United Nations A/AC.105/C.1/115

General Assembly

Distr.: General
13 November 2018
English
Original: English/Spanish

**Committee on the Peaceful Uses of Outer Space**
**Scientific and Technical Subcommittee**
**Fifty-sixth session**
Vienna, 11–22 February 2019
Item 7 of the provisional agenda*
**Space debris**

# Research on space debris, safety of space objects with nuclear power sources on board and problems relating to their collision with space debris

## Note by the Secretariat

## I. Introduction

1. At its fifty-fifth session, the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space agreed that Member States and international organizations having permanent observer status with the Committee should continue to be invited to provide reports on research on space debris, the safety of space objects with nuclear power sources on board, problems relating to the collision of such space objects with space debris and the ways in which debris mitigation guidelines were being implemented (see A/AC.105/1167, para. 146). Accordingly, a communication dated 29 August 2018 was sent to Member States and international organizations with permanent observer status, inviting them to provide their reports by 5 November 2018 so that the information could be made available to the Subcommittee at its fifty-sixth session.

2. The present document has been prepared by the Secretariat on the basis of information received from two Member States, namely Japan and Mexico, and from the International Astronautical Federation (IAF). Further information provided by Japan and IAF, which includes figures related to space debris, will be made available as a conference room paper at the fifty-sixth session of the Subcommittee.

* A/AC.105/C.1/L.373.

V.18-07683 (E) 201118 211118

Please recycle

# II. Replies received from Member States

## Japan

[Original: English]
[2 November 2018]

**Overview**

Responding to a request from the Office for Outer Space Affairs of the Secretariat, Japan reports that its debris-related activities are conducted mainly at the Japan Aerospace Exploration Agency (JAXA).

The following debris-related activities conducted at JAXA during 2018 have been selected as examples of major progress to be presented at the next session:

(a) The thirty-sixth annual meeting of Inter-Agency Space Debris Coordination Committee (IADC);

(b) Conjunction assessment results and research on core technology for space situational awareness;

(c) Research on technology to observe objects in low-Earth and geosynchronous Earth orbits and determine their orbits;

(d) In situ microdebris measurement system;

(e) Protection from impact of microdebris;

(f) Propellant tank easy to demise during re-entry;

(g) Active debris removal.

**Status**

*The thirty-sixth annual meeting of the Inter-Agency Space Debris Coordination Committee*

The thirty-sixth annual meeting of IADC was held in June in Tsukuba, Japan. More than 100 technical experts from 11 agencies participated in this meeting. JAXA organized and hosted this meeting. The main topics were:

- IADC statement on large constellations of satellites in low-Earth orbit

  IADC has already released the statement which has only qualitative considerations on large constellations, because there were limited research results on the impact of large constellations on the space debris environment at that time. In this meeting, the simulation results on large constellations performed by IADC members was shown and IADC members reached a consensus that large constellations have a negative impact on the space debris environment. Thus, an update of the statement, including more limiting conditions with numerical figures, is being prepared among IADC members.

- IADC Space Debris Mitigation Guidelines

  The Guidelines were released in 2002 and revised in 2007. Currently, many countries and international entities are beginning to prescribe quantitative conditions on space debris mitigation for their standards, whereas for the Guidelines a large number of qualitative expressions had to be adopted. Therefore, IADC began discussions to update the Guidelines with numerical values in order to build more concrete common understanding among members.

*Conjunction assessment results and research on core technology for space situational awareness*

JAXA receives conjunction notifications from the Combined Space Operations Center. As at August 2018, 131 meetings had been held to consider a collision avoidance manoeuvre based on notifications, and JAXA has executed 26 collision avoidance manoeuvres for low-Earth orbit spacecraft since 2009.

*Core technology for space situational awareness*

JAXA determines the orbit of space objects using radar sensor at Kamisaibara Spaceguard Center and optical sensor at Bisei Spaceguard Center, predicts close approaches using the latest orbit ephemerides of JAXA satellites and calculates the probability of collision. JAXA also evaluates the criteria for conjunction assessment and collision avoidance manoeuvres based on our experiences. In the evaluations, the trends of each conjunction condition and of prediction errors due to perturbations (e.g., uncertainty in air drag) are analysed.

