New space, new dimensions, new challenges
How satellite constellations impact space risk
The number of active satellites in orbit is set to multiply over the next ten years, driven by sustained growth in the use of new satellite constellations as opposed to large single satellites. Lower orbits in particular are becoming increasingly populated and also littered with debris, placing satellite operations at risk from collision and space debris impact.

This challenges the existing business paradigms for satellite manufacturing, launch, operation and insurance. How can the many players best navigate the increasing complexity of the rapidly evolving space risk landscape? What is the likelihood of a collision in low Earth orbits and how can liability be attributed in such a loss scenario?

Swiss Re Corporate Solutions has been a leader in the space insurance industry for many years and continually adapts its solutions as the space market advances. We trust this new publication – a sequel to our first on the subject in 2011 – will stimulate discussion across the space and insurance industries.

Serge Tröber
Chief Underwriting Officer
Swiss Re Corporate Solutions
The space sector has seen a substantial shift over the last decade, from ‘old space’ to ‘new space’: what was once the sole domain of governments has become the province of an industry that has revolutionised access to space and supported many new private operators. According to the United Nations, 70% of space activity is now led by the private sector. Missions to provide persistent Earth imaging, global communications and internet connectivity, to name just a few, have been driven by rapid and disruptive advances in technology, and developments in manufacturing capability, which have enabled smaller spacecraft to be deployed in Earth orbit at lower cost. In particular, we have seen the emergence of constellations – some made up of thousands of satellites – to realise these ‘new space’ missions.

Constellations, especially in low Earth orbit, possibly represent the greatest disruption to space traffic and our use of space for a generation. The inundation of this hugely important orbital region by large numbers of satellites is likely to challenge international efforts to address the hazards from orbital debris and to test the ability of operators to manage the safety of their spacecraft. Satellites face the risk of collision with each other or with orbital debris, which makes up more than 90% of the tracked population of objects orbiting the Earth today. The growing number of new operators, less familiar with good practices to mitigate this hazard, and the substantial increase in the number of satellites manifested within this ‘new space’ activity may add to the potential for collisions, which are a key source of debris.

Drawing on expertise from the technical, legal and insurance disciplines, this publication outlines the broader industry developments, underlines the implications for collision risk in Earth orbit, highlights legal challenges, and examines how the insurance industry is responding to the needs of increasingly complex satellite operations, such as constellations. The publication is a highly informative read for specialists and laypersons alike, and provides a sound basis for fruitful discussions on the topic.
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Introduction

A new space era is unfolding. Advances in technology and spacecraft manufacturing have enabled the proliferation of smaller and less expensive but fully capable satellites. This in turn has allowed new countries and entities around the world to enter the space arena. New space applications and businesses are now in various stages of planning and implementation with such varied applications as commercial asteroid mining, in-space refuelling of satellites, orbital debris removal and not least large distributed constellations with hundreds or even thousands of satellites for communications and Earth observation missions.

An increasingly dynamic space environment

These new satellite constellations and their impact on the space environment are the focus of this publication. Several constellations are now in the planning or implementation phase, and even if only a few of them are actually deployed, they could eventually increase the population of active satellites in low Earth orbits (LEO) by an order of magnitude. What will such deployments mean for the space environment and existing satellite operations? Can all of these constellations be deployed and operated without internal collisions or collisions with each other? What impact will the rapidly increasing orbital debris population have on these constellations? And how much are constellations themselves likely to contribute towards increasing debris in orbit? We address these questions in Chapter 2. A technical perspective.

Legal aspects of collisions in space

In Chapter 3, A legal perspective, we use a hypothetical scenario: a discarded satellite is drifting uncontrollably in an orbit of 750km following a miscarried end-of-life disposal manoeuvre by US-based company Top View. This altitude also happens to be where a brand new satellite constellation is being deployed. Unfortunately, the discarded satellite collides with one of the newly deployed satellites, causing it to fragment and trigger an alleged total loss of USD 800m.

"Planned constellations with hundreds or thousands of satellites will be at risk from space debris impact and are themselves a potential source of debris."
With no insurance available to cover the losses due to an agreed policy deductible, the UAE-based company considers two legal avenues to recover: the international track and the domestic track. In both scenarios, the analysis quickly turns to two key legal questions: does Top View’s conduct amount to “fault” or negligence, and what are the prerequisites for liability under international and domestic law? Are the causal links between Top View’s conduct and the accident sufficient to justify imposing liability?

A new challenge for insurers

Chapter 4, The insurance perspective, examines how the emergence of large constellations of smaller satellites in LEO has created a new challenge for the insurance industry. Insurers have been accustomed to providing a proven insurance product designed to respond to the total loss or damage to large, high-value communications satellites that were primarily positioned in GEO. Today, the insurance industry is facing an increase in demand for products that require similar financial protection for systems or networks of up to thousands of satellites operating primarily in LEO.

As the purpose and composition of these new constellations are tailored to the individual requirements of the operators, underwriters need to take into account a set of specific considerations when designing coverage for this highly specialized class of business. At the same time, the growing density of satellites and orbital debris in LEO is increasing the probability and consequence of collision. How can insurers reconcile the need for carefully crafted, bespoke insurance products with the increased risk involved in the deployment of such a large number of new satellites clustered in an already densely populated LEO?
What’s changed since our last publication

In our 2011 publication, we observed that after half a century of space exploration and commercial and military uses of space, there were more than 16,000 catalogued man-made space objects in orbit around the Earth. Only about 900 of those objects were operational spacecraft. In other words, 93% of the objects then circling Earth were orbital debris. Today, the catalogued orbital population has increased by 19% to around 19,000. The chart below depicts the distribution of catalogued space objects in 2011 and today, highlighting that the greatest increases in volume have been in operational payloads and fragmentation debris.

Total in-orbit population across all Earth orbits

<table>
<thead>
<tr>
<th>Category</th>
<th>2011</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational payloads</td>
<td>7%</td>
<td>9%</td>
</tr>
<tr>
<td>Non-operational payloads</td>
<td>14%</td>
<td>15%</td>
</tr>
<tr>
<td>Derelict rocket bodies</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>Mission-related debris</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>Fragmentation debris</td>
<td>57%</td>
<td>58%</td>
</tr>
<tr>
<td>Total</td>
<td>16,000</td>
<td>19,000</td>
</tr>
</tbody>
</table>

“Overall, the total in-orbit population has increased by 19% over the last seven years with increases in operational payloads and fragmentation debris.”
An update on the debris population in GEO

Our 2011 publication focused on the Geostationary orbit (GEO) at the altitude of 35,786km in the plane of the equator, where satellites are stationary with respect to the Earth and where most large communications satellites reside. The chart below shows how object families in GEO have changed over the last seven years.

The population of man-made objects in GEO has increased dramatically, from 1,039 in 2011 to 1,460 today, an increase of roughly 40%. While this increase is partly due to the launch of new satellites that are still operational, it was mainly caused by growth in the debris population. The number of operational spacecraft in GEO has increased by 43%, from 350 in 2011 to 500 today. The growth in the debris population is primarily due to satellite breakups. There has been an increase in almost every category of debris, as there is no natural cleansing mechanism (such as atmospheric drag) in GEO. On the positive side, compliance with re-orbiting guidelines has been improving in GEO and satellite servicing/removal capabilities appear to be emerging over the next decade.

Changes in GEO population across all categories

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2018</th>
<th>Change absolute</th>
<th>Change percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1,039</td>
<td>1,460</td>
<td>+421</td>
<td>40%</td>
</tr>
<tr>
<td>In detail</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>830</td>
<td>1,135</td>
<td>+305</td>
<td>37%</td>
</tr>
<tr>
<td>-</td>
<td>350</td>
<td>500</td>
<td>+150</td>
<td>43%</td>
</tr>
<tr>
<td>-</td>
<td>480</td>
<td>635</td>
<td>+155</td>
<td>32%</td>
</tr>
<tr>
<td>-</td>
<td>190</td>
<td>249</td>
<td>+59</td>
<td>31%</td>
</tr>
<tr>
<td>-</td>
<td>16</td>
<td>36</td>
<td>+20</td>
<td>125%</td>
</tr>
<tr>
<td>-</td>
<td>3</td>
<td>40</td>
<td>+37</td>
<td>1,233%</td>
</tr>
</tbody>
</table>

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The dawnning of a new space era

The use of space has changed in many ways over the past decade. Space has become increasingly globalised in that more and more countries and companies are building and operating spacecraft. The use of space is also becoming more diverse as new technologies and manufacturing processes have paved the way for new space applications. Private companies are now planning Moon missions, asteroid mining, satellite servicing in orbit, orbital debris removal, space habitats, small satellites (cubesats and nanosats) and large constellations consisting of hundreds or even thousands of satellites. This phenomenon is often referred to as “new space”. In reality, “new space” contains everything of “old space”; there are just more options and capabilities layered together, creating a more complex and challenging space environment in both physical and operational terms.

Several factors have contributed to this new trend. Barriers to entry are lower today thanks to advances in technology and manufacture that have enabled smaller and less expensive but fully capable spacecraft. The same factors have contributed to new space applications and missions. The advent of satellite constellations is a good example of how these new technologies have been leveraged successfully. Several large, distributed constellations – some with satellites as small as a loaf of bread – have already been deployed in LEO, with many more planned over the next five to ten years. Table 1 compares and highlights the key characteristics of traditional and new space activities.
Table 1:
Contrasting “old space” with “new space” provides a logical foundation for examining the evolving space environment.

| Characteristic                              | Old space                                      | New space                                                                 
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite in a typical space system</td>
<td>1-2</td>
<td>1 to 100s (or 1 000s)</td>
</tr>
<tr>
<td>Mass of typical satellite</td>
<td>500–2 000kg</td>
<td>Many less than 200kg and a few greater than 4 000kg</td>
</tr>
<tr>
<td>Typical space operator</td>
<td>Large entities or countries</td>
<td>Start-up companies and smaller countries</td>
</tr>
<tr>
<td>Number of spacefaring countries</td>
<td>~10</td>
<td>~90</td>
</tr>
<tr>
<td>Number of launch options</td>
<td>Few dedicated launch opportunities</td>
<td>Rideshare and new launch systems</td>
</tr>
<tr>
<td>Space lifetime philosophy</td>
<td>“Launch and forget”</td>
<td>Service extension, satellite replenishment, and end-of-life strategies</td>
</tr>
<tr>
<td>Space business priority</td>
<td>National security and national infrastructure</td>
<td>Global economics, and national security and infrastructure</td>
</tr>
</tbody>
</table>

Orbital debris – on the increase?
The new space era presents new challenges in terms of orbital debris. Focusing on satellite constellations, a 10cm piece of debris impacting a single satellite in a constellation and causing it to fragment, depending on the satellite’s size, mass, and orbital altitude, could increase the debris population significantly (see section 2.1). The risk of collision between satellites within a constellation is small provided that the constellation is competently designed and managed, and populated with highly reliable spacecraft. However, resident groupings of large derelict objects (such as spent rocket stages and abandoned payloads) present a substantial debris generation risk that could affect LEO constellations (see section 2.2). We are likely to see a polarisation among losses, ie many very small losses alongside a few very large ones.
2.1 Debris impact of constellations

The deployment of several large, distributed constellations with hundreds or even thousands of satellites is likely to have a profound impact on the business landscape and LEO environment over the next decade. To illustrate: Earth-imaging company Planet has deployed a constellation of +200 small remote sensing satellites, OneWeb is deploying a constellation of 720 satellites initially for broadband connectivity, SpaceX has proposed a constellation of roughly 4,000 satellites, and Telesat and LEOSat plan to deploy more than 100 satellites each. All of these are slated for completion by 2025.

