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Orbital Debris Threat for Space Sustainability and Way Forward (Review Article)

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ABSTRACT Over the past 60 years, satellite technology has demonstrated its usefulness successfully. However, this usefulness is at stake from a future point of view, due to the well-admitted orbital/space debris threat. This article thoroughly reviews all aspects of space debris issue including causes, amount and sizes of orbital debris, potential threats, counter-strategies with their latest status and related legal issues to highlight the criticality and urgency of the problem. This review elaborates the fact that despite all the worries and threats, the efforts to confront this challenge are considerably insufficient until today. This bitter reality demands for at-least curtailing the number of future launches to ensure the long-term sustainability of space, until the improvement in debris situation. However, contradictory to this necessity, large satellite constellations have been proposed that can drastically increase the existing orbital population in coming years. This approach will certainly not help in improving the space environment in the future; instead, it can worsen the space environment situation as recent studies shows. Also, space resources (i.e. orbital slots and frequencies) are limited to accommodate many more satellite projects from commercial and government organization in the future. So, there is a serious question of how the space industry can move forward to maintain a balance in controlling the future number of the satellite while accommodating many commercial or government space entities. This article also identifies two optimized approaches as a way forward for future satellite projects that can also enhance the effectiveness of space technology in the future.

INDEX TERMS Mega constellations, multi-mission satellite, satellite, space debris, space information network.

I. INTRODUCTION

Since the beginning of satellite history in 1957, at least 9033 satellites have been launched (as of December 31, 2019), according to the United Nations Office of Outer Space Affairs (UNOOSA) as shown in fig.1 [1]. Among the total launched objects, approximately 2200 satellites are currently operational in different orbits around the earth [2], [3].

The satellites launched over the past 60 years have been providing different services, such as communication, remote sensing/earth observation, navigation, weather monitoring, and space exploration, etc. for defense, civil and commercial purposes, as shown in fig. 2 and fig. 3 [4].

This quick outlook of the satellite industry shows that satellite technology has not only successfully demonstrated its usefulness but also enabled us to see, from figs.1, 2 and 3, an escalating trend in the utilization of space technology over the years. From fig.1 we can see that 2017, 2018 and 2019 were three exceptional years in space history by having the most number of launched objects (453, 452 and 583 respectively) ever in history, in a single year.

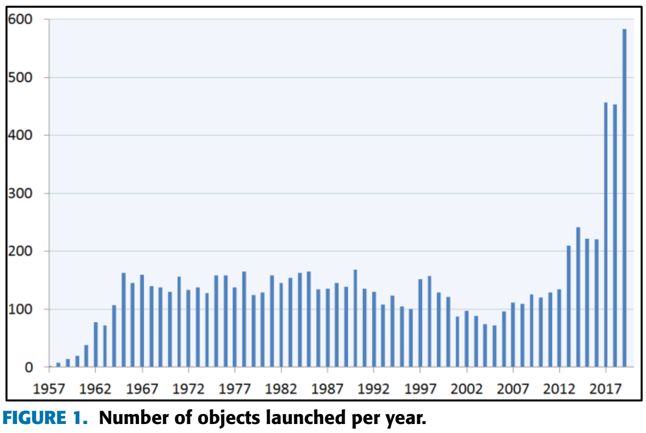

FIGURE 1. Number of objects launched per year.

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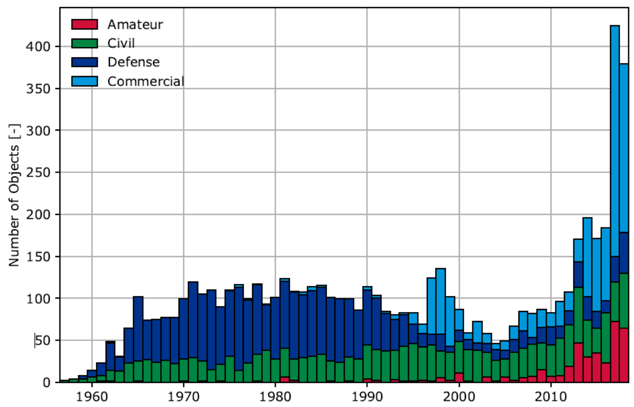

FIGURE 2. **LEO Objects Evolution [4].**

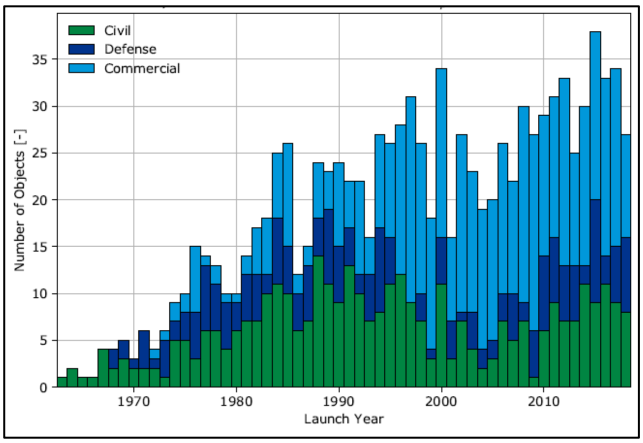

FIGURE 3. **LEO Object Evolution [4].**

Additionally, from figs.2 fig 3 we can observe an apparent rise in the commercial use of space technology. These trends point towards the impending growth of this industry in the future.

However, as a consequence of the progression mentioned above, the number of useless objects in space has also grown over the years. These useless objects are known as orbital debris or space debris. The topic of space debris is not new, and it has been in discussions from at least the past five decades among people involved in space science [5]. The famous scientist Kessler has made a significant focus of his research on the topic of the risk of collisions of spacecraft with particles in space, starting from the early 70s [6]–[8]. The most critical concept introduced by Kessler is Kessler syndrome [9] that says a collision could ignite a deadly avalanche of progressively more orbital debris. However, now, the situation of debris in space is much worse than that in the 80s, as will be seen in the following sections.

The space debris poses a significant threat to operational satellites, due to high orbital velocities (8-10 Km/s) of debris and its uncontrolled nature. Space debris could have a harsh impact on spacecraft and space environment, such as debris about 10cm can merely demolish any operational satellite in a collision and create thousands of smaller danger objects in orbits for several years to decades. Such kind of generated debris cloud increases the likelihood of further collision which could eventually lead to a long-feared Kessler syndrome phenomenon that could make space un-usable for future.

The space community has identified three different approaches to confront with the challenge, i.e., mitigation (to limit the creation of more debris), remediation (to remove debris from orbit), and space situational awareness (to prevent operational satellite collision). However, unfortunately, the practical efforts on these three fronts are insufficient as of today. So, the threat persists till today and therefore, really high stakes of the industry coupled with this issue, demands at a minimum, curtailing the number of future satellite launches. This is necessary to avoid worsening of debris situation, and to ensure the long-term sustainability of space, especially until the improvement in debris situation.

However, contradictory to this demand of curtailing the number of future satellites, satellite technology seems to enter into a new phase where organizations such as SpaceX, OneWeb, Boeing, Telesat, and others have plans to launch more than 15,000 satellites in the near future [10], [11] for providing broadband service. These constellations are also known as big or mega satellite constellations. These mega satellite constellations would change the situation of the space population drastically. Thus, the total number of space-launched objects in the next 10 years may become more than the total number over the past 60 years. This contradictory approach will certainly not help in improving the space environment; instead, it can worsen the debris issue and space environment situation as recent studies shows. This paper provides a detailed review on all fundamental aspects of space debris challenge, including sources, debris population, threats, dealing efforts along with their status, and mega constellations and space debris to emphasize the criticality and urgency of the challenge.

Another significant and related concern is the saturation of space resources such as orbital slots and frequencies that could limit the accommodation of many more satellites in the future. Many countries in the world want to have their independent space resources. We can take the example of a navigation satellite system, where U.S. China, Russia, India, Japan, and ESA are either have or on their way to have their own Navigation Satellite System. Also, projects like mega constellation can ignite other similar large-scale projects for the same or some other application from different commercial and governmental entities. So how to accommodate them all these potential competitors is another associated challenge, while having limited space resources. The financial viability of proposed mega constellations is also an important aspect, because, in the past, similar projects (e.g., broadband constellations from Teledesic, Iridium, and Global star) had failed due to bankruptcy. Hence it is essential to ensure that these proposed projects at-least have sufficient potential customers that could keep these projects survive. Launching thousands of satellites in orbit only for internet service may not be economically viable, especially if the target market is people in undeveloped areas.

Therefore, all these concerns raise a critical question that how to maintain a balance in controlling the future number of the satellite which is essential to ensure the long-term sustainability of space meanwhile accommodating many interested government and commercial space entities together with ensuring the economic sustainability of large-scale projects. The latter part of this article highlights two optimized future approaches; Multi-mission satellites and Space Information Network (SIN) as the way forward for the satellite industry. These approaches are not only suitable to adequately address the highlighted concerns but could also enhance the effectiveness of space technology in the future.

The remainder of this paper is arranged as follows. Section 2 discusses the causes of space debris. Section 3 talks about the numbers and the mass of the debris. Section 4 highlights the threats of space debris. Details of approaches to address the space debris issue are discussed in Section 5. Section 6 discusses space debris in the context of the mega Constellation. Section 7 discusses legal aspects of debris issue. While section 8 identifies possible alternate approaches as a way forward for the future. Finally, the paper is concluded in section 9.

II. SOURCES OF SPACE DEBRIS

Formally, the Inter-Agency Space Debris Coordination Committee (IADC) defines space debris as ''all man-made objects including fragments and elements thereof, in Earth orbits or reentering the atmosphere, that are non-functional'' [12]. This definition includes explosive bolts, exploded fuel tanks, paint chips, upper stage rockets, rocket fairings, defunct satellites, and debris generated from disintegrated and destroyed satellites [13]. The first important matter to discuss regards the sources of this unwanted population.