**Research on technology to observe objects in low-Earth orbit and geosynchronous Earth orbit, and determine their orbits**

Generally, objects in low-Earth orbit are observed mainly by radar, but JAXA has been endeavouring to apply the optical system to reduce the cost of both construction and operation. A large complementary metal-oxide semiconductor (CMOS) sensor for the observation of low-Earth orbits was developed. Analysing the data from the CMOS sensor with the field-programmable gate array (FPGA)-based image-processing technologies developed at JAXA enable us to detect objects in low-Earth orbit that are 10 cm or less in size. An optical observation network to reduce the load of collision avoidance was considered, using real weather data of the National Oceanic and Atmospheric Administration of the United States of America. In order to increase the observation opportunities of objects in low-Earth and geosynchronous Earth orbits, a remote observation site was established in Australia, in addition to the Mount Nyukasa observatory in Japan. Two 25-cm telescopes and one 18-cm telescope are available for various objectives.

*Protection from impact of microdebris*

The amount of microdebris (less than 1 mm in diameter) in low-Earth orbit has increased. The impact of microdebris can inflict critical damage on a satellite because its impact velocity is 10 km/s on average.

To assess debris impact on a satellite, JAXA has developed a debris impact risk assessment tool named Turandot. Turandot analyses debris impact risks against a three-dimensional model of a spacecraft.

*Propellant tank that is easy to demise during re-entry*

A propellant tank is usually made of a titanium alloy, which is superior because of its light weight and good chemical compatibility with the propellant. But its melting point is so high that such propellant tanks would not demise during re-entry, and it would risk causing casualties on the ground.

Since 2010, JAXA has conducted research to develop an aluminium-lined tank overwrapped with a carbon composite that melts at lower temperatures. As a feasibility study, JAXA has conducted fundamental tests, including a test to see whether the aluminium liner material was compatible with the propellant hydrazine, as well as an arc heating test.

After the manufacture and testing of the shorter engineering model EM-1 tank, the full-size EM-2 tank was manufactured. The shape of the EM-2 tank is the same as that of the nominal tank, which includes a propellant management device. A proof pressure test, vibration test (under wet and dry conditions), external leak test, pressure cycle test, and burst pressure test were conducted and all showed good results. Following the manufacture of the EM-2 tank, the manufacture and testing of a prototype model is planned.

This composite propellant tank has a shorter delivery period and lower cost compared with a titanium propellant tank. However, additional studies and tests are ongoing to determine the demisability during atmospheric re-entry.

*Active debris removal*

JAXA has organized and structured a research programme aimed at realizing a low-cost active debris removal mission. The research and development of key technology for active debris removal has three major themes: non-cooperative rendezvous, capture technology for non-cooperative targets, and de-orbiting technology to remove massive intact space debris. JAXA is cooperating with private companies in Japan pursuing low-cost active debris removal as a business and working to provide these essential key technologies for the purpose.

An electrodynamic tether is a prospective candidate for the de-orbit propulsion in active debris removal activities because it can contribute to downsizing the overall system and thus lowering the cost. To demonstrate some of the technologies that are essential to the electrodynamic tether, JAXA planned and conducted the KITE mission, which was an on-orbit experiment with the electrodynamic tether on the H-II Transfer Vehicle 6 (HTV-6), conducted in 2017. Although tether deployment was unsuccessful, the field emission cathode, which is an essential part of the electrodynamic tether system, was operated well and effective on-orbit data were obtained for further development of the electrodynamic tether.

## Mexico

[Original: Spanish]
[7 November 2018]

Mexico, through the Mexican Space Agency, has been collaborating with the Working Group on the Long-term Sustainability of Outer Space Activities in the four expert groups on sustainable space utilization supporting sustainable development on Earth (expert group A); space debris (expert group B); space weather (expert group C); and regulatory regimes and guidance for actors in the space arena (expert group D).