The sheer number of satellites in some of the proposed constellations will multiply the population of active satellites in orbit. Their potential impact on the space environment, including the debris population, could be significant. These constellations are challenging the existing business paradigms for satellite manufacturing, launch, and operation.

**Figure 1:**
Constellations are simply multiple satellites working together to provide a total mission effect; a constellation can be made up of two or up to thousands of satellites.

**Reasons for using constellations vs a single satellite:**

1. Constellations offer more complete spatial coverage
2. Deliver a shorter time between measurements, often called the revisit rate
3. Provide resiliency (reserve capability in the overall architecture when a single asset fails)
**What is a constellation?**

Constellations consist of multiple satellites working together to provide an overall mission effect; a constellation may comprise two or up to thousands of satellites. Constellations are not new and reasons for using them rather than a single satellite may be to provide: (1) complete spatial coverage over the Earth; (2) a shorter time between measurements, often called the revisit rate; or (3) resiliency, ie to have reserve capability built in to the overall architecture to load balance when a single asset fails.

**The sweet spot in LEO**

The new surge of constellations in LEO results partly from new technology (eg higher resolution small cameras, superior attitude control and greater power density for solar arrays) and partly from new demands for global services (eg Earth observation, internet connectivity, internet for mobile users, voice communications). Constellations have some physical limitations due to the physics of spaceflight. Very inexpensive satellites are often deployed in very low orbits (ie below 600km) to reduce communications latency or increase effective image resolution, but also to benefit from atmospheric drag, which can act as a natural orbit cleansing mechanism. This results in a short orbital lifetime for those satellites, which is acceptable, since the shorter lifetime allows operators to refresh their technology more frequently by launching replacement satellites.

Many of the large constellations being proposed are slated for deployment in LEO. For communications satellites, LEO offers the advantage of low latency; latency is a concern for GEO satellite operators competing with fibre. For remote sensing satellites, LEO is optimal since they are closer to Earth and achieve better image resolution with the same sensors. Orbital altitudes between 600km and 1 000km are the sweet spot for the coveted sun-synchronous orbits which produce the unique capability for a satellite in a single orbit to fly over a specific point on the Earth at the same time of day on a recurring schedule (ie revisit rate). The downside is that these coveted orbits, due to their utility, are also the most densely populated and littered with debris. Satellites above 800km are only marginally affected by atmospheric drag and therefore could become a source (and victim) of long-lasting debris.

**The higher the altitude, the longer debris will remain**

LEO constellations deployed above 1000km are still close enough to Earth to have a low latency of signal transmission relative to a GEO satellite, and yet the altitude places the constellations above the most debris-littered regions of LEO. In addition, atmospheric drag is hardly an issue in these high-LEO orbits. This makes satellite orbit propagation much easier, as it allows for better positional certainty. However, it also makes the orbit less forgiving with debris-generating events, since debris will linger for centuries at these altitudes. This stands in stark contrast to satellites deployed under 600km, whose orbital lifetimes are in the order of years.
The space population at a glance

The growing volume of man-made orbital debris is a threat to vital satellites orbiting the Earth.

In LEO, a hypervelocity collision between two massive derelict objects would produce up to 3 trackable fragments and 30 lethal, non-trackable fragments per each 1kg of mass involved in a collision.

Collisions in LEO may be catastrophic while they can be mission-terminating in GEO.

Space debris collision risk is not random in time and space.

Over 19,000 catalogued objects in orbit, of which over 17,000 are in LEO. A growing number of these are operational satellites. The rest is debris ranging in size from ~10cm to the object size of a schoolbus.

Debris in LEO

- **>1cm** 700,000 objects
- **>10cm** (size of tennis ball) 18,000 objects
- **>100cm** to size of schoolbus 4,000 objects

In GEO, the probability of collision is clumped by longitude (two geopotential wells) and latitude (high latitudes are generally worse). Likely impact direction changes twice an orbit.

GEO

- Probability of collision is clumped by altitude and latitude (high latitudes are generally worse)
- Likely impact direction changes twice an orbit
- Plane of equator
- 105°W 75°E
- 6hrs
- 36,000km

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- 105°W 75°E
- 6hrs
- 36,000km
Debris impact events in LEO to date

Assuming the deployment of three notional satellite constellations, two things become clear:

- Individual satellites are exposed to the risk of detrimental impact by existing debris; and
- Satellites may themselves become a source of new debris if they fail and become uncontrollable or if they fragment due to a collision with debris.

There are currently around 19,000 catalogued objects in orbit, of which over 17,000 are in LEO, where objects larger than 10 cm are trackable. A growing number of these are operational satellites. The rest is debris ranging in size from 10cm to objects the size of a school bus. The debris collision probabilities spike at an altitude of around 800–850km, where the current debris fragment population is the highest. The greatest risk for debris generation and collision in LEO stems from groupings of large resident debris objects, such as spent rocket bodies and discarded payloads, scattered across most of LEO.

Apart from the catalogued objects larger than 10cm in Earth orbit, there are also an estimated 500,000–700,000 smaller fragments that are not catalogued. While the impact of a 1cm debris object with a satellite in a constellation would be likely to severely disrupt or terminate the operations of that satellite, a 10cm impact would be likely to not only terminate its mission but actually cause the satellite to completely fragment. Depending on the size of the impacted satellite and its orbit, a collision could increase the debris population by hundreds to thousands of lethal fragments, thus adding further risk to operations in space.

Has debris ever really affected an operational satellite system?

Most people who follow space issues are aware of the collision between the derelict payload Cosmos 2 251 and the operational Iridium-33 satellite in 2009. However, many other events attributed to debris impacts have created varying degrees of operational degradation. As mentioned earlier, the primary debris collision risk is from the 1cm–10cm debris population, estimated to comprise 500,000–700,000 objects in LEO that can deliver a lethal blow to an operational satellite. However, these objects cannot be tracked reliably by ground space surveillance assets.

A last look at the sensitive points of the launcher: here, the nozzle of a Vulcain engine.
Table 2:
Possible debris impact events in LEO show that lethal, yet non-trackable debris may indeed be making its mark on LEO space operations already.

<table>
<thead>
<tr>
<th>Event</th>
<th>Object(s)/(Satellite Number)</th>
<th>Altitude (km) &amp; Inclination</th>
<th>Anomaly Date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNSAT (SO-35)</td>
<td>South African university (25636)</td>
<td>400x838km i=93°</td>
<td>19/01/2001</td>
<td>Irreversible multi-point physical failure</td>
</tr>
<tr>
<td>JASON1</td>
<td>NASA/CNES Science sat, (26997)</td>
<td>~1 336km i=66°</td>
<td>03/2002</td>
<td>Impulse of 0.365mm/s from GPS residuals; hit left solar array from behind; lost 10% of array struck; orbit change of 30cm</td>
</tr>
<tr>
<td>Cosmos 539</td>
<td>Russian geodetic sat (6319)</td>
<td>1340x1380km i=74°</td>
<td>21/04/2002</td>
<td>Decrease in period of 1 sec. with a 20cm x 50cm object created</td>
</tr>
<tr>
<td>JASON1</td>
<td>NASA/CNES Science sat 2001-55A; (26997)</td>
<td>~1336km i=66°</td>
<td>09/2005</td>
<td>Impulse of 0.182mm/s from GPS residuals; orbit change of 10cm</td>
</tr>
<tr>
<td>EOS-Terra</td>
<td>NASA A-Train satellite (25994)</td>
<td>705km i=98.2°</td>
<td>13/10/2009</td>
<td>One battery cell in hexbay unit and heater failed simultaneously with attitude disturbance; 3mm impactor suggested</td>
</tr>
<tr>
<td>Aura</td>
<td>NASA atmospheric science sat (28376)</td>
<td>685x885 i=98.2°</td>
<td>12/03/2010</td>
<td>Panel #11 lost 50% of power and had 875 asec angular disturbance</td>
</tr>
<tr>
<td>BLITS altitude drop</td>
<td>Laser ranging target (35871)</td>
<td>832x800km i=98.6°</td>
<td>22/01/2013</td>
<td>Split into two trackable objects</td>
</tr>
<tr>
<td>Pegaso unresponsive</td>
<td>Ecuadorian cubesat (39151)</td>
<td>650x654km i=98.1°</td>
<td>22/05/2013</td>
<td>Close pass to rocket body but no hit</td>
</tr>
<tr>
<td>Iridium-47</td>
<td>Commsat 1997‒082C (25106)</td>
<td>785x795km i=86.4°</td>
<td>07/06/2014</td>
<td>Ten high velocity (80m/s) debris produced hinting at impact</td>
</tr>
<tr>
<td>Iridium-91</td>
<td>Commsat (27372)</td>
<td>785x795km i=86.4°</td>
<td>30/11/2014</td>
<td>Four low velocity debris produced hinting onboard anomalous event</td>
</tr>
<tr>
<td>WorldView-2</td>
<td>Payload (35946)</td>
<td>770km i=98.54°</td>
<td>19/07/2016</td>
<td>Nine pieces detected but WorldView says satellite is still working</td>
</tr>
<tr>
<td>Sentinel-1A</td>
<td>Payload (39634)</td>
<td>693km sun-synch; i=98.18°</td>
<td>23/08/2016</td>
<td>6–8 pieces produced (6 catalogued) and visual verification of solar array damage; impactor of 1cm and 0.2gm at 11km/s</td>
</tr>
</tbody>
</table>

These events hint at the uncertainty in the collision risk from lethal yet non-trackable debris, which is the likely way in which an operational satellite will be affected by debris in the future, since this population is 50 times larger than the catalogued population.

On top of this, the potential drastic growth in the number of operational satellites in LEO due to the deployment of many large constellations may be a game changer for all LEO space entities, as it provides more opportunities for debris impact victims and, if not managed well, could in itself be a source of future debris.