We know that approximately 9000 objects have been launched into space with the help of approximately 5450 rockets whose last stages and fairings have also become part of the orbiting population. However, to the best of author' knowledge until now, there is no mechanism of bringing back a satellite from space to ground after its retirement has been demonstrated. Therefore, the industry either totally relies on only the natural decay process, or at maximum satellites are moved by propulsive means to an orbit closer to earth before retirement, where earth's drag eventually brings objects back into the earth's atmosphere. This natural process lasts from decades to centuries depending on the orbital altitude. Debris left in orbits below 600 km usually falls back to Earth within several years; at altitudes of 800 km, the time for orbital decay is often in decades, and above 1000 km, orbital debris normally continues circling Earth for a century or more [14]. As most satellites launched above 600 Km, this is the main reason why retired satellites and rocket bodies are still out in orbit after decades. Secondly, international guidelines suggest the proper disposal of satellites into graveyard orbits after

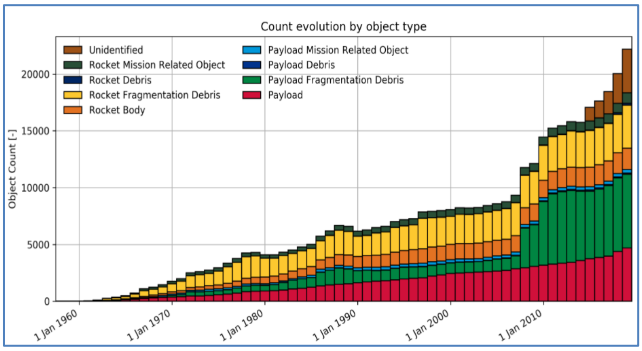

FIGURE 4. Orbital evolutions by object type [4].

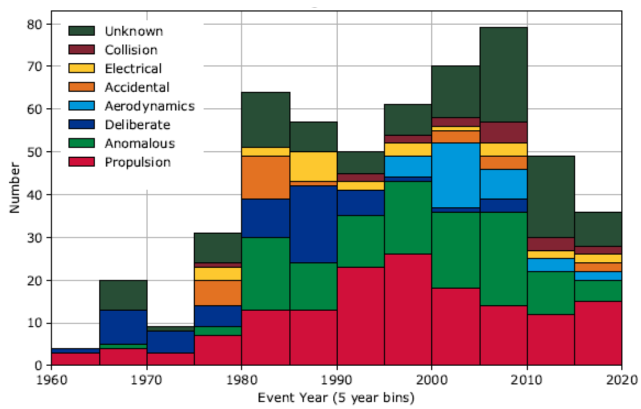

FIGURE 5. The historical trend of fragmentation events per event cause (5-year bins) [4].

the end of a satellite's life, but only approximately 60% of the satellites are appropriately managed [15]. This noncompliance with international mitigation recommendations is another reason.

Fragmentation or disintegration of large-sized objects such as rocket bodies and satellites (either functional or nonfunctional) is the other main contributor of useless objects in earth orbits, as seen in fig. 4 (green and yellow).

There were 489 confirmed on-orbit fragmentation events up to the end of 2017 [4]. The majority of these events were explosions of spacecraft and upper stages, and a few were collisi5ons. The leading causes of many of the explosion events are the energy sources that remain on board, such as fuel left behind in tanks, fuel lines, and batteries. However, for significant numbers of fragmentation events, the reason is unknown, as shown in fig. 5.

Over the past 20 years, on average, 11.6 non-deliberate fragmentation events occurred per year; however, the debris generated by most of these events spent less time in orbit. Thus, after assuming a minimum lifetime of 10 years for generated debris, this number comes down to 2.4 per year for the past 20 years [4]. Another study shows the surprising fact that most breakups occur during the first year of operation in space. Moreover, over 80% of the objects experienced a breakup during the first ten years of service [16], as seen

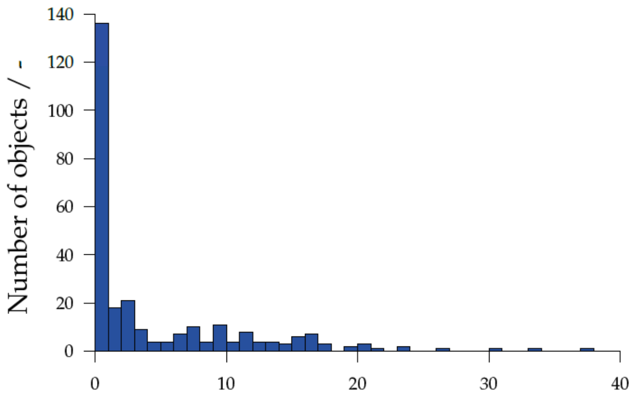

FIGURE 6. Age of object at breakup epoch [16].

Rank	International Designator		Common Name	Year of Breakup	Altitude of Breakup	Cataloged Debris	Debris in Orbit	Assessed Cause of Breakup
1	1999	25	Fengyun-1C	2007	850	3428	2880	intentional collision
2	1993	36	Cosmos 2251	2009	790	1668	1141	accidental collision
3	1994	29	STEP-2 Rocket Body	1996	625	754	84	accidental explosion
4	1997	51	Iridium 33	2009	790	628	364	accidental collision
5	2006	26	Cosmos 2421	2008	410	509	0	unknown
6	1986	19	SPOT-1 Rocket Body	1986	805	498	32	accidental explosion
7	1965	82	OV2-1 / LCS 2 Rocket Body	1965	740	473	33	accidental explosion
8	1999	57	CBERS 1 / SACI 1 Rocket Body	2000	740	431	210	accidental explosion
9	1970	25	Nimbus 4 Rocket Body	1970	1075	376	235	accidental explosion
10	2001	49	TES Rocket Body	2001	670	372	80	accidental explosion
* as of 04 January 2016						9137	5059	

FIGURE 7. Top ten satellite breakups in space history [18].

TABLE 1. Currently tracked orbital population.

Object Classification	ESA Space Debris Office [21]	Space-track.org [22]	Celestrack [3]
Intact in orbit Satellites	5400	5548	5646
Large Rocket Bodies	2921	2231	14807
Debris > 10cm	34000	12344	
Unidentified	3858	137	
Total tracked objects	22028	20460	20453

TABLE 2. Orbital Debris classification by size.

Object Size	Objects Sub-division	Data Source			
		ESA SDA [21]	Space-track.org [22]	Celectrack [3]	Statistical Model (e.g. MASTER) [23]
Large Size	Retired Satellites	3200	About 3248	2837	-
	Rocket Bodies	4007	2230	14807	-
Medium Size	>10 cm	15093	12544		34000
Small size	1cm to 10 cm		-	-	900,000
	1mm to 1 cm-		-	-	128 million

in fig. 6. This tells us that disintegration is not only associated with old or retired satellite; instead, the modern satellite also suffers from this phenomena.

It is important to state here that despite being much lower in numbers, the few collision events (in fig. 5) are the most significant contributor as far as the amount of generated debris is concerned. From the number of debris viewpoint, the worst incident in space debris history was the Fengyun-1C spacecraft collision, which was the target of an anti-satellite (ASAT) missile test in January 2007 [17]. This incident alone accounts for almost 20% of the entire population of cataloged human-made objects in orbit [18]. The other largest event in space debris history was the first ever collision of two intact spacecraft, a Russian (Cosmos 2251) and American (Iridium 33) satellite on Feb 2009 [19]. This event produced the 2nd and 4th most significant amount of debris in space debris history. Fig. 7 lists the top debris contributor events by NASA [18].

Apart from the above sources, operational debris (e.g. lenses cover) known as mission-related debris (fig.4) and some other historical causes of space debris described by ESA in [20] are the other sources of space debris.

III. SPACE DEBRIS NUMBERS

Now we have seen why the unwanted objects in orbit have grown in number; the next important matter is to know how much actual space debris there is in space. What are the sizes and quantity of these debris objects? Moreover, where do they reside in useful orbits around the earth?

The United States' Space Surveillance Network (SSN) is the primary global source of information on trackable space objects. Different online resources show variant but similar figures of the total orbital population obtained from SSN as shown in the table below.

From the table, we can see that the current total orbital population is more than 20,000. On the other hand, the number of useful operational satellites is around 2200 [2], [3]. This means that among the total currently trackable orbital population, only around 11% objects are useful assets and the rest around 18,000 tracked objects (approx 90%) are useless objects and hence belongs to space debris.

We can divide space debris into three main categories based on their size: large-sized (intact retired satellites and rocket bodies), medium-sized (>10 cm) and small-sized (<10 cm) as shown in table 2 below. From table 1 we can see that more than 5000 intact satellites are currently tracked and we also know that only around 2200 satellites are currently operational. This means that around 3000 intact but non-operational payloads and approximately 2000 rocket bodies (e.g., spent upper stages, fairings) are still in orbit. Thus, at least 5000 large-sized debris objects are in orbit around the earth which are regularly tracked. Next, Table 1 also shows that SSN currently tracks more than 12000 (60% of the total) objects of medium sized by SSN. For the small debris, most

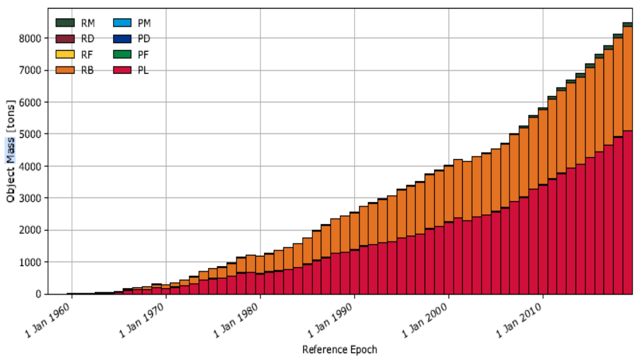

FIGURE 8. **Mass evolution by object type [21].**

of the information is estimated by statistical models, because small debris is difficult to detect from ground-based observations. The most recently updated numbers of small-sized space debris by ESA [23] and others are shown in table 2.