In that regard, with respect to national research on space debris and in accordance with practice relating to the elimination of such debris, Mexico, through its public universities, has undertaken research on that topic. For example, the National Autonomous University of Mexico, through its Faculty of Engineering and its High Technology Centre in Juriquilla, Querétaro, has been carrying out work aimed at planning future missions with a focus on sustainability.

That work covers the detection of space particles, the development of mathematical models of debris generation, the measurement of such debris and the creation of protection plans. Furthermore, the National Autonomous University of Mexico is working to install a vacuum chamber and an electromagnetic radiation chamber for testing satellites and their capacity to cancel out such interference, which reduces the likelihood that they will malfunction during space operations and become space debris. Work is also being carried out to develop electrical power propulsion units in order to ensure that once satellites reach the end of their useful life, they leave their orbit, re-enter the Earth’s atmosphere and disintegrate, thus avoiding the generation of additional space debris.

With respect to the monitoring of space debris in order to ensure the safety of space infrastructure, the Autonomous University of Sinaloa, through the use of its telescope, has joined international efforts led by the International Scientific Optical Network. Space debris has been monitored since 2012, and almost a dozen new objects are discovered every year, including fragments and lost satellites beyond the geostationary orbit. The astronomical observatory jointly operated by the Autonomous University of Sinaloa and the International Scientific Optical Network records up to 864 images per night, and between 30 and 70 space objects are detected. Under the programme, automatic processing is carried out and coordinates are noted. The recording can also be carried out manually.

The Centre for Research on Physical and Mathematical Sciences of the Autonomous University of Nuevo León, which is part of the international project for monitoring space debris comprising a network of 25 observatories in more than 15 countries under the coordination of the Keldysh Institute of the Russian Academy of Sciences, has also joined those efforts. The space debris observatory at the University, operated by the Faculty of Physical and Mathematical Sciences, is also involved. The observatory conducts space debris monitoring with the aim of identifying debris that could cause damage to satellites and, as a result, disrupt services such as mobile telephone signals or flights, or cause GPS errors.

In addition, the National Polytechnic Institute and the Ticomán School of Mechanical and Electrical Engineering (ESIME) founded the ESIME Ticomán Aerospace Association, one of the activities of which is to carry out research on subjects such as space debris. Those bodies frequently publish articles on the topic, disseminating information within the Institute and among the general public.

Another organization, operating since 2011, is the Science and Technology Network, a group of researchers interested in space technology and science in Mexico who seek to raise funds to conduct multidisciplinary seminars, workshops and projects involving coordination among national and international actors from academia, government institutions, businesses and civil society, with the aim of promoting the development of space technology and science in Mexico. One of its specific objectives is to foster research on scientific topics such as space debris, implementing annual projects and encouraging Mexican experts and researchers to take part in that research.

All of the aforementioned activities are conducted in accordance with international regulations, such as the Space Debris Mitigation Guidelines of the Inter-Agency Space Debris Coordination Committee, International Telecommunication Union recommendation ITU-R S.1003 on environmental protection of the geostationary-satellite orbit, the standards of the European Code of Conduct for Space Debris Mitigation and International Organization for Standardization standard ISO 24113 on space systems: space debris mitigation requirements.

Mexico also took part, along with Germany, Canada and Czechia, in the initiative to create a compendium of space debris mitigation standards, which was presented at the fifty-third session of the Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space. It is the first document to contain information contributed by Member States, including Mexico, on their regulatory measures to reduce and eliminate space debris.

**Safety of space objects with nuclear power sources on board and problems relating to the collision of such objects with space debris**

This topic is addressed in the guidelines for the long-term sustainability of outer space activities. In accordance with the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty), Mexico has maintained its position in favour of the non-militarization of outer space and the peaceful uses of outer space. The use of nuclear power sources is not part of any of its space-related programmes. The standards issued by the International Atomic Energy Agency govern the use of such power sources. In that regard, and in all matters relating to the use of nuclear power sources, the safety of humans in outer space and of the outer space environment are key elements.

In this respect, the aforementioned guidelines provide an essential foundation for the safety framework.

Neither the Principles Relevant to the Use of Nuclear Power Sources in Outer Space nor the guidelines are binding. Article IV of the Outer Space Treaty provides protection, albeit to a limited extent.