“The potential drastic growth in the number of operational satellites in LEO may be a game changer for all LEO space entities.”
Three notional constellations for analysis

In this section, we analyse the risk that constellations pose to the space environment and characterize the potential hazards that the LEO environment poses to the satellites within these constellations. Examining the range of risks imposed on and potentially created by constellations helps to establish how the community may respond to the fielding of potentially hundreds to thousands of new satellites in LEO. To perform this analysis, we will use three representative notional constellations to expose issues relevant to space safety, collision risks and debris mitigation activities.

The notional constellations are representative of three major business areas that prospective constellation operators are currently pursuing:

- A mobile satellite communications constellation (COMM);
- A fixed satellite service (FSS) constellation for global internet connectivity (G-CON); and
- An Earth observation constellation (E-OBS).

These three constellations provide a good coverage of the types of satellites to be deployed into LEO over the next 10 years. Figure 2 below provides a qualitative summary of some of the characteristics of the three constellations examined relative to each other.

**Figure 2:**
A comparison of the three constellations

<table>
<thead>
<tr>
<th>Constellation mission</th>
<th>Background debris hazard</th>
<th>Constellation thickness</th>
<th>Total mass</th>
<th>Aggregate areal cross-section</th>
<th>Number</th>
<th>Manoeuvre capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications (COMM)</td>
<td>High</td>
<td>Thin</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>✓</td>
</tr>
<tr>
<td>Global internet connectivity (G-CON)</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>✓</td>
</tr>
<tr>
<td>Earth observation (E-OBS)</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>✗</td>
</tr>
</tbody>
</table>
The disposal plan for both COMM and G-CON is to lower the perigee of its satellites to 400km and then rely on atmospheric drag to deorbit these satellites within 25 years. The perigee produced by the deorbit manoeuvre is directly proportional to the available propulsive capability. The perigee height will, in turn, drive the remaining orbital lifetime of the satellites. The lower each constellation can get the perigee, the faster it will re-enter. E-OBS needs no disposal plan since their orbital lifetime will not exceed 25 years.

We now turn to a risk assessment of each of the notional constellations.

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMM</td>
<td>Operates at an altitude with a significant background debris hazard (~800km), spans a small altitude (ie thin constellation), is moderate in mass (~50 000kg total), moderate in areal cross-section (~400m² in aggregate) and of moderate size (100 satellites) compared to many other proposed constellations.</td>
</tr>
<tr>
<td>G-CON</td>
<td>Represents an FSS constellation comprising 1 000 satellites centred at 1 200km spread across a wide range of altitudes. This configuration typifies the large FSS constellations proposed by operators such as OneWeb, SpaceX and Telesat. Like COMM, G-CON satellites have manoeuvre capability, are located in a fairly uncluttered orbit, are high in mass (~200 000kg total), high in areal cross-section (~3 000m² in aggregate) and are part of much larger constellations than COMM (~1 000 vs ~100 satellites).</td>
</tr>
<tr>
<td>E-OBS</td>
<td>A constellation centred at 600km which spans a large range of altitudes. It comprises 300 non-manoeuvrable 3U cubesats so is much smaller in both total areal cross-section and aggregate mass.</td>
</tr>
</tbody>
</table>
Collision risk to a space object from the debris environment is probability of collision multiplied by consequence.

Calculating probability of collision

The probability of collision for a satellite from the background debris hazard is given by:

$$PC = 1 - \exp(-SPD \times VR \times AC \times T)$$

Where

- **PC**: probability of collision over time T
- **SPD**: spatial density, number of debris per km³
- **VR**: relative velocity, km/s (12km/s is typical in LEO)
- **AC**: areal/collision cross-section, km²
- **T**: time, seconds

Critical phases in a satellite’s lifetime

When measuring debris collision risk, one must look at all phases of a satellite’s life: deployment, operations and retirement (usually end-of-life disposal). While much focus tends to be placed on the operational phase of a satellite’s orbital life, deployment and retirement are often overlooked. However, it is precisely during these phases that there may be a significant risk both to and from members of these constellations. The higher the operational altitude, the more transit time and exposure to the background population the satellite will have during deployment and retirement. In addition, for retirement it is important to know how long the operators will maintain control of their satellites. More specifically, if a retiring satellite’s manoeuvre capability fails and the satellite is left to be removed by atmospheric drag, it will be unable to avoid collisions with other objects during this time. Similarly, if a satellite operator does not reserve sufficient propellant to complete the intended orbit lowering manoeuvre and the satellite becomes uncontrollable debris, it is again a potential collision hazard.

“A 1cm impact would be likely to severely disrupt or terminate the operations of a satellite. A 10cm impact would not only terminate the mission, but may even destroy the satellite.”
Spatial density for the three notional constellations

The primary variable in determining the probability of collision is the spatial density of existing resident space objects (such as debris fragments and derelict hardware) of an orbit. Thus we must first examine the background spatial density of the orbits where the COMM, G-CON, and E-OBS constellations (will) transit and reside.

Figure 3 shows the operational locations for each constellation overlaid on the spatial density curves derived from NASA’s ORDEM engineering model provided by NASA/ODPO. It shows that the background spatial density is greatest for COMM at 800km, lower for E-OBS at 600km, and lowest for G-CON at 1200km.

Throughout the analysis, the >1cm threshold will be used to represent the lethal, yet non-trackable (LNT) debris and the >10cm threshold to represent the catalogued population which is trackable and potentially avoidable, if a satellite has manoeuvre capability and successfully executes a collision avoidance manoeuvre. A 1cm impact would likely severely disrupt or terminate the operations of a functioning satellite, while a trackable object would be likely to not only terminate the mission of a functioning satellite but cause the satellite to completely fragment. The >3cm population is plotted to provide some insight on the transition between the >1cm and >10cm populations.

**Figure 3:**
The locations of the three notional constellations plotted on the spatial density curves for LEO.
A technical perspective
Debris impact of constellations

Probability of collision

Table 3 quantifies the probability of collision for one member of each of the notional constellations during its respective deployment, operations and retirement phases. Neither deployment nor disposal is relevant for the E-OBS constellation since these cubesats operate where they are deployed (at 600km) and are removed from orbit via atmospheric drag. Both G-CON and COMM nominally will have their satellites deployed initially at ~600km and then slowly raised to their respective operational altitudes. The time to deploy COMM satellites is shorter than for G-CON due to the lower operational altitude for COMM (~800km vs ~1 200km for G-CON). The intent of this deployment plan is to ensure that no satellites are dead on arrival (DOA) at their operational altitudes, which would pose collision risks to their respective constellations and other operational satellites in the vicinity. However, the transit does itself pose a non-trivial collision risk to the constellation members, as shown in the table below.

Table 3:
Probability of collision values for all phases of the three constellations.

<table>
<thead>
<tr>
<th>Cluster/Constellation</th>
<th>Number of satellites</th>
<th>Altitude and span (km)</th>
<th>Spatial density (#/km²)</th>
<th>Single satellite cross-section/mass</th>
<th>Total aggregate cross-section</th>
<th>Start altitude and duration</th>
<th>Probability of collision (1cm/10cm)</th>
<th>Operational collision risk/year (1cm/10cm)</th>
<th>Time to dispose</th>
<th>Probability of collision (1cm/10cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMM</td>
<td>100</td>
<td>800 ± 10</td>
<td>1E-6</td>
<td>2E-8</td>
<td>4m²</td>
<td>500kg</td>
<td>400</td>
<td>600km 3 months</td>
<td>1.5E-4</td>
<td>4E-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 months</td>
<td>1.5E-4</td>
</tr>
<tr>
<td>G-CON</td>
<td>1 000</td>
<td>1 200 ± 100</td>
<td>1E-7</td>
<td>6E-9</td>
<td>3m²</td>
<td>200kg</td>
<td>3 000</td>
<td>600km 6 months</td>
<td>3E-4</td>
<td>7E-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 months</td>
<td>3E-4</td>
</tr>
<tr>
<td>E-OBS</td>
<td>300</td>
<td>600 ± 50</td>
<td>1.5E-7</td>
<td>1E-8</td>
<td>0.09m²</td>
<td>5kg</td>
<td>27</td>
<td>600km n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The probabilities above are associated with potential collisions with the background population only (i.e. they do not consider collision probabilities arising from failed constellation satellites); collision probability values for the retirement phase assume a 600km orbit.

The collision risk per year of operation for a single satellite is worst for COMM at 800km, which has the highest spatial density of debris due to previous breakups. E-OBS has 100x and 1 000x lower collision risk from resident space debris per satellite than G-CON and COMM, respectively. Assuming all goes according to plan, the deployment transit poses little risk to other operational satellites, since COMM and G-CON satellites have the capability to avoid catalogued objects. Yet the rules of the road have not yet been established as to how these potential encounters between two operational and manoeuvrable satellites will be determined.
G-CON is exposed to as much collision risk during its six-month deployment as during three full years of operation due to its transit through orbital regions with higher background spatial density than that of G-CON’s operational orbit. The collision risk during operations will fluctuate for E-OBS based on the solar cycle (which will modulate the debris population by changing atmospheric drag) while G-CON’s collision risk should stay constant unless debris-generating events happen near it. A large debris-generating event at 1 200km will materially change the orbital environment and increase the probability of collision for many decades because atmospheric drag at 1 200km has little effect on orbital lifetimes. Of course, a disabled satellite in any part of the transit (either during deployment or retirement) then poses a background debris risk to other satellites in that orbit.

This long transit does raise at least three questions: First, if a G-CON or COMM satellite during deployment has a predicted close approach with another operational satellite, who must/should move? Second, should the satellite whose orbits are being crossed have the “right of way” during G-CON’s or COMM’s elective journey to their operational altitude? Third, is the risk imposed by the transit higher or lower than the risk of deploying a DOA satellite at their respective operational altitudes?

The lifetime of an intact satellite in LEO depends greatly on the altitude of its orbit since the atmospheric density that drives the lifetime varies exponentially with altitude. A few 100kms in altitude can make a drastic difference in the orbital lifetime of an object. The solar cycle lasts about 11 years and the effects of atmospheric drag are about double the average during solar maximum and about half the average during the solar minimum. Unfortunately, while space weather experts predict the timing and magnitude of the solar cycles decades in advance, there is natural variability during and between solar cycles, so there is a significant amount of uncertainty in the actual orbital lifetimes of objects in LEO. This effect is amplified for debris fragments whose area-to-mass ratios are larger than intact objects and possibly even varying during their flight, if they are tumbling.
Consequence of a collision

Table 4 provides an assessment of the consequences if a single satellite of each of the representative notional constellations fragments completely due to a collision with a catalogued debris fragment or explosion due to some internal failure. For each event, there will be 1.5 trackable fragments (ie >10cm) per kg of mass of satellite and 15 LNT (ie >1cm) per kg of mass of satellite. These fragments will largely be spread above and below the centre of each constellation by 100km (ie a total spread of 200km).