From the mass point of view, among the approximately 8493 tons of current mass that is in orbit, approximately 854 tons (more than 98%) is concentrated in large intact spacecraft (both functional and nonfunctional) and rocket bodies [21] as shown in fig. 8.

About the estimated number of small debris objects, it is important to mention one key point here. The validated historical population of the MASTER model (developed by ESA) is provided up to a specific reference epoch, and it is mostly related to the release date of the model (i.e., May 2009 for the MASTER latest version). However, because many more disintegration events have occurred from that time until today, all of those events must be incorporated in the model for an accurate space debris model. Additionally, the trackable number of debris objects (>10 cm) generated by any disintegration event in the past can vary over time. For example, Fengyun-1C satellite debris cataloged objects in 2007 were 1000, which is 3438 in 2018 according to SSN, i.e., an increase of 3.5 times for a period of 10 years [16]. There is also a direct effect on the object numbers in the 1 cm and mm regime. Therefore, the number of estimated objects larger than 1 cm has increased from 60000 (in 2007) to 204000 (2018) for that particular event. There are similar cases for other historical events. Thus, after updating both the fragment numbers of past events and the incidents that occurred after 2009, the estimated population of small size debris objects in the LEO region (200-2000 km) is significantly higher than that assumed initially in 2009 (See fig. 9) [16].

Thus, the estimated small debris numbers might always increase whenever new disintegration events are added, and historical events are updated in the statistical models. From fig. 9, it can also be seen that the most populated region is approximately 800 km to 1000 km.

IV. IMPACT AND THREAT OF SPACE DEBRIS

After knowing about the causes and population of space debris, it is now important to highlight the threat that space debris poses to the operational spacecraft and space

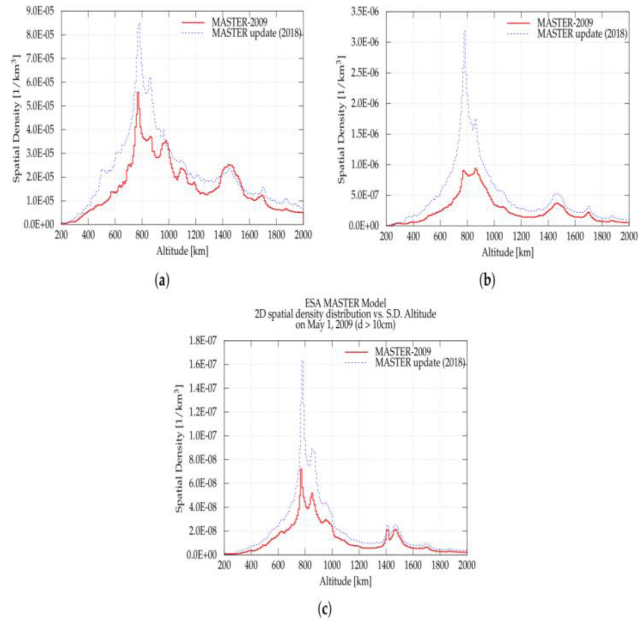

FIGURE 9. **Evaluation of spatial density distribution in LEO for different size regimes. (a) > 1 mm; (b) > 1 cm; (c) > 10 cm. [16].**

environment. Let us begin with the large debris; because space debris is uncontrolled bodies that revolve with high velocities in orbit, if they collide with any operational spacecraft, the result would be simply none other than the destruction of spacecraft and the generation of thousands of medium size and millions of small size debris. This outcome occurred when an operational Iridium 33 satellite was hit by a retired Cosmos 2251 satellite at a relative speed of approximately 10 km/s (22,300 mph) [24]. However, this incident was among the rarest incidents in space history, and currently, with the assistance of SSN, a collision avoidance maneuver can be performed with prior warning. Thus, the probability of such an incident occurring again is still very low.

Conversely, it is essential to know that if any single such incident occurs for any reason, then such a collision can drive the long-feared ''Kessler syndrome'' process, which means that each collision between objects generates more space debris, which increases the likelihood of further collisions [9]. Moreover, if this phenomenon occurs, space will eventually become unusable. The study shows that doubling the number of objects will increase the collision risk by approximately four times [25]. It is estimated that if two 1000-kg rocket bodies collide in LEO, the collision will produce approximately 4,000 trackable objects and more than 100000 non-trackable fragments [26]. There could be many possible reasons for such an accident, such as the collision of a retired satellite with another retired satellite or a large rocket body. Some other hypothetical reasons for such a collision are also discussed in later sections, but the critical point to state here is that even one such incident could have extremely severe consequences on the space environment.

For the medium and small debris threat, it is essential to state that regardless of how small the size is of the space debris, a collision can cause significant damage to any useful space infrastructure because of the very high velocity (typically 8-10 km/s), which is usually termed hypervelocity. Hypervelocity impacts by millimeter-sized objects could cause local damage or disable a subsystem of a satellite. Collisions with debris larger than 1 cm could disable an operational satellite or break up a satellite or rocket body. Impact by debris larger than 10 cm can lead to the complete destruction of a spacecraft and generation of a debris cloud [27]. Some studies elaborate on the risk of hypervelocity impact of small particles, especially on the degradation of performance of the electrical systems of satellites [28]–[30].

Apart from the theoretical and experimental studies, many practical examples in space history demonstrate the threat of small-sized space debris to space missions. Among them, a few examples are the following: the Sentinel-1A satellite incident [31], puncture of a STS-118 Radiator [32], damage impacts on the Hubble Space Telescope [33], [34], Japanese ADEOS 2 incident [35], U.S. Space Shuttle Endeavour impacts [36] and the International Space Station [37]. These events tell us that a satellite faces many such small debris collisions in the real environment. It should be noted here that many of these incidents occurred before the Fengyun-1C incident (when the population of space debris was not as high) and at an altitude much lower than densely populated regions.

One aspect that should be understood is that there could be many more small debris incidents that were not reported because satellite operators are not bound to report every anomaly. It may be damaging for them to report them, especially from the business point of view. Even if every anomaly is reported still, we cannot be confident that the reason behind anomaly is any collision with small debris or any other technical failure or malfunctioning of onboard devices or components. Therefore, the anomalies that partially damaged a satellite or its subsystem cannot be quantified. Concerning the frequency of the collisions, the number of medium-sized object collisions over 45 years is approximately 2.82 per year on the average, whereas the small debris collision interval is in between 6 and 10 days for the interval 2000-2015 [38].

The environmental impact of a collision depends on both the total mass involved and the altitude at which the accident occurs [39]. Analysis of the Iridium-Cosmos Collision and Fengyun-1C shows that the higher the altitude of a satellite is, the more severe the potential threat to the environment because the debris will remain in place for a longer duration [40], [41]. Therefore, knowing the object population with altitudes in LEO is also essential. Fig. 10 shows the mass and density distribution of objects (trackable) with given heights in LEO [42]. Fig. 10 validates that the most populated region is approximately 800-1000 km, as mentioned in the previous section.

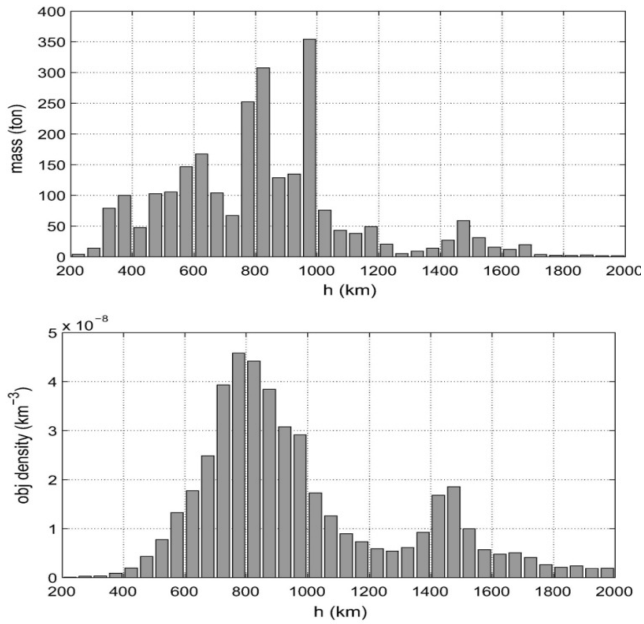

FIGURE 10. Mass and density distribution of LEO objects [42].

V. CONFRONTING THE DEBRIS CHALLENGE

There are three approaches identified by the scientific community to address with the space debris challenge: mitigation (to limit debris generation), space situational awareness (to prevent collision with operational satellites), and remediation (to remove the debris from orbits).

A. MITIGATION

The objective for the mitigation approach is to reduce the future collision probability by limiting the number of debris objects in the regions that are already densely populated [43]. IADC and the United Nations Committee On the Peaceful Uses of Outer Space (UNCOPUOS) have published their mitigation guidelines in 2002 and 2007, respectively, [12], [44]. The main points of these guidelines include the following:

1. Limit debris released during normal operations.
2. Avoid intentional destruction and other harmful activities.
3. Minimize the potential for post-mission breakups from stored energy.
4. Minimize the potential for breakups during operational phases.
5. The proper end of mission disposal of spacecraft; in GEO to graveyard orbit and in LEO to an orbit that can ensure a maximum of a 25-year post-mission orbital lifetime.

