux
- Lunar and solar gravitational perturbations
- Solar radiation pressure with Earth shadow effects

IV.I Setup Parameters

The orbits were propagated for 100 years or until re-entry, whichever occurred first. Re-entry was assumed to occur at 120km altitude.

The software OptiSLang provided an interface with OSCAR to run the Monte-Carlo simulation. Latin hypercube sampling with normally distributed and uniformly distributed data was utilized for this simulation. Latin hypercube sampling is a statistical method that ensures that the entire probability space is sampled evenly. The input parameters for the run are shown in Table 3.

IV.II Simulation Results

100,000 upper stages with random physical and orbital parameters were simulated in the Monte-Carlo analysis. 97,447 simulations successfully completed, with the remaining failing due to invalid input parameter outliers at the edges of the normal distribution (e.g. negative mass, apogee being lower than perigee, invalid solar radiation coefficient).

Figure 5 shows the results of the Monte-Carlo simulation as grouped by various orbital and physical parameters. For some parameters, the results are further grouped by initial orbital perigee. The results are discussed in more detail in the following sections.

	Parameter	Min.	Max	Mean	Std. Dev
Physical Parameters	Mass (kg)	-	-	2932	951
	Mass/Area (kg/m²)	-	-	201	80
	Drag coefficient	-	-	2.50	0.17
	Solar radiation coefficient	-	-	1.50	0.17
Orbital Parameters	Apogee (km)	-	-	33964	8090
	Perigee (km)	120	600	-	-
	Inclination (°)	0	50	-	-
	RAAN (°)	0	360	-	-
	AoP (°)	0	360	-	-
	Date	2004	2012	-	-

Table 3: Monte-Carlo input parameters

IV.II.I Perigee

As expected, a lower initial perigee altitude leads to a larger probability that the debris will decay within 25 years. At higher perigees, it is still possible for the upper stage to decay within 25 years, but only for certain combinations of other parameters (e.g. when sun-synchronous resonance occurs). **200km is hence suggested as an appropriate, general limit on perigee altitude, which leads to 80% of upper stages decaying within 25 years.**

IV.II.II Apogee

A larger initial apogee altitude was found to lead to more upper stages being compliant with the 25 year decay limit as shown in Figure 5. GTOs with larger apogees generally having large eccentricities. Third body effects, are more pronounced at higher eccentricities, therefore leading to faster re-entry times.

For cases with low perigees (<200km), the initial apogee has minimal effect on the probability of decaying within 25 years. This is because at these low perigees, atmospheric drag will cause the debris to decay before other perturbations display a noticeable impact.

IV.II.III Inclination

At low inclinations, inclination had only a small effect on decay time. However, there is an unusual peak at about 45° inclination. It is theorised that this is due to the interactions of the J2 effect, third body effects and sun-synchronous resonance.

At larger inclinations, third body effects more strongly affect an object's orbit as a function of $\sin^2 i$. However, the J2 effect which determines the occurrence of sun-synchronous resonance depends on $\cos i$. Larger inclinations therefore have lower chances of accelerated decay rates due to sun-synchronous resonance.

These two identified effects work against each other, resulting in the peak at approximately 45° as seen above.

IV.II.IV Other Parameters

Drag coefficient, solar radiation coefficient, RAAN, Argument of Perigee, mass and launch date had negligible effect on the percentage of upper stages that decayed within 25 years.

The specific RAAN, Argument of Perigee and launch date for an upper stage can have a significant impact on that specific stage's decay time. However, as the variables are all interrelated, when considered individually each parameter appears to have only a negligible effect.

The mass/area ratio had a small but noticeable effect on decay time as shown in Figure 5. A larger mass/area ratio led to a longer decay time; or put differently a larger area/mass ratio led to a shorter decay time. This occurs due to a larger area resulting in more drag.

IV. CONCLUSIONS

This paper has analysed the debris that has been placed in orbit by GEO launch vehicles. 294 pieces of debris, including upper stages, payload adaptors and fuel tanks were identified as being generated by 185 individual launches from 2004-2012. It was found that:

- 43 bodies had already decayed and re-entered Earth's atmosphere,
- 4 bodies were in orbits with perigees sufficiently small to ensure orbital decay and re-entry within 25 years of launch,
- 43 bodies were in orbits which did not cross LEO or GEO and were unlikely to decay within 25 years of launch,
- 204 bodies were located in orbits that crossed LEO and/or GEO and were unlikely to decay within 25 years of launch.