What emerges from Table 4 is that for any one catastrophic breakup of a satellite in one of the constellations studied in this publication, E-OBS’s satellites pose the least consequence in an absolute sense or relative to the debris environment (and its own orbit). A breakup in the COMM constellation has the greatest absolute effect (due to the larger spacecraft), causing an increase in spatial density of 31%.

Table 4:
The contribution to the debris environment from a single fragmentation event, within our three notional constellations, is a function of the individual satellite mass. The increase to the background hazard from such an event is shown below assuming all debris produced stays within ±100km of the centre of the constellation.

<table>
<thead>
<tr>
<th>Satellite mass (kg)</th>
<th>&gt;1cm</th>
<th>&gt;10cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fragments produced</td>
<td>Increase to spatial density</td>
</tr>
<tr>
<td>COMM 500</td>
<td>~7 500</td>
<td>6%</td>
</tr>
<tr>
<td>G-CON 200</td>
<td>~3 000</td>
<td>21%</td>
</tr>
<tr>
<td>E-OBS 5</td>
<td>~75</td>
<td>0%</td>
</tr>
</tbody>
</table>

"The fragmentation of a single 500kg satellite at 800km may increase the debris population by 31."
2.2 Large resident debris: a hazard to LEO constellations

Due to constellations’ reasonably large aggregate areal and total mass characteristics, they do pose a collision risk to other space operators. However, the existing groupings of abandoned resident space objects in LEO may be more troublesome to future debris growth than any of the constellations being considered for deployment in LEO. These massive derelict object groupings – called clusters – present considerable near-term debris generation potential that may pose significant collision risk exposure to LEO constellations and all satellites in LEO.

Three clusters of massive debris objects

Three clusters of massive derelict objects will now be detailed and compared to the notional three constellations. Each cluster is named by the centre altitude of each cluster (eg C850 is a cluster centred at around 850km). A cluster is defined as a set of massive space objects with similar inclinations and altitudes.

Table 5 provides some key characteristics of each of these three clusters relative to the three constellations being analysed. Note that each cluster is basically comprised of a set of rocket bodies (RB) and the payloads (PL) that the RBs deployed, but which are no longer operational. The clusters were largely populated between 1990 and 2007 due to a practice of leaving behind spent upper stages and discarded satellites; this practice is no longer used. The derelict objects in each of these clusters carry the risk of randomly colliding with each other. As a result, such a collision between two massive objects will produce significant debris since so much mass will be involved in the event.

Clusters were populated due to a past practice of leaving behind spent upper stages and discarded satellites.

Table 5: Comparing the three notional constellations against three clusters of massive derelicts provides a perspective on the criticality of these disparate space hardware collections.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Number of objects</th>
<th>Average cross-section (m²) / mass (kg)</th>
<th>Total area (m²)</th>
<th>Total mass (kg)</th>
<th>Altitude span (km)</th>
<th>Annual inter-cluster collision rate</th>
<th>Catalogued fragments from collision event (lethal non-trackable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C775</td>
<td>89</td>
<td>RB: 14/1 434 PL: 6/800</td>
<td>~900</td>
<td>~100000</td>
<td>775 ±30</td>
<td>~1/500</td>
<td>~4,000 (~45 000)</td>
</tr>
<tr>
<td>C850</td>
<td>36</td>
<td>RB: 44/8 300 PL: 8/3 250</td>
<td>~950</td>
<td>~208000</td>
<td>850 ±22</td>
<td>~1/1200</td>
<td>~16,000 (~160 000)</td>
</tr>
<tr>
<td>C975</td>
<td>286</td>
<td>RB: 14/1 434 PL: 6/800</td>
<td>~3000</td>
<td>~560000</td>
<td>975 ±42</td>
<td>~1/120</td>
<td>~4,500 (~45 000)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Number of objects</th>
<th>Average cross-section (m²) / mass (kg)</th>
<th>Total area (m²)</th>
<th>Total mass (kg)</th>
<th>Altitude span (km)</th>
<th>Annual inter-cluster collision rate</th>
<th>Catalogued fragments from collision event (lethal non-trackable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMM</td>
<td>100</td>
<td>4/500</td>
<td>~400</td>
<td>~50000</td>
<td>800±5</td>
<td>N/A</td>
<td>~750 (~7500)</td>
</tr>
<tr>
<td>G-CON</td>
<td>1000</td>
<td>3/200</td>
<td>~3,000</td>
<td>~200000</td>
<td>1200±100</td>
<td>N/A</td>
<td>~300 (~3000)</td>
</tr>
<tr>
<td>E-OBS</td>
<td>300</td>
<td>0.09/5</td>
<td>~27</td>
<td>~1500</td>
<td>600±50</td>
<td>N/A</td>
<td>7 (~75)</td>
</tr>
</tbody>
</table>
Consequences of collision within the debris clusters

Now for some perspective on consequences of the results in Table 5: A collision in C850 will have the greatest consequence in terms of number of fragments generated as the rocket bodies in C850 are SL-16s* with a mass of at least 8 300kg, a length of 11m and diameter of 3.9m. If two of these were to have a hypervelocity collision, about 16 000 trackable fragments would be created. This would double the catalogued population in one instant. The payloads that occupy C850 with the 18 SL-16s have masses of 3 250kg; a collision between them would also be likely to create around 16 000 large fragments, since the dense construction of payloads would couple the collision energy more efficiently than that of rocket bodies.

Alternatively, C975 has the greatest probability of a collision occurring with nearly 300 derelict objects spanning only ~85km. Collisions in C975, while not as severe as the C850 collisions, could still create about 4 500 trackable fragments and 45 000 LNT. One such collision would be one of the worst breakups ever and there is a 1/120 chance (ie ~1%) each year of such an event occurring. The C850 annual inter-cluster collision rate is smaller but is still 1/1 200 (~0.1% per year). In addition, if a collision occurs in C975 or C850, the resulting debris will remain in orbit for many decades, while debris from C775 collisions would have significant wash-out over a few decades.

The fact that an event capable of doubling the catalogued population has at least a 1/1 200 chance of occurring annually gives rise to concern. Any of these inter-cluster collisions would produce significant amounts of debris that would measurably affect satellites within ±100km. By examining the cumulative risk from these clusters, the following observations are even more disturbing:

- For C975, within which a collision would produce about 4 500 catalogued fragments, there is an ~11% chance that statistically such a collision could have already occurred.
- Similarly, for C850, within which a collision would generate around 16 000 trackable fragments, there is a ~1% chance that statistically such a collision could have already occurred.

There is a 1/1 200 (0.1%) chance per year that the debris population could double as a result of two SL-16s within C850 colliding.

* Sowjet zenit rocket body
Risk posed to LEO constellations

Table 6 highlights the very probable large number of impacts from LNT over the long term for the entire clusters and the three LEO constellations (COMM, G-CON and E-OBS). These types of impact will trigger anomalies to the operational satellites and bursts of small numbers of more LNT from non-debilitating impacts on constellation members but much more so from the clusters of massive derelicts.

<table>
<thead>
<tr>
<th>Name</th>
<th>Altitude (km)</th>
<th>SPD* 1cm</th>
<th>SPD 10cm</th>
<th>&gt;1cm (LNT)</th>
<th>&gt;10cm (trackable debris)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1cm</td>
<td>10cm</td>
<td>PC 1yr</td>
<td>PC 10yr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PC 1yr</td>
<td>PC 10yr</td>
</tr>
<tr>
<td>C775</td>
<td>775</td>
<td>8E-07</td>
<td>2E-08</td>
<td>0.203</td>
<td>0.897</td>
</tr>
<tr>
<td>C850</td>
<td>850</td>
<td>1E-06</td>
<td>3E-08</td>
<td>0.256</td>
<td>0.948</td>
</tr>
<tr>
<td>C975</td>
<td>975</td>
<td>3E-07</td>
<td>2E-08</td>
<td>0.247</td>
<td>0.942</td>
</tr>
<tr>
<td>COMM</td>
<td>800</td>
<td>1E-6</td>
<td>2E-8</td>
<td>0.140</td>
<td>0.780</td>
</tr>
<tr>
<td>G-CON</td>
<td>1200</td>
<td>1E-7</td>
<td>6E-9</td>
<td>0.110</td>
<td>0.679</td>
</tr>
<tr>
<td>E-OBS</td>
<td>600</td>
<td>1.5E-7</td>
<td>1E-8</td>
<td>0.0015</td>
<td>0.015</td>
</tr>
</tbody>
</table>

**Total constellation/cluster**

<table>
<thead>
<tr>
<th>&gt;1cm (LNT)</th>
<th>&gt;10cm (trackable debris)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*SPD: Spatial density

It should be noted that these three clusters amount to about 20% by mass and number of derelicts in LEO, so this continual interaction may become relevant as massive non-operational objects continuously create large numbers of additional LNT. Overall, the probability of collision (PC) values for the entire clusters are larger than the same values for all of the constellations.

The number of satellites in G-CON (1,000 satellites) makes up for the lower spatial density of debris at its operational altitude, so that the probability of collision for G-CON is within a factor of two of the COMM constellation. On the other hand, E-OBS has a consistently lower PC value than the other constellations. In addition, if something were to "go wrong" (such as a large debris-generating event), the E-OBS altitude will be naturally cleansed quickly, whereas this will not be the case for the higher altitude constellations. For most scenarios, the PC from the >1cm fragments is about 10x that from >10cm fragments, except when the PC values mathematically start to approach one (eg for many of the 10-year and 20-year levels).

COMM is precariously deployed between clusters C775 and C850. Figure 4 shows the three constellations and three clusters plotted on the same ORDEM-derived spatial density curves for LEO. G-CON is the only constellation safely away from the three clusters. However, this debris risk avoidance comes with the liability of much less cleansing contribution from atmospheric drag, so that any debris deposited in their constellation will linger for thousands of years unless actively removed.

Any debris deposited in G-CON will linger for thousands of years unless actively removed.
Obviously, the large debris-generating collisions possible within these three clusters will have direct and indirect impacts on any constellation deployed in LEO (especially those operating below 1 100km). Constellations deployed below 1 100km will be directly impacted by the burden of avoiding collisions, with the resulting trackable fragments and indirectly by survivability concerns from LNT produced. However, even constellations that may eventually be deployed over 1 100km will still have to transit altitudes littered with debris during their deployment and retirement.

Figure 4:
Cluster locations relative to the constellations show how future collisions in the clusters might influence the potential survivability of constellation members.
Artist’s impression of space debris in Earth orbit.
How debris collision risk is managed today

Generally speaking, there are three ways to manage debris collision risk: (1) debris mitigation, (2) debris remediation, and (3) active traffic management and rules of the road. Today, debris mitigation is the primary method used with some rudimentary traffic management principles starting to evolve.