However, studies show that the global compliance rate of the 25-year post-mission guideline is 59% between 2000 and 2013 [15], [45]. Among these, the vast majority are naturally compliant due to orbit, and only 10% of spacecraft performed a successful deorbit maneuver [15]. The other finding of this study was that there was no clear trend of improvement concerning global compliance with the mitigation guidelines over the years. Another study determined that among 103 spacecraft in geostationary orbit that reached the end of their life between 1997 and 2003, only one-third were disposed of to a graveyard orbit [46]. A similar situation is a case for small satellites, where among the CubeSats launched between 2003 and 2014, every 5th satellite violates the international guidelines to deorbit within 25 years of retirement [47].

The fundamental flaw that has been observed with these mitigation guidelines is that they are voluntary and non-binding; therefore, they do not carry any legal force with them. Hence, member nations of IADC and the U.N. are only encouraged to incorporate these guidelines into their laws and regulations. For this reason, we have seen noncompliance and evident violations of international mitigation guidelines such as the deliberate destruction of the satellite through missile in 2008 by U.S.A [16] and by India on 28th March 2019 [48]. As a result, the level of compliance with the mitigation guidelines is not satisfactory at all.

B. ACTIVE DEBRIS REMOVAL (ADR)

Space debris mitigation measures, if strictly and thoroughly applied, are even then still found to be inadequate to stabilize the debris environment (while the actual current compliance is around 60%). Long-term debris environment projection indicates that even a complete halt of launch activities will not result in a stable LEO debris environment [49]–[51]. An official IADC study of six different models to assess the stability of the current LEO also suggests that remediation measures, such as ADR, should be considered to stabilize the future LEO environment [52]. Additionally, from fig. 11, it can be seen that the orbital population is continuously increasing, not only because of new satellites being launched but also because in-orbit fragmentation events are continued despite the presence of mitigation guidelines since 2002 [53]. The large-sized debris objects in orbit provide a potential source for tens of thousands of fragments in the future. We have seen that collisions such as the 2007 Chinese satellite and Iridium-cosmos in 2009 increased the population drastically (noticeable in below figure), which means that a single such collision event can destroy the mitigation efforts of decades. Therefore, the need to remove a potential collision and fragmentation contender, i.e., large-sized retired satellites and rocket bodies, has been realized as the only way forward for controlling this situation [54].

Some studies suggest that removing five to ten large objects per year from the LEO region can prevent the debris collisions from cascading [55], [56]. For an active removal of space debris, the primary task is to select which objects should be removed first. The following principles need to be applied for the efficient selection of removal targets, and this strategy can be used to generate a criticality index of the debris objects [25]:

- The selected objects should have high mass.
- Should be in densely populated regions.
- Have a large cross-sectional area.
- Should be at high altitudes (i.e., having a longer orbital lifetime of the resulting fragments).

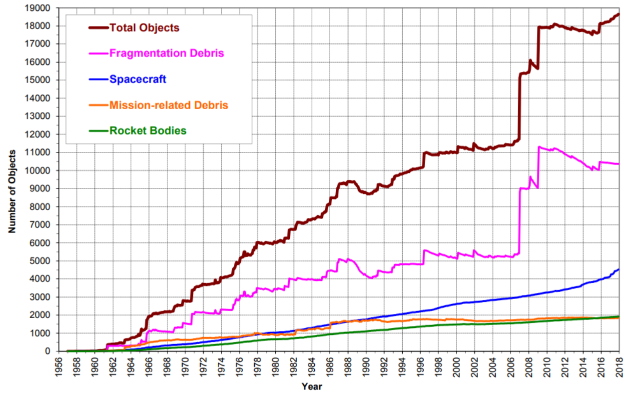

FIGURE 11. Evolution of the orbital population [53].

There is much work already done on this aspect as many studies are there with the same objective of prioritizing retired satellites and rocket bodies for ADR based on criticality [57]–[62].

After the selection of the target, the next most crucial objective is how to catch and remove that object away from the populated region. Many methods and systems have been proposed by researchers for removing space debris [51], [63]–[67]. Some of the most famous removal concepts are based on directed energy, tethers (momentum exchange or electrodynamics), aerodynamic drag augmentation, solar sails, auxiliary propulsion units, retarding surfaces and on-orbit capture (Johnson, Nicholas L. Klinkrad, 2009). Among the proposals, some are more realistic and practical than others. For example, an assessment of these methods showed that the net, space-based laser, and robotic arm methods appear to be the most promising [69]. While some of the ADR proposals are to remove single larger-sized debris objects, there are also proposals to remove more pieces to save on the mission costs [51], [70], but a more extended ADR mission will also increase the collision probability with the ADR mission itself [71]. There is also a proposal that suggests the repositioning of large debris objects from crowded regions to a relatively less crowded altitude with a smaller lifetime [42].

Many studies provide a good technical review of ADR proposals [67], [72]–[75]. However, without going in the technical details of the ADR proposals, the bottom line is that despite all of the discussion and research on ADR, until now, not even a single debris item has been removed from orbit. The reason for this disappointing result is that there are many technical challenges of the ADR missions (such as less information on the kinematics of the debris) [76]–[78]. Additionally, many other nontechnical but vital issues are also present. For example, who is going to invest in the ADR missions? While mitigation guidelines are not binding and there are many violations, then from the viewpoint of a country that would fund for ADR, cleaning the space debris does not make much sense. Because without a general broader global consensus, other space nations may have the least concern or are even they might be creating space debris through incidents like ASAT missile test. Studies [79]–[81] elaborate many significant political and legal challenges of less practical demonstrations of ADR despite being realized as an essential future need.

The most recent practical advancement toward space debris removal is mission RemoveDEBRIS, which is led by the Surrey Space Centre (SSC) at the University of Surrey, which was launched into orbit from the International Space Station (ISS). Currently, the experiments of RemoveDEBRIS project are underway. However, the experiments are being conducted below the orbit of the ISS [82], which means that even if successful, it will not improve the situation of the concerned populated regions; instead, it will only demonstrate that technologically it is possible to perform ADR. The other significant effort is End-of-Life Service (ELS-d) by Astroscale, which is a spacecraft retrieval service for satellite operators and is scheduled to launch in late 2019 [83].

C. SPACE SITUATIONAL AWARENESS

Until the improvement of orbital debris situation through mitigation and remediation, Space Situational Awareness (SSA) is the essential strategy to ensure the protection of useful operational satellites from space debris collisions. SSA means the tracking of orbiting satellites and debris continuously using ground-based radar and optical stations in such a way that the orbital paths of debris can be predicted so that satellite operators can avoid possible collisions with space debris by maneuvering the operational spacecraft in advance from the debris' predicted orbit.

We already know that the SSN, with the help of ground infrastructure, is capable of tracking space objects and therefore is a principle system that performs the same job of providing potential warnings of any collisions. The SSN uses approximately 30 different systems, and they are of four main types: satellites, optical telescopes, radar systems, and supercomputers. Observation data are fed to supercomputers, and supercomputers continuously check the orbits of all satellites and cataloged space junk to see whether there is any risk of future collisions, days in advance [84]. The U.S. military's Joint Space Operations Center (JSpOC) is responsible for SSN and is currently providing warnings, 72-hours in advance, to the satellite operators for close approaches within 1 km for LEO and 5 km for GEO [24].

One can wonder that if such a warning system was already present, why would two satellites (Iridium and Cosmos) collide? The fact is that as a result of the sheer number of warnings and the inaccuracy of the data provided by the U.S. military, the warnings were stopped before the collision in February 2009, and therefore, there was no warning issued of a potential collision before the incident. After the collision, JSpOC has expanded high-accuracy screenings (used for human spaceflights) to cover all of the active satellites that are in Earth orbit [24].

However, there are still many limitations with the current state of SSA through SSN. Among them, the first and most significant weakness is that SSA can track and catalog objects above 10 cm only. Thus, a collision with debris less than 10 cm cannot be predicted and avoided. While we are already aware of the threat of debris smaller than the 10-cm size, it is vital to have systems through which we can obtain motion information on smaller debris objects. The bulletin [85] of ESA highlights the different aspects of detecting the tracking and measurement of small debris.

Another limitation of the current SSA is that there is reduced space surveillance coverage of SSN in the southern hemisphere, which compromises SSA. However, the U.S. plans to launch the Space Fence project by the end of 2019 and its second site in 2021 in Western Australia, and thus, this approach could overcome this southern hemisphere coverage limitation. Besides, this space fence project also claims to improve the space surveillance dramatically, due to its ability to detect small objects in LEO up to approximately 1 cm. The project is therefore expected to grow the current catalog objects up to 100,000 depending on the background assumptions [86].

Smaller space debris (mm-sized) cannot be detected or tracked by ground-based observations, and it can be said that detailed debris modeling is becoming an urgent task for sustainable space development, considering the small debris threat. For modeling, in situ measurements are also important, and that is the reason that we have seen some in situ measurements, for example, the DEBIE (Debris In-orbit Evaluator) sensor and DEBIE2 [87], [88]. Returned exposed surfaces from spaceflights, such as the Long Duration Exposure Facility (LDEF), Space Shuttle, and Hubble Space Telescope also helps in modeling small fragments. However, these examples are limited in number; therefore, they are not sufficient to thoroughly enlighten us on the real situation of small-sized debris in orbit. Several debris evolutionary models have been developed. The predictions performed with such models, in particular beyond a few decades, are affected by considerable uncertainty. These uncertainties are the result of a significant number of endogenous and exogenous variables [89]. Some of these variables are under the relative control of modelers, while others are entirely out of the control of modelers [89]. For example, for accurate modeling, it is also essential to know the precise times of the breakups. Authors in [90] provide a precise time estimation of on-orbit fragmentation, but there are not many effective methods that can estimate the time precisely.