# III. Replies received from international organizations

## International Astronautical Federation

[Original: English]
[5 November 2018]

**Ensuring the future sustainability of space operations: the orbital debris question**

*An ever-growing orbital population*

The first ever launch to orbit, that of Sputnik 1, on 4 October 1957, opened the field to all the space applications that we enjoy today. Our daily lives depend more and more on applications that turn out to be indispensable and of strategic importance for the climate and for telecommunications, localization, security, defence, science and exploration. Those applications are also of great economic importance, with millions of jobs throughout the world and trillions of euros in corresponding activities.

However, one has to realize that the flight of Sputnik 1 also marked the very first step in orbital pollution; on the very same orbit as the 82 kg satellite was the main stage which brought it to orbit, the 6.5 tons Semiorka Block A, and a small 100 kg fairing which protected Sputnik during the atmospheric ascent. Thus, nearly 99 per cent of the mass injected into orbit had no useful function there. Sputnik emitted its beep-beep during 21 days, but spent a total of 92 days in orbit before re-entering the atmosphere. It means that the satellite had no useful function during three quarters of its orbital life. This “dead” satellite, its main rocket stage, and the protective cap were all artificial, orbital, non-functional objects, which is the definition of orbital debris.

Since 1957, the number of objects in orbit and their mass has drastically increased.

It is obviously a sign of good health of the space sector and the near-explosion of the number of associated applications, but it also raises questions about the long-term sustainability of our orbital operations. The mass of objects in orbit has increased linearly since 1957, reaching nearly 8,000 tons nowadays, and the number of catalogued objects (large enough to be followed from the ground, typically 10 cm in low-Earth orbits or 1 m close to geostationary orbit) has now reached 20,000. Such a strong increase may seem surprising, given that the number of successful orbital launches has drastically decreased compared with the cold-war period (140 successful launches in 1967, 52 in 2005) and international regulations to control the increase in the orbital population were first put in place more than 20 years ago, in 1995.

Out of the 20,000 catalogued objects registered today, some 1,700 are active satellites; the remainder are space debris, representing 92 per cent of the orbital population. This debris is found mostly in low-Earth orbits, with altitudes varying from 600 to 1,200 km, as well as in the vicinity of the geostationary orbit, at 35,800 km. Half of the catalogued debris consists of integer elements, dead satellites, upper stages left in orbit or leftovers from space operations; the other half consists of fragments of any size, residue from collisions or explosions in orbit.

In addition to these catalogued large objects, some 750,000 objects larger than 1 cm, and more than 170 million larger than 1 mm, also orbit the Earth.

These figures may appear impressive, but one has to keep in mind that space is infinitely wide above our heads. The 8,000 tons of artificial orbital objects, equivalent to the mass of the Eiffel Tower, are spread all around the space surrounding Earth.

The corresponding density is exceedingly small, reaching a maximum of 0.1 object per 1 million cubic km in the most densely populated region.

Nevertheless, these objects have three very distinctive characteristics. The first is that, once an object is in orbit, it generally remains there for a long time. For instance, a satellite placed at an altitude of 1,000 km will remain there for 1,000 or 2,000 years. The second is that it travels at an orbital velocity close to 8 km/s or 30,000 km/h. Such a velocity, integrated over thousands of years, constitutes a significant collision risk. The third is that any object placed into low-Earth orbit is bound to fall back to Earth and in doing so risks causing casualties.

**Orbital debris raises two major problems**

*Uncontrolled atmospheric re-entry of large space objects poses a risk to populations*

During re-entry, debris is fragmented by the very high dynamic pressure proportional to the square of the velocity. Next, the resulting fragments are submitted to very high thermal fluxes proportional to the cube of the velocity due to the friction with air molecules, which tends to melt and sublimate materials. Unfortunately, this process is generally incomplete and some 10 to 20 per cent of the total mass of the debris may survive re-entry, depending on its design. Refractory materials, such as titanium, carbon and some varieties of steel, do not melt during re-entry and strike the surface of the globe.

Fortunately, 71 per cent of the Earth’s surface is covered with water, the rest being composed mostly of large desert areas. Densely populated zones represent only 3 per cent of the Earth’s surface, so the risk to populations remains low.