Debris mitigation

Debris mitigation as used here refers to guidelines and, in some cases, regulatory requirements that satellite and launch vehicle operators follow during satellite deployment, operations, and end-of-life disposal. These mitigation measures are designed to limit operational debris, avoid collisions, ensure safe end-of-life disposal, and prevent fragmentation due to battery explosion or over-pressurization in discarded satellite payloads and rocket bodies. Safe disposal may be in the form of “graveyard” orbits or hastening atmospheric re-entry. International and US domestic policy and practice today is to boost GEO satellites at end of life to an orbit of least 300km above the geostationary orbit and to lower the orbits of LEO satellites to allow for a natural decay of the orbit within 25 years. (See Chapter 3, A legal perspective). There is some debate whether 25 years is sufficient given the current debris environment and increased importance of reliable space operations.

Debris remediation

No orbital debris removal service is in operation today. A number of technical proposals for active debris removal have been put forward, such as using spacecraft with robotic arms that grapple or tow debris or using lasers to push debris to lower orbits. Several companies are in various stages of design, prototyping or testing such concepts. The problem is commercializing these techniques. There is no ready commercial market for debris removal services, except for a few one-off requirements. One reason is that there are presently no legal requirements on space operators to remove debris. Another reason is that governments seemingly see no compelling moral imperative to do so, yet that may take one or more catastrophic accidents.

Traffic management

Rules of the road, including right of way and similar behavioural norms, are in their infancy today for space in the way of practice, domestic policy or international guidelines. The Space Data Association (SDA) has started to develop and apply means of having operational space users cooperate for the mutual benefit of all through sharing information, coordinating manoeuvres, etc. More formal rules have been adopted for other navigable domains, such as the high seas and international airspace, and will be required at some time also for spaceflight and satellite operations. For example, section 2.2 discussed the transit the G-CON or COMM satellites must make through debris-crowded orbits to reach the deployment attitude of their respective constellations at 1,200km and 800km. This transit does raise at least two sets of questions:

- If a G-CON or COMM satellite during deployment has a predicted close approach with another operational satellite – who must/should move? Should the satellite whose orbit is being crossed have the “right of way” during G-CON’s or COMM’s elective journey to their operational altitude?
- Should a satellite in its end-of-life deorbit phase always be required to yield to an operational satellites or a satellite in transit to its operational altitude? Should all spacecraft be required to have propulsion sufficient to perform avoidance manoeuvres?
- Is the risk imposed by the transit higher or lower than the risk of deploying a DOA satellite at their respective operational altitudes? And, to whom?
Observatory antennae in the sunset.
A legal perspective

The following hypothetical scenario illustrates the complicated interplay between legal, technical and insurance issues from a sequence of collision events in LEO related to a constellation deployment. While the scenario is by no means suggested to be the most likely event to occur, analysis of risk for space events has made it very clear that the most likely event, is likely not the next event to occur.

3.1 The scenario

Four satellites are now out of commission in the NasirSat communications satellite constellation. NasirSat Ltd. of Abu Dhabi, UAE is currently deploying a 60-satellite constellation. Three months ago, TopView-1, a remote sensing satellite owned by Top View Inc. of Peak Park, California, collided with and totally destroyed one of the satellites in the constellation, NasirSat-23. Three additional NasirSat satellites have suffered mission-terminating impacts since then, attributed with very high probability to debris generated by the TopView-1-NasirSat-23 collision. The total replacement cost for the lost NasirSat satellites is USD 200 million, with substantial risk of additional losses from the collision debris.

Using up reserve propellant to stay in operation longer

Top View had operated TopView-1 for 24 months past its design life so as to take advantage of a lucrative US government contract for satellite imagery. And to keep the satellite operational, TopView-1 used up most of the propellant that had been reserved to ensure its orderly and safe deorbiting and disposal. In fact, Top View ignored the promise it made to the US Federal Communications Commission (FCC) and the National Oceanic and Atmospheric Administration (NOAA), on the basis of which these agencies had issued licenses to Top View: to begin end-of-life disposal of TopView-1 in January 2016. As a result, the satellite ended up not in its intended disposal orbit (at 550km) but in the orbit of the NasirSat constellation, at 750km.

Could the collision have been avoided?

The NasirSat satellites have limited manoeuvrability to avoid collisions, but in this case NasirSat-23 was not moved due to conflicting information about the collision risk and indications that the collision risk had diminished. Twenty-four hours prior to the collision, NasirSat’s Network Operations Center received a conjunction warning from the U.S. Joint Space Operations Center (JSpOC) of a very high (in astronomical terms) probability of a collision with TopView-1 (11%). NasirSat had received several conjunction warnings since the beginning of the constellation’s deployment, but those had all projected a collision risk of less than 0.1%.

Given the high risk, NasirSat’s Director of Spaceflight Operations was called in to assess the situation and to make the final call on performing an avoidance manoeuvre. By the time he arrived, new data had come in from the Space Data Association’s Space Data Center (SDA), indicating a modified trajectory for TopView-1 and a significantly diminished collision risk. The discrepancy in information received from JSpOC and SDA caused some uncertainty and the spaceflight operations director, needing to make a quick call, decided against the avoidance manoeuvre. The discrepancy was later attributed to the uncertainties inherent in calculating debris collision risk. NasirSat received no conjunction warnings prior to the impairment of the other three NasirSats, presumably because the debris causing the impairment was too small to be tracked. Several organizations were able to confirm based on simulations the high likelihood that the debris stemmed from the collision with NasirSat 23.
NasirSat’s losses and potential claims
For NasirSat, four satellites down represented a loss of USD 200 million, and it still faced substantial risk of additional impact and impairment of other satellites in the constellation. NasirSat is now looking for ways to recover.

NasirSat commissioned M.A. Space Consultants, Ltd. of Surrey, UK to quantify the collision risk to the remaining NasirSat satellites from debris fragments generated by the TopView-1-NasirSat-23 collision. Fifty of the 60 satellites in the constellation had been deployed by the time of the collision. M.A. Space Consultants assessed the risk of mission terminating impacts to be higher than 20% for eight satellites over seven years. They also advised that launching the final 10 satellites to complete the constellation could increase the risk significantly. For NasirSat, the increased risk is a vexing issue because having less than a complete constellation will result in impaired communication service to key customers with contracts for high-capacity broadband connectivity.

NasirSat estimated the risk of additional losses and the revenue loss associated with degraded service as a result of not launching the final 10 satellites to be USD 600 million. Together with the satellite losses already suffered, this brings NasirSat’s alleged total loss to USD 800 million.

The insurance policy deductible precludes recovery
NasirSat had purchased satellite property insurance for the launch and 24 months in orbit for the satellites in the constellation. The policy, as is typical, was an all-risk policy; it covered the replacement value of the satellite in the event of a launch failure and loss due to satellite malfunction or defect or external causes, including orbital debris.

The insurance policy included a deductible of three satellites in each of the four planes. Unfortunately for NasirSat, the four satellites that suffered losses were spread over three planes and therefore fell into the deductible category, which NasirSat recognizes and accepts as part of the agreement it reached with its insurers. Deductibles are common in satellite constellation policies because these satellite operators typically have a few in-orbit or on-the-ground spares with which to fill up a plane if necessary. NasirSat is also resigned to the fact that coverage under its insurance policy is triggered only when the destruction or impairment of a satellite has manifested itself in an occurrence and not when there is merely a possibility of future damage and loss. Therefore, not even a quantified risk of future loss will form the basis of a valid insurance claim in the absence of an occurrence. Finally, as far as the unlaunched satellites are concerned, risk has not yet attached for these satellites, so the failure to launch them does not trigger the policy. NasirSat had not purchased revenue insurance, although this type of insurance is available to satellite operators.

Top View has no liability insurance
Top View has no liability insurance for the damage TopView-1 caused to the NasirSat constellation. Liability insurance for in-orbit operations or end-of-life disposal of satellites is not presently a requirement under US law. The FCC, which granted the license for TopView-1, has said that the existence of an insurance policy may be a factor in its licensing decisions, including whether to approve a proposed satellite disposal plan, but the FCC does not presently have the authority to impose an insurance requirement on a satellite operator. Top View’s satellite end-of-life disposal plan was approved without insurance. The problem is that Top View did not adhere to its plan.
Avenues for legal recourse for uninsured losses

Given the lack of insurance coverage, NasirSat is now looking for legal avenues to recover its losses. It has two options:

- Petition the UAE government to file a claim on its behalf against the United States under the international space treaties, which would mean resolving the claim initially through diplomatic channels (the international track); or
- Sue Top View in a national court, eg in the US (the domestic track). NasirSat will need to determine which approach, the international or domestic, is more likely to provide effective and timely relief. It cannot pursue both tracks for the same claim.\(^2\)

The fact that Top View is a US company and the US has a well-developed judicial system to address tort claims may weigh in favour of suing Top View in a US court. California, where Top View is domiciled, is known to have a legal system with a victim-oriented approach. On the other hand, Top View is a relatively small company, with limited assets and ability to pay claims, which speaks in favour of the international track.

Any attempt by NasirSat to sue the US government in a US court for failure to exercise adequate regulatory oversight over Top View would likely be met with a sovereign immunity defence.\(^3\) NasirSat will need to decide which approach to pursue.

### Seeking legal recourse – the avenues open to NasirSat

<table>
<thead>
<tr>
<th>International track</th>
<th>Domestic track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevant sources of law</td>
<td>Jurisdiction</td>
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<tr>
<td>Outer Space Treaty of 1967</td>
<td>California federal court</td>
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<td>Liability Convention of 1972</td>
<td></td>
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<tr>
<td>General principles of international law</td>
<td>Relevant sources of law</td>
</tr>
<tr>
<td>Considerations for UAE, claimant</td>
<td>California tort law</td>
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<tr>
<td>Must show that the US is a launching state</td>
<td>US federal regulations for satellite licensing</td>
</tr>
<tr>
<td>Must prove fault on the part of Top View or the US to NasirSat satellites; no definition of fault in the treaties</td>
<td>Considerations for NasirSat, plaintiff</td>
</tr>
<tr>
<td>Must prove damage as defined in the Liability Convention</td>
<td>Must show: Top View owed a legal duty to avoid collision</td>
</tr>
<tr>
<td>Timeframe for recovery and outcome uncertain</td>
<td>Top View breached that duty; and the collision was the proximate cause of NasirSat’s alleged injuries</td>
</tr>
<tr>
<td></td>
<td>Must show that damages are recoverable</td>
</tr>
<tr>
<td></td>
<td>Outcome uncertain; delay possible</td>
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</tbody>
</table>
3.2 The international track: UAE vs USA

If the UAE agrees to take the case on behalf of NasirSat under international law, it would bring a claim against the United States of America, based on the Outer Space Treaty, the Liability Convention and general principles of international law. The parties would use diplomatic channels to resolve the dispute, as prescribed by the Liability Convention. Article 3 of the Liability Convention provides:

In the event of damage being caused elsewhere than on the surface of the earth to a space object [NasirSat’s satellites] of one launching State [UAE]... by a space object [TopView-1] of another launching State [USA], the latter [USA] shall be liable only if the damage is due to its fault or the fault of persons for whom it is responsible.