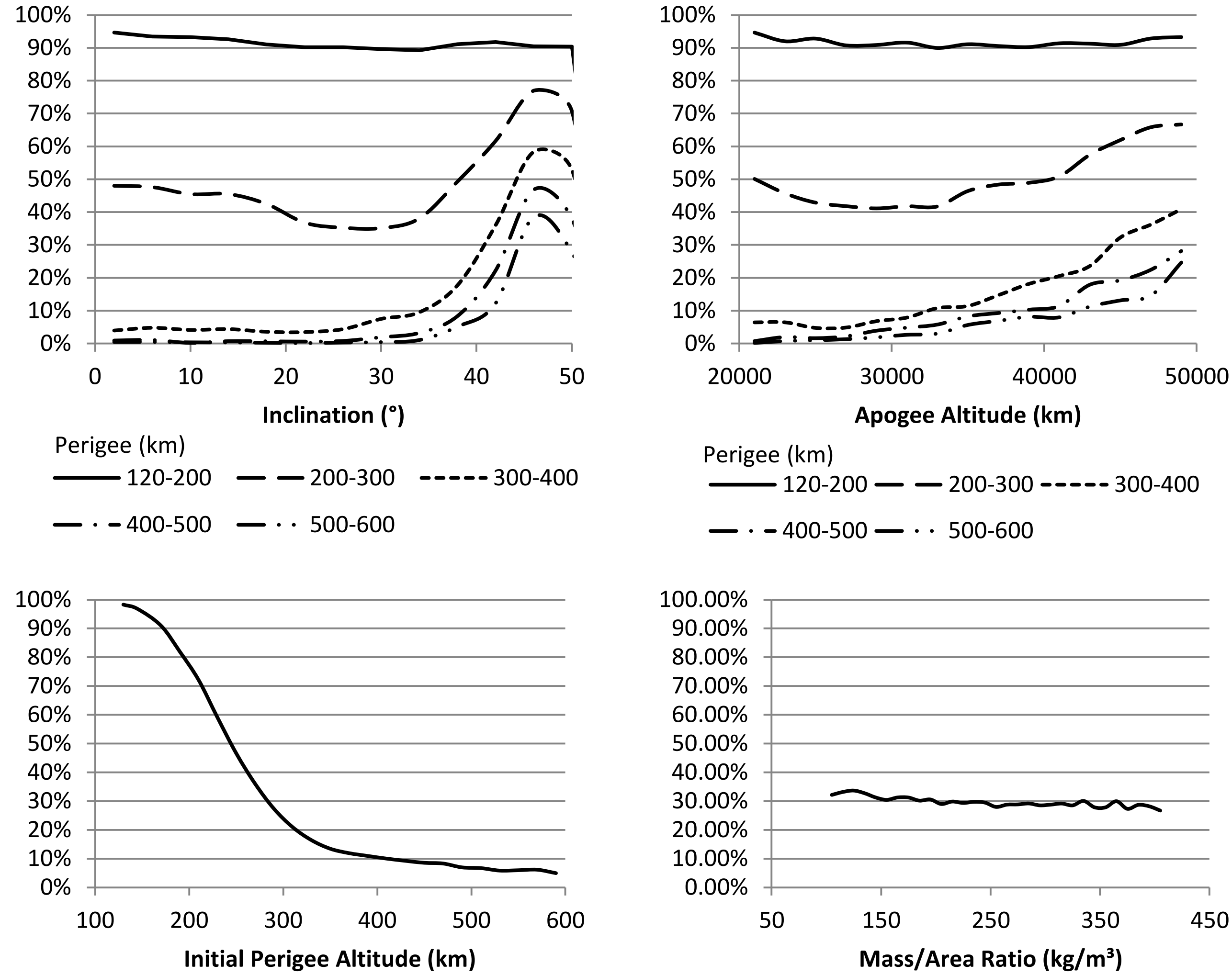

Fig. 5: Probability of debris decay within 25 years for various initial orbital and physical parameters.

This paper has also outlined the results of a Monte-Carlo analysis of decay of GTO upper stages. The perigee altitude was identified as having an extremely strong effect in determining the probability of whether an upper stage's orbit would decay in less than 25 years or not, with 80% of stages with perigees below 200km experiencing decay within 25 years.

At higher perigees, both apogee altitude and inclination had moderate impacts on decay time due to coupled third body, atmospheric drag and J2 effects. Larger apogees resulted in shorter decay times, and inclinations near 45° also had short decay times. The mass/area ratio also had a small but noticeable effect on the decay time, with a larger mass/area ratio resulting in a shorter decay time.

V. REFERENCES LIST

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