To indicate the order of magnitude, one large satellite or launcher stage a week re-enters the atmosphere randomly, causing a risk of 1 in 10,000 to hurt someone. To date this has never resulted in any known casualties, although numerous large pieces of debris have been found near inhabited zones, with some rare occurrences of minor damage to buildings. The problem hangs over our heads like a sword of Damocles: we continue to launch large stages or satellites, knowing that they will end up re-entering randomly, generating considerable risk to populations.

*Collision risk in orbit*

Collisions have different consequences. They no longer are a problem of safety, but a commercial risk associated with damage done to active satellites, useful or often fundamental to our everyday lives.

There are several potential risks.

A collision between a small piece of uncatalogued debris and an active satellite can cause the functional loss of the spacecraft. The kinetic energy released in a collision is extremely high (a collision with a piece of debris 1 mm in diameter has an energy of 1 kilojoule, equivalent to that of a bowling ball launched at 100 km/h). Under those circumstances, even a small impact can cause the loss of a satellite, for instance if it hits the on-board computer. Several studies have shown that the probability of losing a satellite due to a collision is in the order of magnitude of 5 per cent. Space debris is currently the first cause of satellite losses in orbit. As small debris is by definition uncatalogued, and therefore hidden from view, there is no way to prevent such collisions.

Collisions between large objects occur very seldom, once every five to eight years, depending on the model. However, each collision generates a large amount of new debris and can therefore increase significantly the global risk in orbit. This regeneration effect following collisions raises the risk of an uncontrolled increase of the amount of debris. It is known as the Kessler syndrome and was theorized as early as 1978. It could lead to an uncontrollable situation, even if we stopped any space activity in the future. As an example, the collision between two satellites, Iridium 33 and Kosmos 2251 in February 2009 generated over 2,200 pieces of large catalogued debris and a myriad of smaller ones.

Simulations led by the National Aeronautics and Space Administration (NASA) of the United States of America, then by seven agencies of the Inter-Agency Space Debris Coordination Committee (IADC), show that even if we completely stop all space activity, the amount of orbital debris would increase exponentially in the coming years. As an illustration, the results of simulations led by NASA considering no further launches after 2006 show a clear long-term increase due to collisions between large objects.

**Measures aimed at limiting the number of orbital debris in the future and guaranteeing sustainable operations in space**

*An international set of requirements, efficient and widely accepted*

The most important measure, indeed fundamental, is to set rules at the international level to prevent the generation of new debris as a result of future space operations. This is known as space debris mitigation, and it can be summarized by five high-level actions.

First, it is compulsory to limit the generation of debris during normal launch operations, and to avoid any voluntary destruction of satellites in orbit.

Second, accidental explosions in orbit must be avoided by passivating all space objects left in orbit, i.e., by eliminating any stored energy sources such as residual propellants, tank pressurization and battery energy, or by stopping the inertia wheels.

Third, it is necessary to limit the orbital life of space objects. It is required that satellites and the upper stages of launchers remain in two protected zones for less than 25 years after their operational life has ended, namely the low-Earth orbits and the vicinity of the geostationary orbit.

The fourth measure is to recommend that satellite operators do their best to prevent in-orbit collisions when information is available with adequate precision and the satellite is manoeuvrable.

Last, it is recommended that the risk posed to populations by uncontrolled atmospheric re-entries be minimized. To that end, operators should perform a controlled re-entry for any mission posing a casualty risk larger than 1 in 10,000.

These rules can be found in numerous texts, both at national and international levels. The following list is aimed only at showing that such recommendations have been made for more than 20 years now.

The very first publication expressing concern about the long-term sustainability of space operations appears to be a Japanese paper dated 1971. Following those initial reflexions, numerous other references were made in work published by NASA, starting in 1974, and in work published in Europe by 1987, leading to the first national standards, notably those issued by NASA in 1995, the National Space Development Agency of Japan, now the Japan Aerospace Exploration Agency, in 1996 and the Centre national d'études spatiales, Paris, in 1999.