Among the more recent development for improving SSA one was the project Space Debris Sensor (SDS), which was installed on ISS on January 1, 2018. However, unfortunately, SDS suffered a failure to recover telemetry on January 26, 2018, and the recent update tells us that all identified recovery options have been implemented, attempted and failed; and no further recovery attempts are planned or scheduled [91]. There are some other proposals to increase the SSA, such as [92], [93], but perhaps they are still on paper only. One in situ measurement project with practical advancement is the IDEA of Kyushu University, which uses a small satellite constellation for in situ measurements [95], [96]. However, unfortunately, the first IDEA satellite was lost in a launch, and thus, we must wait until the next IDEA satellite launch.

Recently, about the surveillance of debris in GEO, a new idea to observe debris in GEO arc by the use of a small satellite in a low polar orbit, equipped with a Schmidt telescope, is presented in [96]. This concept gives us some other ideas as well, for example, we could see an opposite approach in the future, which means the use of satellites in MEO for surveillance of debris in LEO.

Even if we have a comprehensive, detailed and faultless SSA system, a tradeoff of the collision avoidance maneuver is that it consumes fuel, and a significant number of collision avoidance maneuvers may reduce the satellites' operational lifetimes noticeably. Additionally, the dependence of the whole space world on a single system which is under the control of the U.S. defense also raises many political reliability questions especially if there are no legal obligations for the U.S to provide such a warning to space nations always.

VI. MEGA CONSTELLATION AND SPACE DEBRIS

From all the discussion to this point, we can confidently conclude that despite all potential threats and high stakes, the efforts to confront with debris challenge are significantly inadequate to improve the debris and space environment situation. So, on the one hand, efforts to deal with the challenge needs to be enhanced radically; on the other hand, it is logical to put control on the future number of satellite launches. Hence curtailing the number of future launches is also very critical in ensuring long term sustainability of space, especially until the improvement of debris situation through remediation measures such as ADR.

But in contrast to this requirement of curtailing the number of future launches, space technology and applications are going to enter into a new phase in the near future, because some commercial companies filed for a U.S. Federal Communications Commission (FCC) license for non-geostationary communications satellites to provide Internet services to users from space [11]. Some of these companies have already obtained approvals, while others are waiting for approval. The idea of the space-based Internet is not new. In the past, Teledesic had a similar plan, which ultimately failed in 1990 due to bankruptcy. However, there are reasons to believe that these satellite broadband projects could obtain success. The reasons for the potential success of these projects include broader coverage compared to its ground contenders, especially coverage over areas where laying ground communications infrastructures such as fiber and cable is a difficult job, such as rural (undeveloped) areas, sea, mountains, and disaster-affected areas. Traditional satellite-based internet services such as Viasat or Hughes Net rely on satellites in geostationary orbit, which causes high latency when using satellite Internet. O3b uses satellites in MEO to provide faster Internet services. However, the proposed satellites in LEO could provide latencies that are comparable to wired cable services to enable users to have much faster and smoother Internet experience. Additionally, SpaceX claims that its satellites will deliver gigabit speeds.

Despite the potential as mentioned above, the big question on their impact on the space debris environment has also become the most critical concern for every space concern entity. Concerning the space debris collision threat, SpaceX and OneWeb have both selected an altitude (above 1100 km) that is less densely populated. Additionally, both have told the FCC that their constellation will comply with international mitigation standards, such as reentry to earth Earth's atmosphere being accomplished within approximately one year after completion of their mission. Additionally, OneWeb's Orbital Debris Mitigation Plan reports that the probability of a OneWeb satellite becoming disabled as a result of collisions with small debris is 0.003, while SpaceX stated that "there is approximately 1% chance per decade that, any failed SpaceX satellite would collide with a piece of tracked debris" [97].

Apart from the claims of SpaceX and OneWeb, some studies have been performed to understand the effect of these constellations on the space environment and the reliability and collision possibilities of the mega constellation with this populated debris environment [10], [98], [99]. A study shows that there is substantial uncertainty in the prediction of the reliability of mega constellation satellites, with considerable risk to the space environment. This is because much of the information about mega constellation satellites, including the detailed designs, is not available [10]. Another recent study shows that a high probability exists for the occurrence of at least one catastrophic collision, i.e., 5% for OneWeb and 45.8% for SpaceX constellations, during an operational phase of 5 years [97]. The study [98] showed that it was estimated that an impact of approximately 3 cm in diameter would lead to a catastrophic collision of a OneWeb sized satellite, while the proposed size of a SpaceX constellation satellite is larger than a OneWeb satellite. The study also shows that the satellites in the constellation would have a 35% probability of fragmenting during the described mission lifecycle catastrophically. Thus, what we can confidently say is that despite the claims of mega constellation proposers, there are serious concerns, doubts, and uncertainty about the interaction of debris and satellites in mega constellations that exist.

NASA has recently completed a parametric study to understand how significantly proposed large satellite constellation can contribute to the existing orbital debris problem. The objective was to quantify the potential negative debris-generation effects from mega constellation to the LEO environment and provide recommendations for mitigation measures [99]. The results show that for the 25-year decay rule at the end of their missions, with a 90% reliability of post-mission disposal, the additional debris population increase with respect to that without these big constellations is approximately 290% in 200 years. Even with 95% post-mission disposal reliability for the mega constellation spacecraft, the additional population increase is still close to 100% as shown in fig.12. While with 99% post-mission disposal, the additional population increase is reduced to 22%.

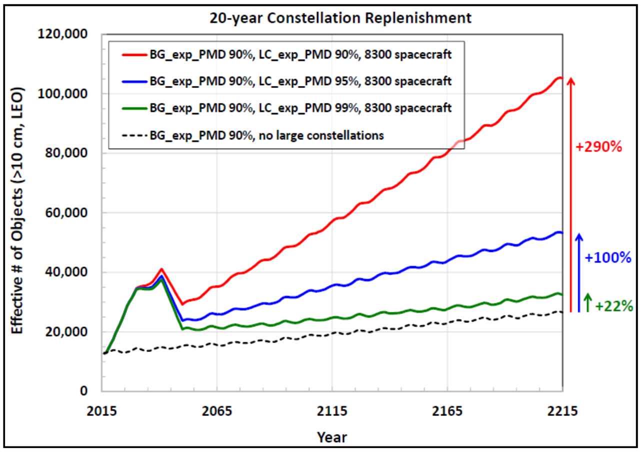

FIGURE 12. Debris population projections for 200 years with and without mega constellation [99].

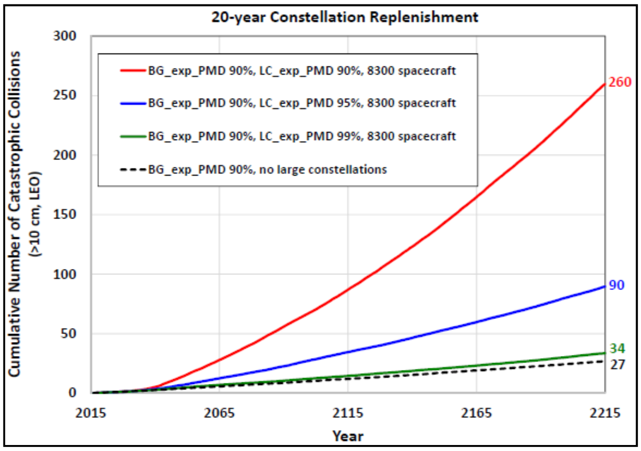

FIGURE 13. Predicted number of catastrophic collisions [99].

The cumulative numbers of catastrophic collisions are shown in fig. 13, which shows that in 90% scenario a non-linear increase from 27 to a total of 260 catastrophic collisions in 200 years. In 95% scenario, the total number of catastrophic collisions is 90 in 200 years. Based on results from this study NASA recommended that 99% spacecraft PMD reliability is needed to mitigate the serious long-term debris generation potential from mega constellation similar in scope to the study scenarios.

Besides this, there are many aspects which are nevertheless not under the control of anyone, such as a collision of two large retired satellites or rocket bodies. Additionally, there could be many hypothetical scenarios that could lead to a catastrophic collision. For example, the accuracy error in tracking the debris data thorough SSN, the human or technical errors in estimated the timing of the collision threats, failure in a collision avoidance maneuver by satellites due to onboard control problems or anomalies in the propulsion system, and any deliberate political reasons and so on. Additionally, so far there is no legal restriction of using ASAT. So, what if the use of ASAT continues in future just like India did recently? Also what if the war between two advanced nations extends from ground to space that could result in the use of ASAT weapons to destroy the satellites of enemies? Thus, the argument is that there could be any reason for a catastrophic collision, and one or more such accident could make the situation worse, which would have severe consequences for everyone especially such as Kessler syndrome.

Hence, we can say that mega constellation projects, despite their potential benefits are not going to help in improving debris and space environment in any way; instead, fair chances of worsening of debris and space environment can be envisioned from the above discussion. It might be negligence if we deliberately continue to underestimate debris challenge and its potential threat to the space environment in the future.

VII. LEGAL AND REGULATORY ISSUES

So far the paper has mostly covered historical and technological aspects of space debris issue. However, there are many associated political, legal, and regulatory issues concerning debris topic that have to be considered to have a complete understanding of the problem and its solution. That is why extensive research and discussion is already there on this non-technical side of space debris issue. This section will briefly review these political, legal and regulatory issues.

A. BACKGROUND FOR THE LEGAL FRAMEWORK

From the literature review, one can easily find that there are many efforts of individual nations, space agencies, or regional countries to achieve a legal framework towards long term sustainability and peaceful use of space. Such as authors in [100] presented the legal and political analysis of China's approach towards space sustainability. The author in [101] discussed the role of India in the UN for this cause. Some authors discussed the approaches of emerging space nations [102] such as Brazil, Colombia, and Mexico towards long-term sustainability in [103]. The author in [104] proposed the role of regional organizations such as APSCO in having a legal framework. China and Russia proposed a draft treaty for demilitarization of outer space known as PPWT. Also in 2006, France, Germany, Italy, United Kingdom, and ESA all signed the European Code of Conduct for Space Debris Mitigation which is similar to those of the IADC and COPUOS.