The UAE would need to show that each of the elements of the clause is satisfied in order for the US to be liable. TopView-1 and NasirSat-23, as well as debris generated from the collision between the two satellites, qualify as “space objects”. A space object is defined as “space object and its component parts”. There is general agreement that a space object includes orbital debris; a contrary interpretation would deprive the Convention of much of its utility, which would run counter to its principle expressed by the Preamble: To ensure “a full and equitable measure of compensation to victims of such damage.”

The US is a “launching State” for TopView-1 because the satellite was launched by a US company from Cape Canaveral in 2008. The United States is responsible for Top View’s conduct in space under Article 6 of the Outer Space Treaty, which makes a state responsible for the space activities of private companies within its jurisdiction and requires that such activities be authorized and continually supervised. The US is the licensing authority for TopView-1.

Are NasirSat’s losses “damage”?

Damage under the Liability Convention includes “loss of or damage to property of States or of persons, natural or juridical ...” The physical destruction of NasirSat-23 is the type of damage that most clearly falls within this definition. The debris impact and resulting impairment of the three other NasirSat satellites may also qualify as damage if NasirSat can establish that the damage was “traceable directly” to the deorbiting manoeuvre of TopView-1 and its collision with NasirSat-23. The matter of indirect damage was only briefly considered by the drafters of the Liability Convention, with the majority taking the position that indirect damage should not be covered as a general matter, but leaving open the door for including such damage on a case-by-case basis.

The risk of future damage to the other satellites in the constellation and the revenue loss resulting from the alleged inability to use the constellation without launching the remaining 10 satellites to complete the constellation would likely not qualify, and the US would probably object. During the negotiation of the Liability Convention, the US took the position that indirect damage for which there is only a hypothetical causal connection is not covered. At this point, the damage has not manifested itself and the potential impairment of the constellation and the resulting revenue loss is speculative and remote.

The issue of what constitutes damage under the Liability Convention arose in the so-called “Cosmos 954” case. In 1979, radioactive debris from a Soviet ocean surveillance satellite re-entered the atmosphere and was scattered over large areas of the Canadian Northwest Territories and other provinces. Canada took the position that the “deposit of hazardous radioactive debris on Canadian territory, and the presence of that debris in the environment rendering part of Canada’s territory unfit for use, constituted ‘damage to property’ within the meaning of the Convention.”
Canada sought compensation, including for clean-up costs, in the amount of CAD 6,041,174.70. The then-Soviet Union rejected the claim, but later agreed to settle with no admission of liability for CAD 3 million “in full and final settlement of all matters connected with the disintegration of the Soviet satellite Cosmos 954 in January 1978.”

No definition of “fault”

The US may be held liable for damage due to “its fault or the fault of persons for whom it is responsible,” ie Top View. The question is whether Top View’s conduct amounts to “fault” under the Liability Convention. Fault is not defined. It presumably requires a lesser degree of culpability than gross negligence as that term is used elsewhere in the Liability Convention. In both civil law and common law, the central principle of fault (culpa or negligence) is the failure to act as a reasonable person would have acted under the circumstances, thus causing injury or damage as a result. With this notion of fault, one must ask whether Top View’s delayed deorbiting of its satellite is consistent with the conduct of a reasonable satellite operator under the same circumstances. Top View wanted to maximize the revenues from its satellite asset given a US government contract. Was that unreasonable? Not in itself, but should Top View have notified the US licensing authorities given its statement in the license application? Could Top View have foreseen the consequences of its delayed deorbiting? Did Top View take precautionary measures before initiating its deorbit procedure? Did it calculate the risk of impact to other satellites? These are all relevant factors.

One might also ask whether the US government was at fault by neglecting to consult with the UAE government prior to the deorbiting of TopView-1. Article 9 of the Outer Space Treaty requires international consultation when a State Party “has reason to believe that an activity or experiment planned by it or its nationals in outer space ... would cause potentially harmful interference with activities of other States Parties...” Arguably, the JSpOC conjunction warning constituted sufficient consultation. One might also query whether the US government was at fault by failing to exercise regulatory oversight over Top View. Arguably, the regulatory agencies were entitled to assume that Top View disposed of its satellite as planned; the agencies have limited resources and ability to police satellite operations in orbit.

The measure of compensation

The Liability Convention provides for compensation for damage in accordance with “international law and the principles of justice and equity.” The purpose is to restore the victim to the “condition that would have existed” had the damage not occurred. The Preamble reflects a victim-oriented approach of the Convention to provide for the “prompt payment... of a full and equitable measure of compensation to victims of such damage.” Nonetheless, recovery is not available unless NasirSat can prove the other elements of the liability clause, including fault, damage and causation.

Uncertain timeframe and outcome

The timeframe of the dispute is uncertain under the international track. The Liability Convention calls for dispute resolution through “diplomatic channels” and if that process fails to resolve the dispute within one year, then for the creation of an arbitration tribunal, called a claims commission. There is no precedent for establishing a tribunal under the Convention and the decision of the claims commission is considered to be final and binding only if the parties have agreed to be bound. The outcome of the international track is also unpredictable, given the ambiguities in the meaning of terms such as “fault” and “damage”. NasirSat would have to pin its hopes on a swift and amicable diplomatic accommodation or settlement.
3.3 The domestic track: NasirSat vs Top View

The Liability Convention expressly allows for the use of national courts as an alternative to bringing a claim under the treaties. "Nothing in this Convention shall prevent a State, or natural or juridical persons it might represent, from pursuing a claim in the courts ... of a launching State." 22

A lawsuit in California Federal Court

Assume that NasirSat decides to bring an action against Top View under California law in US federal court in California, where Top View is headquartered. The court has personal jurisdiction over Top View because it is headquartered there. The court has subject matter jurisdiction because of the international nature of the suit (the parties are in diversity) and the amount in question is over the requisite amount, the total claim being USD 800 million.23

Top View will probably assert procedural objections to the lawsuit. Perhaps it would seek to have the suit dismissed on the grounds that the court lacks extraterritorial jurisdiction over torts in space. The Outer Space Treaty establishes space as res communis (free for use by all, but cannot appropriated). NasirSat would counter that (1) the tortious act (Top View’s decision-making and commanding of the satellite) was committed in California, (2) the res communis status of space is irrelevant since the US has jurisdiction over TopView-1 under Article 8 of the Outer Space Treaty, 24 and (3) the Liability Convention expressly permits an aggrieved private party to use national courts. Any assertion by Top View that a California federal court is forum non conveniens is highly unlikely to prevail. 25

Top View may object to the application of California law, asking the court instead to apply international space law since the tort occurred in space (lex loci delicti). California courts abandoned lex loci delicti as a choice of law rule years ago in favour of the governmental interest approach, 26 and California has an interest in applying its own tort law here. Nonetheless, state courts are bound by treaties to which the US is a party and would have had to apply the Liability Convention if it in fact controlled tort actions between private entities. 27 It does not, as it applies only to claims between states. Accordingly, the court may revert to the default rule for the diversity cases and apply the substantive law of the forum state, here California tort law, and federal procedural law. 28

A tort action for negligence

NasirSat would sue for negligence. Under California law, a person is responsible for injury it causes by failure to use ordinary care or skill in the management of its property. 29 To prevail on a negligence claim, the plaintiff must show that (1) the defendant owed it a legal duty, (2) the defendant breached the duty, and (3) that the breach was a proximate or legal cause of the plaintiff’s injuries. 30

Top View had submitted a plan for end-of-life disposal of TopView-1 as required with its license applications to the FCC and NOAA. 31 These agencies granted licenses to Top View premised on that plan. Accordingly, NasirSat would argue, Top View had a duty to deorbit its satellite as stated in its license applications. Top View violated that duty by delaying the deorbiting of TopView-1 and using up the satellite fuel reserved for deorbiting, thereby increasing the risk that the satellite would end up as an uncontrollable piece of debris at the altitude of a large satellite constellation and damaging the satellites in that constellation (such as NasirSat-23).
NasirSat would argue that this scenario is sufficient to create a presumption of negligence under California’s negligence per se doctrine, which holds that the violation of a law or regulation designed to protect a class of persons from the type of harm actually suffered (as was the case here) creates a presumption of negligence. The FCC’s orbital debris regulations and 2004 Orbital Debris Mitigation Policy were designed to ensure safe end-of-life disposal and to avoid collisions with other satellites by requiring satellite applicants to submit an orbital debris mitigation plan, including planned end-of-life disposal. Top View’s best argument is that no express regulation specified the end-of-life disposal procedure and what Top View submitted to the FCC and NOAA was merely a plan. Nonetheless, FCC policy does require re-entry within 25 years, a norm that Top View could not satisfy by deorbiting only to 750km.

If a presumption of negligence cannot be established via the negligence per se doctrine, the issue of Top View’s negligence will be likely to turn on (1) whether Top View as an ordinary satellite operator could have foreseen that its conduct could lead to collisions with or impairment of other satellites (not necessarily the specific NasirSat satellites), an element necessary to establish a duty; and (2) whether the cause of the collisions and/or impairments was proximate. The analysis has two elements: The latter prong requires a finding that Top View’s conduct in fact caused the collision and that it is “so closely connected with the result [ie the damage to the NasirSat satellites] and of such significance that the law is justified in imposing liability”.

Recoverable damages

As a general rule, the measure of damages in tort under California law is “the amount which will compensate for all the detriment proximately caused thereby, whether it could have been anticipated or not.” California law does allow for compensation for loss of profits in certain instances. A plaintiff may recover damages for profits lost during the time necessary to repair or replace the property. Recovery for business interruption requires a plaintiff to show with reasonable certainty based on experience with past sales and other provable data, eg existing contracts. Recovery is not necessarily foreclosed when only injury to prospective economic advantage is claimed. Regardless, NasirSat will be under a duty to mitigate its damages.
Assessing liability

Under both the international and the domestic legal tracks, the issue of liability as a general matter comes down to a number of specific questions. In order to recover, NasirSat must score on each and all of the aspects below.

Culpability

Was Top View’s conduct sufficiently blameworthy to meet the requisite legal standard of fault or negligence? (Top View’s conduct is imputed to the US under the international treaties.) Both civil law and common law jurisdictions would ask this simple question to determine culpability or negligence: Did Top View act as a reasonable satellite operator would have acted under the circumstances?

A reasonable satellite operator would have wanted to continue to operate the satellite. It would have requested permission from its regulators to extend the satellite’s operational life and delay deorbiting of the satellite. A reasonable satellite operator would have evaluated the risk of deorbiting with inadequate fuel, including the risk of disposal in a crowded orbit and the potential for colliding with other satellites (not necessarily with NasirSat-2342). Assuming Top View failed to perform the evaluation or that it performed the evaluation and ignored the result if a collision was foreseeable, that may be sufficient to establish fault or negligence, as the case may be, with respect to the initial TopView-1-NasirSat-23 collision.