The first text adopted at the international level was the IADC Space Debris Mitigation Guidelines, a collection of recommendations prepared by IADC which currently groups the 13 main space agencies. It was adopted unanimously in 2002 and revised in 2007. A similar standard at the European level was finalized in 2000 and approved in June 2004.

The IADC Guidelines have been adapted by the space committee of the United Nations, the Committee on the Peaceful Uses of Outer Space and by the United Nations General Assembly in a resolution adopted during a plenary session in 2007.

France was the first country to enact a law dealing with the subject, the Space Operations Act (*Loi relative aux opérations spatiales*), which entered into force in 2010 and was amended in 2017.

Since 2011, the International Organization for Standardization (ISO) has issued a number of standards dedicated to space debris, in particular ISO standard 24113, which acts as the highest-level standard. That standard, if it could effectively be made applicable to all operators and constructors, would make it possible to slow down the increase in space pollution efficiently.

In parallel, in 2010, the Committee on the Peaceful Uses of Outer Space established the Working Group on the Long-term Sustainability of Outer Space Activities, tasked with producing a consensus report containing voluntary best-practice guidelines for all space actors to help to ensure the long-term sustainable use of outer space. The approval process of the 37 guidelines, by the consensus of all members, raised some difficult points, and so far, only 12 guidelines have been approved. However, the Working Group is still active, and once the complete compendium of United Nations guidelines is approved, it should turn out to be a very efficient tool.

Last, a dedicated charter has recently been prepared by a large number of operators, in which more stringent guidelines are proposed than in the other documents. This set of best practices has still draft status, and it is as yet unclear how it could become a regulatory document.

*Protection against impacts*

A second measure aimed at reducing the effect of the orbital population is to equip active satellites with shields. Metal or Kevlar sheets, or even dense foam, placed on the outside of a structural wall will shatter incoming debris and reduce it to a cloud of tiny particles unable to pierce or otherwise damage the main structure.

The potential assemblies are very diverse, depending on the type of debris to be stopped, and so are the orbit of the shielded satellite, its orientation and the criticality of the zones to protect. A very large number of tests are being performed throughout the world to find optimal combinations. Ground tests are performed using light gas guns, often two-staged, propelling small metallic marbles with a diameter of 1 mm to velocities up to 12 km/s.

Unfortunately, shields of the kinds described have limited effectiveness. They can protect a wall from impactors of up to 1 cm in diameter, but not really more. To avoid damage from the impact of larger debris, satellites therefore have to be manoeuvred out of harm’s way, and that is possible only if the orbit and position of that debris are known. Debris larger than 10 cm in diameter is catalogued and therefore satellites can be protected against it by performing a collision avoidance manoeuvre. However, it is not possible to protect satellites from debris that is smaller than 10 cm (because it cannot be catalogued) but larger than 1 cm (because protective shields cannot withstand it).

The shields also pose numerous problems of bulk, mass, cost, or even system problems such as the thermal equilibrium of the satellite. In practice, shields are currently deployed only on inhabited satellites such as the International Space Station, the European automated transfer vehicles, the Japanese H-II Transfer Vehicle, or some very large military satellites of the United States

*Collision avoidance*

An efficient measure to protect operational satellites equipped with on-board propulsion is to avoid collisions with catalogued objects.

This is a very complex activity, as one needs to “propagate” the orbits of all the potentially dangerous objects over several days in order to identify possible collisions. The statistical computations are based on collision probabilities determined by the covariance matrices of each object. Every alert triggers an analysis of the potential impactor's trajectory, winding back in the past, and can require dedicated measurements from dedicated space surveillance means, such as radars and telescopes. Some conjunction data messages are also directly provided by the Combined Space Operations Center.

This process takes advantage of existing space surveillance and tracking networks, mainly that of the United States, but also the International Scientific Optical Network, national networks, such as the French system based on the Grand Réseau Adapté à la Veille Spatiale (GRAVES), and commercial initiatives such as the AGI Commercial Space Operations Center or LeoLabs.

These analyses make it possible to see when a satellite must be manoeuvred to lower the probability of a collision. As a rough order of magnitude, each satellite will have to be manoeuvred once per year to avoid collisions.