The major problem with all the above individual or regional efforts is that until the agreement of all the space-faring nations on space debris, the efforts will remain less effective. So, the consensus must be on an international level to be more productive. There are efforts for such a broader and global level right from the early 1980s. For example, the topic of the prevention of an arms race in space was introduced by USSR into the agenda of the 36th UN General Assembly (UNGA). They had also submitted a "Draft Treaty on the prohibition of the stationing of weapons of any kind in outer space. This draft treaty remained unsuccessful, but the UNGA adopted a resolution on the Prevention of an Arms Race in Outer Space (PAROS) in 1981. Since 1994, COPUOS has

TABLE 3. United nations treaties for space activities.

S. No	Treaty	No of Countries signatory or with Ratification [105]
1	The 1967 Outer Space Treaty (OST) [106], sometimes referred to as constitution of space law	132
2	The 1968 Rescue Agreement [107]	124
3	The 1972 Liability Convention [108]	119
4	The 1975 Registration Convention [109]	76
5	The 1979 Moon Agreement [110]	22

the mandate for disarmament issues and ways and means of maintaining outer space for peaceful purposes. COPUOS and subcommittees periodically meet to review, discuss topics related to the peaceful use of space.

B. EXISTING SPACE LAWS

Five United Nation treaties providing the legal framework for space activities are mentioned in table 3;

Apart from the above-mentioned united nation treaties, there are numbers of agreements signed or ratified by many countries. Some of those have more acknowledgment than UN treaties such as "Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water" [111] and "Agreement Relating to the International Telecommunications Satellite Organization (ITSO)" [112] are acknowledged by 137 and 150 countries respectively [105].

The legal issues related to space debris topic can have two sub-divisions; i.e., related to debris mitigation, related to debris remediation.

C. LEGAL ISSUES RELATED TO DEBRIS MITIGATION

We have seen that mitigation efforts are primarily to slow down future debris generation. The center point of the mitigation guidelines is to stop the deliberate creation of debris; in particular use of ASAT is the most significant source of debris. One central dimension of ASAT often discussed is concerned with the strategic and security circumstances and is a part of space militarization topic [113], [114]. There have already been many discussions on space and weaponization topic [115], [116]. However, the other primary dimension connected with the environmental effects of ASAT is very crucial, as the consequences are severe for everyone concern with the peaceful use of space [117]. The strategic and security dimension is generally considered more critical and hence dominates the environmental aspect often. This is why we have seen that some states have opposed any action aimed at amending the existing space law rules dealing with military uses in space. Considering the adverse environmental effects of ASAT, logically there must be some "legal" restriction on the use of ASAT in particular and space militarization in general to ensure the peaceful use of outer space.

If we see the existing space laws from debris mitigation or ASAT perspective, The OST is the only UN treaty limiting the weaponization of outer space. But there are two significant deficiencies of outer space treaty. First is that this prohibits only the deployment of nuclear weapons and weapons of mass destruction (WMD) in outer space, which means there is not any restriction of deploying conventional weapons on objects in space (e.g., satellites). Secondly, the issue of the use of force from Earth against space objects (e.g., using ASAT) is unaddressed in the Outer Space Treaty.

Currently, there are no clear regulations agreed between the space-faring nations about space debris mitigation, including ASAT [118], apart from non-binding mitigation guidelines from IADC and COPUOS. Therefore, until now, there is a deficiency of the law or international treaty that prohibit testing, deployment, and use of space-based weapons and ASATs [117] for environmental protection. This deficiency leaves the door open for states to develop conventional orbital and ASAT weapons. This is why we have witnessed the use of ASAT, even recently [48]. Also, if conventional weapons are deployed on satellites, obviously they will become a military target for the enemies; hence, ASAT might also be used more frequently probably in that particular case. Also, spy satellites and the so-called strategic-warning satellites which detects missile launch in real-time could become ASAT targets for the enemies. While we know some countries already demonstrated their capability of ASAT, such use of ASAT could be terrible for the space environment. Therefore, international space laws need to be updated to address space militarization debate by possibly applying legal restrictions on the weaponization of space to ensure the peaceful use of space.

The mitigation guidelines either from IADC or those currently in the process of finalization of COPUOS [119], are not legally binding and do not create rules for international law, so the violation would also not impose responsibility. The approach of COPUOS so far is to encourage states to incorporate these guidelines in their national laws, applicable to government and non-government both entities as binding within that state [120]. Therefore, there are many states which have incorporated these guidelines in their national laws such as Argentina, Netherlands, Poland, Switzerland, Spain, etc. Also, other tools such as "2004 European Code of Conduct for Space activities" [121] or "2014 ESA Space Debris Mitigation Policy for Agency Projects" [122] are applicable to projects or countries in ESA are examples of voluntary compliance of mitigation guidelines. But there are also countries which have not included these guidelines in national laws such as Australia, Germany, and Japan. Those who oppose making these guidelines as legal binding said in a latest COPUOS meeting that "since those approaches were linked to evolving technologies, and given the cost-benefit trade-offs of using them, it was not necessary to develop legally binding space debris mitigation standards at present" [123].

In summary, we can see that the legal response to the space debris mitigation challenge has not been so effective so far by relying on the voluntary compliance of states. To make the mitigation guidelines more effective, the appropriate way forward is to make mitigation guideline compliance as binding for every space-faring nation according to the view of authors. Because, even a few non-compliance events, such as in the form of use of ASAT could destroy the mitigation efforts of many years of those complying countries.

D. ADR RELATED LEGAL ISSUES

Similar to mitigation, there are several legal concerns related to ADR as well. Right from the definition of space debris, there are many unaddressed questions in existing space laws from debris remediation perspective. Few of them are as follow:

What is the criterion for declaring an object as space debris? Either its controllability or functionality? On the other hand, ''non-functionality'' or ''controllability'' of satellites or space objects may only be known to the satellite operator or controller. This is because according to the UN registration convention, UN registry maintains the basic parameters of space objects, such as launching state, date, and territory where launched, the general function of the satellite, orbital parameters (inclination, perigee, etc.). So, no centralized system or regulation determining the state of functionality or controllability of space objects.

Similarly, the risk associated with the debris objects to other useful space assets also cannot be prioritized because of not having any centralized data about space debris, in particular for non-functional satellites. Then how to select a high-risk target first for ADR is a question yet unaddressed. Also, according to the OST, states shall retain jurisdiction and control over the space objects carried on their registry. It must be with the permission of state registered that objects as per Registration convention and OST. But what if a state does not allow a third party to remove its object through ADR due to security concerns, especially in case of a military satellite? Also, who will be responsible if there is any damage that occurred to a third party asset in space during an ADR mission? Because according to the Liability Convention article III, the state whose object was removed through ADR will be liable for such a damaged, not the entity who performed the ADR [124].

Another question is that as ADR is just a capability to remove space object, then how it will be ensured that this capability is only used for debris, not for functional assets?

Apart from the above questions, there is an obvious need of a suitable form of international cooperation and legal framework to cope with the financial, strategic, security and military aspects of ADR, as highlighted in the findings of the International Congress on Space Debris Remediation [121].

Similar to mitigation, we have seen that law is far behind technological advancement for ADR. This is why we have seen that member states raised the same concerns in the latest meeting of Legal Subcommittee of COPUOS, where participants highlighted the need for discussion on legal issues relating to space debris and space debris removal. Including: the legal definition of space debris; the legal status of space debris fragments; the role of the state of registry; jurisdiction and control over the space objects to be declared as space debris; and responsibility and liability for active removal activities, including liability for damage caused as a result of debris remediation operations [123].

In summary, we can say that existing space laws or legal framework are practically insufficient to address critical aspects of the debris challenge. Hence, efforts are required on the legal front as well on the international level to deal with debris issue effectively. More specifically, binding rules must be created based on existing non-binding guidelines and policies to provide a legal framework for mitigation efforts. There is also a definite need for an international legal framework to provide cover and support to all the issues related to the remediation of orbital debris.

VIII. WAY FORWARD TOWARDS LONG TERM SUSTAINABILITY

Now we have seen in detail the space debris threat for the space environment; next, we want to discuss the way forward for long term sustainability of space. However, before that, it will be useful to consider relatively less critical yet important and related issues for the future of space technology.

A. OTHER CHALLENGES FOR THE FUTURE OF SPACE TECHNOLOGY

In the past, only very few countries were able to demonstrate expertise to build, launch and operate satellite successfully. Nowadays many of the countries in the world have already obtained the satellite expertise as can be seen in fig. 14 [2].