Militating against a finding of fault or negligence is the fact that there is no US domestic law or regulation and no binding international rule that mandates a specific procedure for disposing of non-GEO satellites to a certain orbit at end of life.

The FCC’s regulations require that satellite license applicants submit a plan for end-of-life disposal, as does NOAA, the other licensing agency. The FCC examines satellite end-of-life disposal plans of satellite applicants on a case-by-case basis. The FCC’s 2004 Orbital Debris Mitigation Policy declares that a disposal method that provides for the placement of a spacecraft into an orbit from which it will re-enter the Earth’s atmosphere within 25 years is generally consistent with the “public interest,” the standard by which the FCC grants satellite licenses. According to the policy, LEO satellite operators are “in the best position to determine how they will dispose of their spacecraft at the end of life and the corresponding amount of fuel to reserve to achieve disposal...” Top View’s plan stated that it would begin a propulsive manoeuvre in January 2016 to lower its orbit to an altitude of 550km to allow for atmospheric drag and decay of the orbit within 25 years. The FCC and NOAA issued licenses on the premise that Top View would adhere to the plan. But this falls short of an express regulatory requirement. Likewise, international guidelines on debris mitigation are non-binding, general and imprecise. For example, the United Nations guidelines on debris mitigation from 2010 in relevant part state that “[s]pacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the LEO region should be removed from orbit in a controlled fashion.”
**Proximate causation**

Is the causal connection between Top View’s conduct and NasirSat’s alleged losses sufficiently close to justify imposing liability? Or are the losses too speculative and remote?

The destruction of NasirSat-23 was caused directly by TopView-1 colliding with it, which was a direct result of Top View’s decision to deorbit the satellite despite the inadequate fuel, a situation it created for itself. That causal chain, if proven, may be sufficient. The causal connection is not so close for the three other impaired satellites. The legal standards for causation will be likely to vary for the international and US track, with the latter perhaps more forgiving of intervening causes. The causal connection is further attenuated and speculative – and unlikely to be sufficient – with respect to the risk of future losses to other satellites and resulting revenue loss.

**Whether such losses are covered**

Are the losses that NasirSat allegedly suffered recoverable under the treaties or US law, as the case may be?

Physical damage to NasirSat-23 and to the three other satellites falls within the categories of recoverable damage under the Liability Convention if the other elements above are met. It is unlikely that any revenue loss would be recoverable under the international treaties. Revenue is recoverable in California in certain instances, but the revenue loss alleged by NasirSat here is remote and speculative. Moreover, the company has a duty to mitigate losses; so NasirSat will probably need to launch the additional 10 satellites and hold off on further claims until more satellite losses, if any, manifest themselves.

All things considered, NasirSat’s chances of recovery are best for NasirSat-23 (a USD 50 million loss), and diminish with respect to the other three impaired satellites (a USD 150 million loss) and further weaken substantially (very unlikely) for the alleged revenue loss (estimated at USD 600 million).
4 New Space – More challenges for insurers ahead?

4.1 The insurance perspective

The emergence of large constellations of smaller satellites in LEO has created a new challenge for insurers. Historically, insurers have been accustomed to providing a proven and tested insurance product designed to respond to the total loss or damage to large, singularly high agreed valued communications satellites that were primarily positioned in GEO. Today, the insurance industry is facing an increase in demand for products that require similar financial protection for multiple lower value satellites operating together to form a system or network, primarily in LEO.

Demand for insurance in LEO is growing

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of insured satellites</th>
<th>Total insured in-orbit exposure (in USD bn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>21</td>
<td>1.0</td>
</tr>
<tr>
<td>2018</td>
<td>93</td>
<td>5.5</td>
</tr>
<tr>
<td>2011</td>
<td>167</td>
<td>18.3</td>
</tr>
<tr>
<td>2018</td>
<td>216</td>
<td>27.5</td>
</tr>
</tbody>
</table>

* This includes the insured satellites in medium Earth orbit (MEO)

The classic single satellite insurance product

The launch and in-orbit insurance policy designed for single satellite or space objects can trace its origins back to the 1970s. It was initially developed within the aviation insurance market and over time developed into a distinct specialist class of insurance providing what is essentially a first party property insurance policy which responds in the event of loss – either partial or total – to the satellite.

The market developed and matured as the number, value and scope of satellites increased. New insurers began to underwrite the class, existing insurers increased their participation, and terms and conditions were established to reflect the requirements of the satellites’ owners and operators.

The typical coverage provided by the dedicated space insurance market is designed to respond to losses during the launch (usually defined as intentional ignition of the launch vehicle’s engine) and in-orbit or “life” phases of the satellite operation, which includes in-orbit commissioning and generally a portion of the satellite’s subsequent operational life.

Coverage for launch and in-orbit policies is typically purchased by the owner or operator of the satellite, and they have predominantly purchased such coverage for a one-year period following a launch, although market conditions have been dictating that insurers are now increasingly prepared to provide initial coverage for up to five years or indeed the entire operational life of the satellite. After this initial ‘launch plus’ policy expires, many operators choose to purchase annual renewal policies for in-orbit coverage throughout the remainder of the satellite’s mission life.
The satellite is underwritten on an agreed value basis which in turn is usually determined by reference to the satellite’s net book value or replacement cost and the cost of launching a replacement satellite.

The trigger for any loss is defined in terms of an occurrence or event leading to the loss of performance or lifetime of the insured satellite and may vary according to the satellite’s payload and mission. More generally, the policy is an all-risk policy designed to cover the loss, damage, malfunction or any defect that impacts the operation of the satellite. Depending on the loss criteria specified in the policy, this includes loss, damage, malfunction or defect caused by collision with space debris.

The standard policy language for classic satellite launch and in-orbit insurance coverage does not normally include a deductible element or percentage of the overall loss that the insured ultimately retains.

The operator of the satellite may also purchase coverage providing the insured with financial protection for any liability that is attributable to the insured/operator. This type of third party liability coverage is designed to address liability arising from:

- damage on the ground from re-entering satellite debris
- damage occasioned in space – such as impact to, or collision with, another satellite in orbit, eg in the scenario described in the preceding chapter. A legal perspective
- damage to persons and property on the ground (see below for the launch phase)

As far as the launch phase is concerned, third party liability insurance is typically purchased by the launch provider. For example, a US-licensed launch provider is required to procure third party liability insurance for the launch for itself and its satellite customer. 51 USC §50 914(a). The insurance must cover the launch provider, its satellite customers and the US government, and the respective contractors and subcontractors of each, as additional insureds. 14 CFR § 440.9(b). The insurance must be in place for 30 days following the later of payload separation, attempted payload separation, or ignition of the launch vehicle. 14 CFR § 440.11(a)(2).

The new space era: Covering multiple satellite constellations

Unlike its single satellite insurance counterpart, the constellation insurance product is designed to consider the impact of losses within the overall network or system of satellites. Depending on the nature of the particular system, the failure of a single satellite or, more commonly, a series of failures across multiple satellites may impact the overall functionality of the constellation. In other words, the insurance product may be expected to respond to the sum of all parts (ie the satellites) that make up the whole (ie the constellation). The trigger for such coverage must therefore be carefully defined to cater for the individual requirements of the constellation owner/insured. As such, it is a truly bespoke insurance product.

In common with its classic launch and in-orbit insurance counterpart, a constellation policy is likely to provide coverage for the launch phase, followed by commissioning and a period of life in orbit.
Constellation coverage: Unique considerations for underwriters

Beyond the basic elements of satellite coverage, constellation insurers need to take into account a set of distinct considerations.

- Constellations are generally deployed with multiple satellites on board several launch vehicles. This accumulation of risk means that a total launch failure is likely to have a material impact on the operations of the overall constellation.

- The launch of multiple satellites also usually requires the use of an additional structure – known as a dispenser – to deploy each individual satellite from the launch vehicle. This dispenser may be custom-designed for the mission in question and consequently may not share the same heritage as the launch vehicle itself. It also presents an increased risk of partial losses during launch in the event that the launcher itself performs as planned but one or more satellites fail to deploy successfully from the dispenser.

- Deploying a constellation often requires multiple launches (sometimes 10 or more), typically over a period of months to years. This again creates additional risk exposure and adds a layer of complexity to the coverage design.

- The constellation operator may not require coverage for each and every satellite lost, as they may have planned redundancy in orbit or on the ground or some other contingency which allows some form of loss retention even in the event of a total loss during launch.

- Likewise, while coverage typically continues through commissioning and life in orbit, the risk profile varies considerably. One obvious distinction is that constellations are more complex in themselves than large single satellites in GEO, as they are made up of multiple smaller satellites, possibly operating in more than one plane and usually orbiting the Earth many times a day in LEO. The smaller satellites may incorporate new technologies and manufacturing processes and may be built by new entrants to the market. This again introduces new and different risks that insurers must evaluate.

- During the in-orbit phase, coverage is also much more dependent on the nature of the constellation itself.

Designing the loss criteria in the policy

As with classic satellite insurance, constellation insurance policies typically define an expected performance and/or lifetime, and the coverage is structured to compare the actual performance and/or lifetime with this definition following an event or occurrence under the policy.

However, for a constellation a great deal will depend on the particular application and design, and loss triggers will vary accordingly. In some cases, there may be high levels of interdependence between satellites, while in other constellation formations, individual satellites may be critical. The constellation design may anticipate a certain number of individual satellite failures before any performance shortfall is experienced, or each satellite may be required to deliver the full service.

A constellation may consist of groups of satellites operating in a number of orbital planes, for example in the scenario described in Chapter 3, A legal perspective, whereby the NasirSat constellation is comprised of four planes. The performance of the constellation may be affected by a certain number of failures within individual or multiple planes.
In contrast to the classic insurance product for individual satellites, both the performance and lifetime aspects for constellations may be relatively complex because of the need to deploy the constellation over multiple launches. This may require a longer than normal policy and/or coverage period than a typical policy period allows. The performance of the constellation will also vary until commissioning of the final satellite is completed after the last launch. Again, this requires a specific and bespoke approach within the policy wording.

**Careful consideration of deductibles in the context of constellation coverage**

Where satellite redundancy is available (eg in the form of in-orbit spare satellites), the policy will typically feature some form of coverage excess or deductible. In the legal perspective scenario detailed in Chapter 3, for example, the deductible for the NasirSat constellation policy provided for a deductible of three satellites in each of the four planes which, given the circumstances of the loss described in that loss scenario, ultimately precluded recovery under the policy for the insured, NasirSat, as the loss falls within the agreed policy deductible. This leads to consideration of pursuing recovery against Top View through the legal channels described in Chapter 3.