The main problem is the lack of accuracy of the orbital parameters of the debris, typically in the range of 100 m to 1,000 m. This leads to an extremely high rate of false alarms, in the order of 99.99 per cent. One of the priority improvements required in the coming years is to gain orders of magnitude in orbital parameter accuracy. This could be achieved using laser ranging techniques, either from the ground or from orbit.

*Just-in-time collision avoidance between large pieces of non-manoeuvrable debris*

The collision avoidance process described in the previous paragraph addresses only active satellites, which represent less than 20 per cent of the very large objects in low-Earth orbit (satellite or launcher stage). This means that it is efficient in protecting operational satellites, but has no slowing effect on the increase of the orbital population due to collisions among large non-manoeuvrable objects, statistically predominant, and therefore has a limited role in ensuring the long-term sustainability of space operations.

An additional measure has therefore been under study in recent years, namely to avoid predictable collisions between large derelicts. The basic idea is that when a collision is likely in the following couple of days, i.e., when the probability of a collision is higher than an allowable threshold, a mission is carried out to adjust the trajectory of one of the two pieces of debris very slightly to avoid the collision or restore acceptable margins.

Various techniques of just-in-time collision avoidance are under study, mainly in the United States and France, consisting for instance of spreading a cloud of gas, dust or particles in front of the debris using a sounding rocket to briefly increase the drag and slow it down. These methods are very promising, as they appear to be much simpler to realize than active debris removal, and they would be used only in case of a highly probable collision, typically every five or six years. Other techniques, also jointly studied by the United States and France, make use of orbital lasers to adjust the trajectory of debris using very short but intense pulses, vaporizing locally the surface of the debris and slightly modifying its velocity. Proposals have even been made to continuously control the position of all large debris using a relatively small orbital laser to minimize the probability of collisions (large debris traffic management).

*Active debris removal*

A significant measure, under study for more than 15 years, is to retrieve very large, potentially dangerous debris, i.e., debris likely to generate the largest amount of secondary debris following a collision. This and similar measures are known as active debris removal.

This strategy follows the findings of studies made first by NASA, published in 2010, then by most of the IADC delegations. Assuming that the mitigation measures are very well complied with (no fragmentation in orbit, 25-year rule in low-Earth orbit), then the retrieval of 5 to 10 properly chosen large pieces of debris from the most populated orbits would be enough to stabilize the orbital population.

A very large number of potential solutions have been proposed, studied, and tested on the ground, in zero-gravity flight conditions and — recently — in orbit, with a view to “cleaning up” outer space. Those solutions fall into a number of categories (the following summary is not exhaustive).

First, there are a few contactless solutions, for instance the virtual electrostatic leash, or a laser to raise the orbit of old satellites abandoned in geostationary orbit.

Next, numerous solutions are derived from fishing techniques, using hooks, harpoons and nets to capture debris and pull it using a long tether until it re-enters the atmosphere in a controlled manner.

In addition, several ideas are based on increasing the drag of the debris in order to accelerate its loss of altitude, for instance using an ad hoc chaser to equip the debris with a large airbag or a sail, drastically increasing the surface of the assembly. It is also possible to install an electrodynamic tether on the debris, a conducting wire that interacts with the Earth’s ambient magnetic field to generate Lorentz forces that slow the debris down, thus reducing its orbital lifetime. These solutions have nevertheless significant drawbacks, as they induce uncontrolled re-entry and are thus potentially dangerous for populations.

Last, more conventional solutions consist of capturing debris with a robotic arm, with numerous variants based on tentacles or clamps holding it, then de-orbiting it in a controlled way to atmospheric re-entry.

The overall technical maturity of these solutions is high, and numerous demonstrations have already been performed, including in orbit. The main problems are therefore not technical in nature but financial, as such operations would be very costly in the absence of a clear business plan opening the way to commercial activities. There are also numerous legal hurdles linked to responsibility for the operations, or even military concerns, some of such operations potentially opening the way to the militarization of space.