With gaining capabilities, and benefits from space technology every country wishes to have its independent satellite resources (GEO satellites, as well as constellations of LEO and MEO satellites) sooner or later. We can take the example of GNSS, while the USA had GPS, Russia has GLONASS, China's BeiDou and European Union's Galileo are about to complete in 2020 and India, France and Japan are also on their way for the same navigation satellite constellations. So, the challenge for the satellite industry is how to accommodate all if more countries wish to have their navigation satellite systems while we only have limited orbital slots and frequency resources? We can see the example of GEO, which is almost full for a long time. This example of the navigation system is equally applicable to other satellites such as communication, remote sensing, and weather monitoring satellites, etc. Also, there is a fair chance that many more commercial and governmental competitors may come up with similar large-scale satellite constellation project for other application if mega broadband constellations get success. On the other hand, it is also not logical to restrict countries to gain expertise, or from utilizing of space technologies, therefore, we must have to consider about the accommodation

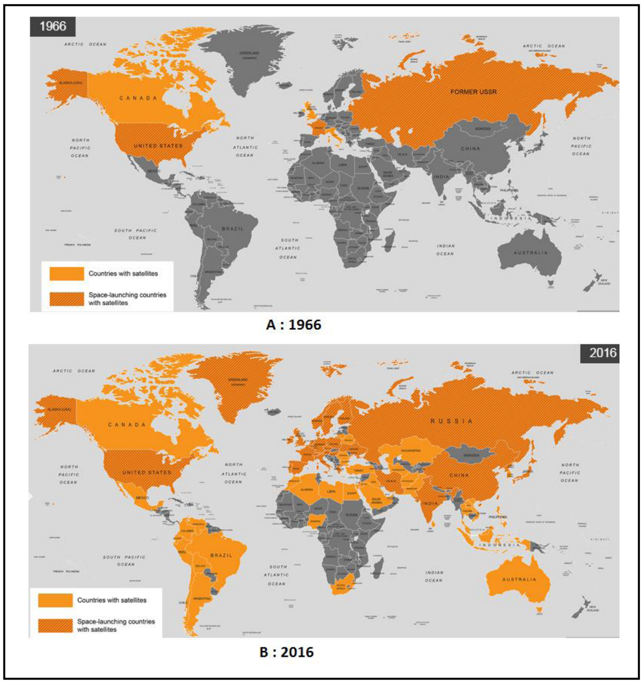

FIGURE 14. **Countries with satellites and launch capabilities A) in 1966, B) in 2016 [2].**

of many such future contenders while keeping an eye on the limitations of orbital slots and frequencies.

If we put aside these space debris and orbital resources issues, even then still there is a genuine question about the success of projects like mega constellations, and that is the economic sustainability of these broadband constellation projects. It is a vital question that, how many of the un-served population want to have space internet when a significant number in the target population is "underdeveloped" and struggling to get necessities. Suppose everyone agrees to have the internet, then how much these companies could lower the price of the internet to keep these projects in profit, while many people in the target market may not have much income for purchasing this internet. This is a crucial aspect because the same idea was not succeeded in the past by Teledesic, Iridium, and Globalstar because of financial crises. So, apparently, it may not be an optimize idea to put thousands of satellites only for providing internet services while we have these significant challenges.

B. POSSIBLE FUTURE APPROACHES

To address all the challenges as mentioned above, we have identified two possible optimize approaches for the satellite industry for the future; these are; Multi-mission satellites and Space Information Network (SIN). These Approaches can help in maintaining a balance between controlling future numbers of launches and accommodating the needs of countries for future with economic survivability of future satellite projects.

1) MULTI-MISSION SATELLITES

Till now most of the satellites are designed and launched for single dedicated application/purpose according to orbit characteristics. For example, LEO orbit is closer to earth and is therefore suitable for earth observation/remote sensing, so currently, most of the earth observation satellites are in LEO orbit. Similarly, GEO orbit has advantages of broader coverage and constant visibility to the ground, which makes this orbit suitable for broadcasting; so, most of the satellites in GEO are for communication (broadcasting) purpose.

So, from a future's perspective, it is important to switch from single-purpose satellite to dual or multi-mission satellites that can serve multiple purposes simultaneously rather than a single dedicated purpose. The idea of for multi-mission satellite is straightforward and is significant especially in the context of mega constellation projects. Because once we have a constellation of satellite in LEO that can provide global coverage all the time for providing internet services (e.g., mega constellation of OneWeb and Space-X), then if we can add together with internet, high resolution cameras for earth observation on same satellites then that will allow us to have additional continuous surveillance of earth. Authors in [100] presented a similar idea to have an additional navigation satellite's payload with the broadband payload on mega constellation satellites. Their study shows that although these constellations are not designed explicitly for navigation, still broadband LEOs beat the performance of navigation core constellations of today. The smallest, OneWeb, beats GPS by nearly a factor of three. Another study presented the feasibility of ADS-B payload on iridium satellite [135].

Similarly in addition to broadband, if we can put voice and data communication services which are currently provided through the terrestrial network by cellular operators then such voice and data communication service through LEO could break the barriers of terrestrial services by providing global coverage, including mountain, sea, disaster-affected area and other areas where deployment of ground telecommunication infrastructure is difficult. So there may be many more similar cases such as incorporating imaging payload in parallel to communication payload on satellites in GEO that will provide an additional global earth observation with only 3 GEO satellites instead of hundreds of satellite in LEO. Practically the Gaofen-4 and COMS satellites perform Earth Observation from geostationary orbits. So, there could be many similar possibilities of a multi-mission satellite system in LEO, MEO and GEO.

This idea of multiple services or mission is not new; we have seen some practical demonstration of them such as, COMS (communication, ocean, and meteorological satellite), EGNOS (The European Geostationary Navigation Overlay Service), small text messages services by Chinese navigation satellites Beidou, SandR payload on Galileo, ADSB receivers on Iridium Next for air traffic monitoring, etc. However, despite these successful demonstrations of multi-mission satellites, we can see that the potential of a multifunctional

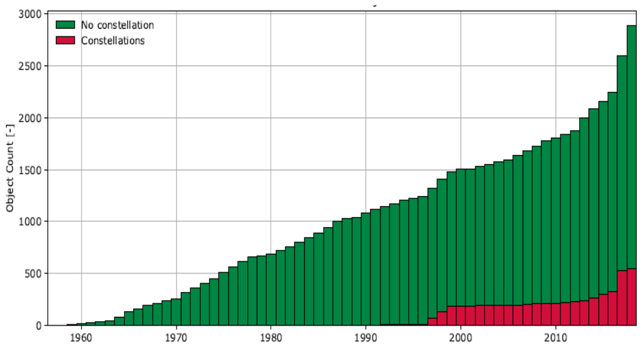

FIGURE 15. Objects evolution in LEO by constellation.

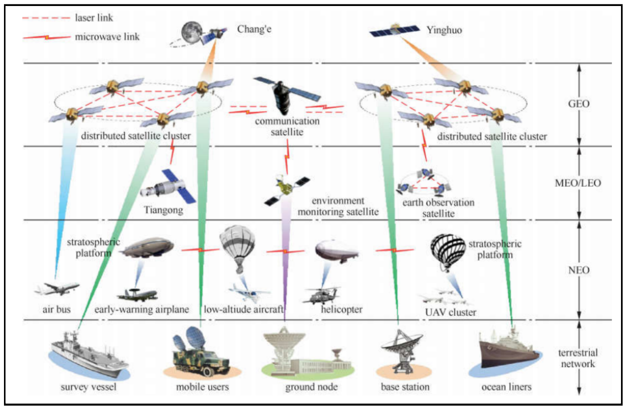

FIGURE 16. Abstract Network architecture of SIN.

satellite can be considered as an unexplored area as not much projects appeared to pursue this multi-mission satellite approach. In fact according to the operational satellite database of UCS, among 1957 currently operational satellites in orbits, the dual purpose satellites are only around 150, including those satellites having Technology Demonstration (TD) as a secondary mission objective. So by excluding TD, The number of multi-mission satellite comes down to around 130 only among 1957, which is only about 6% of total operational satellites.

So, we can say that having two or more function on a single satellite is an optimized approach for the future of the satellite industry particularly in the context of projects like mega constellations because this approach can significantly reduce the number of the future satellite while fulfilling future needs of satellite services. Additionally, it will also address the economic viability challenge for projects like the mega broadband constellation. Because, incorporating another potential market such as earth observation, navigation, etc. will make mega constellation projects economically viable. Having multiple functions on a single satellite may also have challenges, and this may be the reason for having less than 7% of dual-purpose satellite currently operational. However, keeping an eye on the challenges of the satellite industry and potential benefits of multi-mission satellites, it is an optimized approach to put efforts toward replacing traditional single-purpose satellite with dual or multi-mission satellite especially for satellites to be launched in the future.

2) SPACE INFORMATION NETWORKS (SIN)

Many countries in the world have few, dozens or hundreds of satellites alone, but these are either isolated single independent satellites providing their services that are suitable from that orbit or in the form of constellation of satellites (e.g., iridium, O3b, GPS, etc.) within the same single layer (e.g., LEO, MEO). However, we can see from fig. 15 [4] that a vast majority of satellites in LEO orbit are isolated independent satellites, and the constellations are very few.

This idea of independent satellites or even constellation is not an optimized use of space resources. A much better and optimized approach could be to form a network of satellites in different layers (orbits) through the inter-satellite link (ISL) and integrating it with ground/terrestrial network. This network of space resources and ground resources is known as Space Information Network (SIN) as shown in fig. 16 [125].

A SIN can provide several unique advantages that cannot be achieved through individual or single layered satellites. For example, in traditional individual approach, data from every single LEO satellite (either individual or in constellation) cannot be received to ground station after few minutes of its visibility to ground station, so every satellite have to store its data (e.g., Images) in onboard memory until it revisit over the ground station later. Also relaying of extensive data during short visibility time demands the fastest transmission rate. However, if these satellites are integrated with a SIN through ISL (inter-satellite link), then individual satellites can transfer their data to the ground station immediately after capturing it in space, with the help of connected GEO satellite which is always visible to the ground station [126]. This kind of real-time earth observation service can also initiate new doors of application such as real-time traffic and security surveillance [127]. The other example could be of Air traffic control and management, where exploiting services of navigation satellites (MEO), together with communication satellites (GEO), and remote sensing satellites, air transport management can be improved significantly.

Additionally, real-time transmission of flight data recorded during flights by black boxes to ground controllers is also possible through SIN. Another example advantage is real-time data transmission of deep space missions to the ground station through SIN. This kind of effective utilization of space resources may not be possible by only utilizing services of satellites in a single orbit.