**Constellation coverage and collision: Heightened risk**

In common with classic insurance products for individual satellites, the underlying policy for satellite constellations can be described as an all-risk policy designed to cover the loss, damage, malfunction or any defect that impacts the operation of defined elements of the constellation. In a LEO constellation with multiple satellites orbiting the Earth multiple times a day, and with potential areas of concentration (such as over the poles), the collision risk is clearly a significant additional consideration for insurers.

Given the heightened probability of debris impact in LEO compared to GEO, insureds operating in LEO, especially in the most exposed regions around 800km, as described in Chapter 2, should give additional consideration to damage to their satellites as a result of such debris impact.

Depending on the terms of the policy, insurance coverage for a constellation would extend to loss, damage, malfunction or defect caused by a collision with space debris. The factors described above mean that the issue is of greater importance for insurers providing coverage for satellites or constellations in LEO as compared to GEO.

**In summary: A multi-dimensional challenge**

Insurance policies for satellite constellations normally take all the above factors into account, with definitions and loss triggers dependent upon the performance and lifetime of the satellites themselves, of individual or multiple planes, of the overall constellation or more commonly a combination of all three.

The interaction between each of these elements, the availability of in-orbit redundancy and the time element from the multi-launch deployment adds further complexity and gives constellation insurance programmes a truly multi-dimensional nature.

As constellations develop, it is foreseeable that insureds will seek coverage for overall constellation performance irrespective of the underlying losses of individual satellites or planes which make up the constellation.
While it is currently the parts of the constellation that make up the whole in terms of insurance coverage and design, in the future the insurance product may simply transition and evolve to coverage intended only for the successful operation of the constellation as a whole, regardless of the parts! For insurers to take that step, more experience with constellation behaviour and a deeper understanding of the functioning of the constellation as a whole may be required, including whether the insured has the opportunity effectively to replenish the constellation in the event of individual satellite failures that impair the functioning of the constellation.

**Constellation collision and third party coverage:**
**A more compelling argument**

Irrespective of whether the insured is operating a singularly high agreed valued communications satellite primarily positioned in GEO or a multiple satellite constellation positioned in LEO, it should consider purchasing third party liability coverage. As the coverage described above and in our hypothetical scenario, Top View would have benefited from such insurance coverage if it was considered to be legally liable to NasirSat. Unfortunately, Top View elected not to purchase such third party coverage and is therefore in any event required to absorb any recoverable third party damages and the associated financial losses on its own.

**The insurers’ response to the new challenge of constellation policies**

As the demand for constellation coverage evolves, so too will the corresponding insurance policies and their unique and bespoke requirements. This will continue to pose a challenge for insurers, although with insurance underwriters devoting more time and developing a better understanding of their unique characteristics and idiosyncrasies, this is not an insurmountable task for the insurance community.

Indeed, the insurance market is already providing such coverage for the growing number of constellations being deployed into orbit. To date, the issues of collision avoidance, situational awareness and deorbiting of decommissioned satellites have formed a background part of insurers’ overall risk assessment for both GEO and LEO insurance programmes. In the future, the probability and consequence of collision are likely to become more primary considerations when underwriting this highly specialised class of business.

**Conclusion**

With many new market players entering the space industry and increasing numbers of satellite constellations, the population of active satellites in orbit is set to multiply over the next five to ten years. The potential impact on the space environment could be significant and in fact challenges the existing business paradigms for satellite manufacturing, launch, operation and insurance.

The real challenge for the insurance market, as both chapters 2 and 3 of this publication demonstrate, will be to find a way to reconcile the carefully crafted insurance product that responds to the bespoke requirements of the constellation operators with the heightened risk that the deployment of such a large number of new satellites clustered in an already densely populated LEO increasingly poses.

Swiss Re Corporate Solutions has been one of the leaders in the space insurance industry for many years and has continually adapted its solutions as the space market advanced. Working in close collaboration with space operators and brokers, we draw up and implement innovative and tailor-made solutions that address the changing needs of this rapidly growing and highly specialised industry. We look forward to continuing our journey together, helping to enable progress and make the world more resilient.
Computer-generated image of objects in Earth orbits from a vantage point above the North Pole.
2. A technical perspective

Endnotes


3. A legal perspective

Endnotes


5. Liability Convention, supra note 2.
6. Id., art. 9.
7. Id., art 1.
8. Id., Preamble, Fourth Clause.
9. Id., art. 1(a).
10. See C.Q. CHRISTOL, THE MODERN INTERNATIONAL LAW OF OUTER SPACE (Pergamon Press, 1982), at 95 (citing Staff of Senate Committee of Aeronautical and Space Sciences, Convention on International Liability for Damage Caused by Space Objects, Analysis and Background, 92nd Cong., 2nd Sess. 44 (Committee Print 1972)).
11. C.Q. CHRISTOL, supra note 10, at 96 (citing F.W. Foster, Convention on International Liability for Damage Caused by Space Objects, 10 Y.B.I.L. 141–142 (1972)).
16. Liability Convention, art. 3.
17. Id., art. 6.
18. Id., art. 12.
19. Id.
20. Id., Preamble, Fourth Clause.
22. Id., art. 11.2.
24. Outer Space Treaty, art. 8 (“A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body.”); see Convention on Registration of Objects Launched Into Outer Space, Jan. 14, 1975, 1023 U.N.T.S. 15. The U.S. registers satellites licensed by it.
25. “A federal court has discretion to dismiss a case on the ground of forum non conveniens ‘when an alternative forum has jurisdiction to hear [the] case, and... trial in the chosen forum would establish ... oppressiveness and vexation to a defendant... out of all proportion to plaintiff’s convenience, or... the chosen forum [is] inappropriate because of considerations affecting the court’s own administrative and legal problems.’” Sinochem Int’l Co. v. Malay. Int’l Shipping Corp., 549 U.S. 422, 429, 127 S. Ct. 1184, 1190 (2007) (citing American

27. U.S. Constitution, art. 6 (treaties are the supreme law of the land). See American Banana Co. v. United Fruit Co., 213 U.S. 347, 356–357 (1909) (recognizing that “in regions subject to no sovereign, like the high seas... [nations] may treat some relations between their citizens as governed by their own law.”)

28. The Supreme Court has held that “except in matters governed by the Federal Constitution or by acts of Congress, the law to be applied in any case is the law of the [forum] state,” including state statutory and common law.” Cnty. of Orange v. United States Dist. Court, 784 F.3d 520, 527 (9th Cir. 2015) (quoting Erie R.R. v. Tompkins, 304 U.S. 64, 78 (1938)). “Erie has come to stand for the general principle that ‘federal courts sitting in diversity apply state substantive law and federal procedural law.’” Id. (citing Gasperini v. Ctr. for Humanities, 518 U.S. 415, 427 (1996)).

29. Under California law, “everyone is responsible... for an injury occasioned to another by his or her want of ordinary care...” Cal. Civ. Code § 1714(a).


31. 47 C.F.R. § 25.114(d)(14)(iv) (requiring applicants to the FCC for a license to operate a satellite system to include a “statement detailing the post-mission disposal plans for the [satellite] at end of life, including the quantity of fuel – if any – that will be reserved for post-mission disposal maneuvers”); 15 C.F.R. Part 960, Appx. 1(d), Sec. V(C) (requiring an applicant for a remote-sensing license from NOAA to “submit a plan for post-mission disposition of any remote-sensing satellites owned or operated by the applicant”).


33. “See supra note 1 (setting forth the policy).

34. See, e.g., Dillon v. Legg, 441 P.2d 912, 921 (Cal. 1968) (remarking that a court will decide whether an “ordinary man under such circumstances should reasonably have foreseen [the accident and loss]”); see also Cooper v. Tokyo Elec. Power Co., 166 F. Supp. 3d 1103, 1119–20 (S.D. Cal. 2015) (cautioning that “the defendant will nevertheless be absolved where there is an independent intervening act that was not reasonably foreseeable...,” i.e., a “superseding cause”).

35. See Evan F. v. Hughson United Methodist Church, 10 Cal. Rptr. 2d 748, 752 (Cal. Ct. App. 1992) (explaining the “two basic components” of proximate cause); see also Alvarez-Machain v. United States, 266 F.3d 1045, 1054-55 (9th Cir. 2001) (“Under California law, a person proximately causes a loss if his actions were a substantial factor in increasing the likelihood of the loss.” (citing Vickers v. United States, 228 F.3d 944, 956 (9th Cir. 2000))).

36. See Hughson United Methodist Church, 10 Cal. Rptr. 2d at 753. Lawson v. Safeway Inc., 119 Cal. Rptr. 3d 366, 379 (Cal. Ct. App. 2010) (discussing when a third party’s intervening act may rise to become “a superseding cause”). Contributing causes do not necessarily preclude proximate cause, even if the contributing clause is substantial, so long as it can be established that Top
View’s conduct was also substantial and that the damage would not have occurred without Top View’s conduct. See id.

37. California Civil Code § 3333.

38. J’Aire Corp. v. Gregory, 598 P.2d 60, 63 (Cal. 1979) (citation omitted).

39. Lucky v. Turner, 53 Cal. Rptr. 628, 633 (Cal. Dist. Ct. App. 1966) (“The basis of this principle is that where the operation of an established business is prevented or interrupted by a tort, damages for loss of prospective profits, that otherwise might have been made from its operation, are ordinarily recoverable for the reason that their occurrence and extent may be ascertained with reasonable certainty from the working experience of the business, from the past volume of the business, and other provable data relevant to the probable future sales.”).

40. Id. at 634 (“[A] defendant cannot complain if the probable profits are of necessity estimated, the rationale being that it was the defendant himself who prevented the plaintiff from realizing profits.”).


42. “Huang v. The Bicycle Casino, Inc., 208 Cal. Rptr. 3d 591, 600–01 (Cal. Dist. Ct. App. 2016) (“We evaluate foreseeability at a relatively broad level of factual generality. [citation omitted] Thus, our task ‘is not to decide whether a particular plaintiff’s injury was reasonably foreseeable in light of a particular defendant’s conduct... [Instead, we must] evaluate more generally whether the category of negligent conduct at issue is sufficiently likely to result in the kind of harm experienced that liability may appropriately be imposed [on the negligent party].” (internal quotations and citations omitted)).

43. 47 C.F.R. § 25.114(d)(14) (requiring, among other requirements, “[a] statement detailing the post-mission disposal plans for the space station at end of life, including the quantity of fuel — if any — that will be reserved for post-mission disposal maneuvers”).

44. 15 C.F.R. Part 960, Appx. 1(d), Sec. V(C) (requiring an applicant for a remote-sensing license from NOAA to “submit a plan for post-mission disposition of any remote-sensing satellites owned or operated by the applicant”).

45. See supra note 1, ¶ 84.

46. Id.

47. Id. ¶ 90 and n.232.

4. New Space – More challenges for insurers ahead?

Endnotes

1. By comparison, coverage prior to launch is provided by a separate and distinct insurance market that offers protection from the moment the satellite leaves the manufacturer’s premises until the moment of launch.