These questions are actively considered within several working groups at the international level, in particular at the Committee on the Peaceful Uses of Outer Space under the initiative regarding the long-term sustainability of outer space activities. The first efforts in active debris removal could be undertaken sooner than hoped thanks to the arrival of space tugs. Several of these multipurpose orbital vehicles are currently under development, in particular in the United States and France, and de-orbiting large debris could be a space tug’s last action or end-of-life manoeuvre after completing its orbital operations. Development of orbital vehicles dedicated to the de-orbiting of stranded constellation satellites is also ongoing, showing the potential for a positive business plan in the domain of active debris removal.

## Conclusion: a preoccupying situation

*Compliance with the mitigation rules currently is very low*

The level of compliance is roughly 55 per cent overall, but this figure may be a bit optimistic, as it includes all the small satellites launched at low altitude, re-entering the atmosphere rapidly. Considering spacecraft at altitudes above 600 km only, the compliance level is lower than 20 per cent. Considering only satellites heavier than 100 kg, the compliance level drops to 6 per cent.

The mass and number of individual pieces of debris in orbit continue to grow without any sign of decrease. Numerous collisions and fragmentations continue to occur in orbit every year, and dozens of large objects continue to be released during launch operations, in addition to satellites and upper stages.

Numerous studies have shown that the level of compliance with the mitigation rules should be higher than 90 per cent if the expansion of debris in Earth orbit is to be limited.

*The emergence of nanosatellites raises numerous questions*

We are currently witnessing an explosion of the number of very small satellites injected into orbit. These CubeSats are game changers, smart satellites taking full advantage of miniaturization, offering a large number of space applications with a very low cost of development, production and launch. As a consequence, several hundreds of them are launched each year, but in most cases they have no propulsion, and are therefore unable to avoid collisions or reduce their orbital lifetime. They are often launched into high-altitude orbits and do not comply with the 25-year rule. Some 430 CubeSats were launched in 2017, and more than 500 per year are expected from 2018 onward.

IADC and ISO are currently defining additional rules for satellites with no capacity to avoid collisions, limiting their orbital lifetime to 25 years after launch and their altitude to about 600 km.

*Large constellations*

Large constellations raise a different problem. There are plans to launch constellations of satellites of 200 to 500 kg each by the thousands, generally on very stable orbits. As an example, under the One Web initiative, nearly 1,000 Internet satellites will be deployed as from mid-2018 on a circular highly inclined orbit at 1,200 km, stable for thousands of years. And this may be just the beginning. The Boeing Company has announced its own constellation of 2,900 satellites. SpaceX has announced its first constellation of 2,800 satellites and a second one with 7,500. In total, the Federal Communications Commission of the United States has received requests for more than 17,000 new satellites to be launched in the coming 10 years (as a reminder, there are only 1,700 active satellites today).

Operators are often newcomers, actors from Silicon Valley with no experience in space operations. However, they appear to be well aware of all the space debris mitigation rules, so there is still good hope that these massive operations on very stable orbits could lead to a controllable long-term situation, provided that the international rules are strictly adhered to.

*New radar space fence*

The Air Force of the United States is constructing a new S-band radar system known as Space Fence, which is to become operational in 2019. It will be capable of tracking objects significantly smaller than those catalogued today, potentially in the range of 3 cm to 5 cm in diameter. This additional asset in the space surveillance and tracking field is excellent news, but it means that the number of catalogued objects will rise by an order of magnitude, potentially to 200,000 objects. This will drastically increase the number of collision alerts if orbital accuracy does not significantly improve in parallel.

*Space traffic management*

There seems to be a growing awareness that swift action is needed to preserve orbital activities for the future. A lot of work is done internationally on space traffic management to ensure security in outer space, defined by the European Space Policy Institute as the protection of space infrastructure from natural and manmade threats and risks to ensure the sustainability of space activities. Some researchers propose the creation of a new international civil space organization with a very ambitious set of tasks ranging from the management of mitigation rules to the imposition of space access fees with powers of enforcement.

Such initiatives are good, but they are essentially aimed at protecting operational satellites in the short term. To date, almost no proposals have been made to avoid the creation of thousands of new pieces of debris resulting from collisions between non-manoeuvrable large debris. As long as there is no solution, future space operations will remain under significant threat.