In addition to the above, the integration of satellite network with the ground network can also provide two advantages that cannot be obtained otherwise. Among them, the first is that a SIN can expand/spread the benefits of terrestrial/ground networks such as the internet, to the all the world using global coverage of satellite, which cannot be possible using the terrestrial network [128]. Secondly, it can provide access to the satellites' data (e.g., images of the earth) to all user through the ground or terrestrial networks such as the internet immediately after capturing in space [129]. The authors in [130] highlighted different possible useful applications of an integrated SIN which are not possible otherwise, such as global air traffic surveillance [131] and communication [132].

Besides these potential advantages, SIN can also address the limited space resources problem, efficiently. Because in SIN, the nodes (satellites) in different orbits may not necessarily be belonging to the same company, country or having similar capabilities, instead a SIN can be formed by connecting satellites of different companies, countries and with different capabilities. Many countries currently have one or few satellites, and even in coming years, they may only get a few more satellites. These few satellites may not be sufficient to fulfill all the service needs for a country. However, instead of having fewer individual satellites, if these countries could jointly have a SIN that could provide more and much better services for all of those countries, including better availability, better and broader coverage at the expense of the same budget and same less number of satellites. Hence SIN can accommodate all of those countries; this SIN approach can thus significantly reduce the number of satellites to be launch in the future.

The SIN can thus also provide a foundation of cooperation in space environment among regional countries rather than competing with each other because SIN can bring mutual benefits for all the countries involved. This cooperation for SIN may not necessarily be limited only for sharing of space resources, but it may be based on a common cooperation framework that includes cooperation in designing, development, funding, and operations for ultimately sharing space resources and benefits between cooperating countries. Such an approach can reduce the need of every country for having its independent space infrastructure. For example, Regional countries can share the BeiDou satellite at the cost of common SIN. So, in future, if we could have, Asian SIN or African SIN, e.g., then this will be a much better approach than having individual satellites of every country if we keep in our eye the challenges of the space industry for future.

The concept of SIN is neither theoretical only, nor is new; NASA already deployed its Space network (SN), back since the 1980s. In the Space Network (SN), a constellation of geosynchronous satellites named the Tracking Data Relay Satellite (TDRS) operate as a relay system between the ground station and Satellites in low Earth orbit (LEO). NASA's SN serves the same concept, that is the data from the satellite in lower earth orbits such as Hubble, and the international space station is to be transferred to ground immediately with the help of TDRS relay satellites [133]. Apart from this there has been some work on SIN, for example, United States' "NAS (National Airspace System) project", "OEP (Operation Evolution Partnership) plan", "Integrated Battlespace programs", EU's BRAIN (Broadband Radio Access for IP-based Network) project, Japan's MIRAI ("future in Japanese") project And China and Russia also working on their SIN plans [125]. However, there are not many practical demonstrations of SIN until now. So, we can say that SIN is an optimized approach than a traditional individual satellite approach. Also, SIN has many potential benefits and ability to counter existing industry challenges, i.e., curtailing the number of future satellites and accommodating more contenders. So, we can say that SIN is the future of satellite industry whether for a single country or multiple countries, and it should be a replacement for traditional individual satellite approach.

TABLE 4. Cost of Satellite Launch against MAss [134].

Launch Orbit = LEO Expected Launch Year =2020				
Mass of one Satellite (Kg)	Cost of Satellite Launch (US$)	Number of satellites	Total Launch mass (Kg)	Cost of Total Launch mass (US$)
50	1750	20	1000	35000
100	3950	10	1000	39500
200	5950	5	1000	29750
450	17500	2	900	35000
1000	28000	1	1000	28000

3) PROS AND CONS OF THE PROPOSED SOLUTIONS

Apart from the benefits of the proposed solutions as discussed above, there could be many challenges for both of the highlighted way forwards. First of all, if we consider the case of multiple payloads solution, the challenge will be increased complexity, increased cost of satellite, increase mass, increased volume, more difficulty in platform stability or pointing, etc. But on the positive side, we can see that there will be financial savings in terms of single platform instead of 2 platforms, single launch expanse instead of two separate launches, cost of one orbital slot instead of two slots etc. Increased mass is also related to higher launch cost, but if we compare launch cost of two separate launches with one bigger object launch cost, there are obvious savings in shared payload approach as shown in table 4 [134].

So, giving cost-benefit analysis, having shared satellites will be cheaper and beneficial for sharing countries in most cases. As for as pointing stability is concern we have examples of international space station and other big mass/volume satellites, which are successfully operating without many difficulties. So, without going in the technical details of pointing/stabilization mechanisms such as momentum wheels/gyros thrusters, etc., We can see the technology is there to solve this issue.

For the legal issues if payload of different entities are shared on the same platform, or for sin also, we have a large number of examples where successful projects were delivered by joint ventures, bilateral, multilateral, mutual agreements by different entities/states or even different government/private organizations within a state or in different states. Copuos also supports and encourages these kinds of agreements as long as they are compliant with the space laws governing peaceful use of space [120].

Similarly, for the SIN, there are some other challenges such as information security concerns of different parties. Although these concerns could be addressed while drafting mutual agreements and designing security solutions considering all aspects and security concerns of participating entities. Still if any party is not agree or satisfied with the security solutions or with consensus by others, the disagreed party always have freedom to join or not that project. Also, there is an important question why an entity should go for a sharing approach rather than having individual approach or competing with others? In particular, in case the entity is a country, and a question of national sovereignty is also there?

Firstly, nations/countries are sovereign in going for any shared project or not. Or what kind and level of cooperation one entity want with other bodies, it is independent for that decision. Secondly from the historic perspective and practical results so far and as stated in the copuos meeting by states that, the success and evolution of space technology and its benefit are the result of mutual cooperation between different government/private entities and different states which are beneficial not only for participating entities but for everyone else as well. Thirdly, the sharing approach instead of competing has an obvious financial advantage for sharing entities. Especially as the space projects are costly and the risk associated are also high, so this approach of distributing the cost and risk among multiple entities instead of one is justified.

This sharing approach and its benefits are not only theoretical as we have examples from the telecommunication sector in the form of shared fiber optics in seas instead of laying independent fibers. Another example of sharing from space industry is multiple launching on a single launch vehicle as increasingly practiced nowadays. To be more specific as highlighted in above sub-sections, there are few successful examples of multi-functional satellites and sin for us to believe more in the proposed solution. Form this brief discussion we can see that the benefits of sharing of resources either in terms of platform or projects, outweighs the challenges and hence could be considered as a convincing and appropriate way forward for future, especially in the presence of orbital debris and associated challenges as highlighted in the paper.

IX. DISCUSSION AND CONCLUSION

From all of the reviewed aspects of space debris threat, other related satellite industry challenges and the identified way forward, we can conclude this article in the following points:

- Space debris is a serious and threatening challenge for an operational satellite; hence, this issue cannot be overlooked as in the past. In particular, for future missions such as mega constellations, every aspect of their possible impact on spacecraft and the space environment should be thoroughly considered beginning at the designing stage.
- Mitigation guidelines appear ineffective so far, to make them more effective, it is necessary to make them binding for everyone to follow as international law rather than to follow voluntarily. Additionally, in monitoring the debris situation continuously, the guidelines should be updated and revised regularly or periodically. For example, the post-mission orbital lifetime may be reduced to 5 or fewer years instead of 25 years.
- The current knowledge of the small debris situation in orbit is not sufficient. The effort is required to upgrade the SSN to at least track the 1-cm size debris. Statistical models used to predict the orbital environment appear to be not as accurate and consistent as they should be. Hence, these models must also be updated to be more accurate and reliable. Shielding must be incorporated as an integral part of the spacecraft design for all future space missions, to protect satellites from hitting mm-sized debris objects. Additionally, the reliance of the whole space world on a single system under the control of the U.S. defense can be more reliable by adding either parallel systems or by incorporating the stakes of other nations (e.g., ESA, China, etc.) into the SSN system, in the form of support infrastructure (telescopes and radar).
- The current efforts for ADR appear to be inadequate from a practical point of view, and thus, ADR projects should be prioritized and expedited. For this purpose, a broader international formal agreement among space-faring nations is obligatory for legal, financial and technical cooperation. ADR is essential because only ADR can improve the situation of the space environment, which is needed by everyone who has a stake or interest in space.
- International bodies such as UNOOSA/UNCOPUOS should take the responsibility of obtaining a global consensus in the form of agreement/laws to address this debris challenge and to ensure the long-term sustainability of space activities. This approach is essential for improved mitigation compliance, expedited remediation projects, and enhanced SSA, as well as for having control over future launches.
- Until the improvement of orbital debris situation through remediation measures, it appears to be sensible to limit future launches because without improving the orbital situation, launching thousands of new satellites would not help to improve the situation, and instead, there is a fair chance of having a much worse condition. At the same time, exploration of other platforms and technologies, such as high-altitude platforms and balloons, should be expedited for future applications.
- While keeping an eye on space debris threat and its anticipated consequences together with related issues such as limitations of orbital resources, we have elucidated that multi-mission satellite is one optimized approach for future and hence it should replace the traditional single-purpose satellite approach. Multi-mission satellites can

significantly reduce the number of potential launches in the future. Additionally, it can also solve the problem of financial survival of projects on the scale of Mega constellation by incorporating other potential customers rather than only internet customers.

- SIN (either having by any country individually or by cooperation among countries) is the other alternate optimize way forward which can also provide a lot of additional benefits that traditional individual or constellation satellites cannot provide. It can also accommodate many more commercial and governmental contenders to address the limited orbital resources issue while fulfilling the requirements of the services of every country.
- Finally, a SIN consisting of dual or multi-mission satellites in LEO, MEO, GEO, and ground network might be even further optimized for the future.

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