Teka Komisji Prawniczej PAN Oddział w Lublinie, vol. XIV, 2021, no. 1, pp. 315-327
https://doi.org/10.32084/tekapr.2021.14.1-26

THE SPACE OBJECTS RE-ENTRY – STATUS AND CHALLENGES OF INTERNATIONAL REGULATORY FRAMEWORK

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Abstract. The basis of the international space regulatory framework relied on the United Nations Outer Space Treaty 1967. The purpose of the paper is to present and assess the current regulatory and legal framework with regards to space security re-entry risks. The particular regulation related to space debris and re-entry may be inferred from the basic international space law (UN space treaties). As surviving fragments originating from a particular space object (usually linked to the owner) may endanger people on the ground or operating aircraft, they are directly linked to the Liability Convention 1971. Therefore nations, international intergovernmental organizations, executive agencies, and non-governmental entities maintain their efforts to create and implement hard and soft laws. Those regulations concern the space environment and its challenges, such as the proliferation of space debris, the increasing activity of space operations, the emergence of mega constellations, and its effects on re-entry characteristics. The entire material included in this article comes from dedicated conferences and seminars about Space security and policy, legal documenttation, and literature review, which refer to re-entry in this subject. The research methods used in this article have comparative and analytical nature – based of the different sources of legislation.

Keywords: space security, re-entry, satellite, policy, space debris

INTRODUCTION

Since the beginning of the space era, i.e., the launch of Sputnik 1 spacecraft in 1957, space activities are concentrated around Earth's orbits. In spite of the fact that humanity performs, strengthens, and plans activities far beyond that is in deep space, Earth's orbits remain and will continue to dominate space activities in coming years as Earth's orbital space systems bring currently the greatest added value to societies and Earth's economy through communication, remote sensing or navigation services.[1] In the above context it is necessary to highlight that besides proper satellites, the orbital or space environment is predominantly both

[1] OECD. Background paper for the G20 Space Economy Leaders' Meeting. Measuring the economic impact of the Space Sector. October 7, 2020; OECD. The Space Economy in Figures: How Space Contributes to the Global Economy, OECD Publishing, 2019. https://www.oecd.org/innovation/inno/measuring-economic-impact-space-sector.pdf [accessed: 24.03.2021], p. 1–10.

oversaturated and concerned with space debris. In this sense, the orbital environment is a mix of all artificial objects, including fragments and elements thereof which currently or previously did, reside in an Earth-bound orbit, and space debris are considered as all artificial objects including fragments and elements thereof, in Earth orbit or reentering the atmosphere, that is non-functional.[2]

In recent decades orbital environment is affected by particular changes resulting from so-called "new space era" trends that will keep reshaping the space sector over the next decades. Among other factors, such as the decrease of launch costs, proliferation of launch and satellite technologies, new commercial and state entrants, commercialization of space, increasing number of space debris or more general democratization of space activities are significantly rebuilding the orbital environment. Moreover, one particular factor i.e., the creation of so-called large or mega-constellations mostly in the Low Earth Orbit (LEO) regime seems to play the predominant role soon.

Maintaining and developing of current space activities, and development of new ones, both in diversity (new services, in-orbit servicing, assembly, and manufacturing) and volume (large constellations) will demand to maintain and upgrade of space-related infrastructure enabling space economy growth (in a sustainable and safe manner) i.e. Space Situational Awareness systems (SSA). The main target of this system is to protect critical services (e.g., navigation, Earth observation) and to verify activities in the vicinity of a protected spacecraft avoidance of unexpected and unplanned "meetings" of satellites and proximity operations reducing the spread of space debris and costs of space operations [Jah 2020].

Moreover, the SSA system will tend to develop with new functionalities such as space traffic coordination (STC) or space traffic management (STM),[3] which will be necessary to handle more and more space traffic safeguarding sustainability of the orbital environment and safety of operations. In general terms and more broadly the orbital environment may be considered as a finite natural resource influencing orbital and space economy needed to be properly managed to sustain growth without causing irremediable damages. In the context of the space environment and its policy, regulatory and technical aspects will be examined from the angle of the atmospheric re-entry as a final stage of post-mission disposal of mainly LEO (Low Earth Orbit) space objects.

[2] OECD Science, Technology and Industry. Policy Papers, *Space Sustainability: The Economics of Space Debris in perspective*, April 2020, No. 87; IADC Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, IADC-02-01, Revision 2. 2020. https://www.oecd-ilibrary.org/docserver/a339de43-en.pdf?expires=1617693388&id=id&accname=guest&checksum=4E999888BE5DF7AB4D755E8899EF349F [accessed: 23.03.2021], p. 22–35.

[3] ESPI (European Space Policy Institute) public Report 71. Towards a European Approach to Space Traffic Management, 2020, file:///C:/Users/m.polkowska/Downloads/ESPI%20Public%20Report%2071%20-%20Towards%20a%20European%20Approach%20to%20Space%20Traffic%20Management%20-%20Full%20Report%20(2).pdf [accessed: 23.03.2021], p. 31–33.

1. RE-ENTRY BASICS

Most of the spacecraft-related activities are performed in four phases – creation, launch, operation, and eventual disposal. Of course, during each of those phases many space debris may be released and at the end spacecraft usually becomes also dysfunctional/derelict and debris itself. Moreover, besides the nominal operation space systems may get to failures or even destruction which generate an additional amount of debris.

Besides the space debris generation, there are also sinks, both natural and artificial. The main natural mechanism to eliminate debris is the slow process of natural decay of space objects pulling them into Earth's atmosphere and its full or partial burn up the over there and eventual fall to the Earth's surface as an uncontrolled re-entry (approximately 70% of all re-entries). That process may be very long in terms of hundreds of years at high altitude over 1000 km and relatively fast, in terms of year below 600 km.

Besides uncontrollable mechanism there are controllable (or de-orbits) too consisting of the intentional and controllable direction of functioning space object into Earth's atmosphere to perform safe destruction and eventual safe fall of surviving elements into the inhabited area, generally located over the ocean (approximately 30% of all re-entries).

Two orbital regimes that are LEO and GEO (the Geostationary Orbit) are the subjects of particular attention where post-mission disposal usually aiming for the clearance from the permanent or quasi-permanent presence of non-functional space objects play an important role. In particular, at the LEO regime, the satellites and rocket bodies at the end of its operational phase should be maneuvered to reduce their orbital lifetime. The recent research allows complementing above mentioned processes there with the technology being lately developed that is an active way to eliminated space debris, so-called active debris removal (ADR). In its current form, there are two basic forms considered i.e., physical debris removal or concentrated energy debris removal. In the first case, Active Debris Removal (ADR) mission as European Space Agency's (ESA) ADRIOS mission led by ClearSpace or end of life (EOL) mission ELISA-d demonstration mission performed by Astroscale is envisaged. In terms of concentrated energy, it is considered to use laser technology to reduce the energy of small objects to trigger re-entry. Several studies indicate that to maintain the orbital environment in a stable form it is necessary to perform at least 5 large objects ADR missions yearly from a region with high object densities and long orbital lifetimes [Alior 2020].

2. POLICY AND FRAMEWORKS

The basis of the international space regulatory framework relied on the United

Nations Outer Space Treaty[4] where the issue of freedom of access and operation in space is considered as a basic right. In this sense maintenance of the finite orbital environment allowing to conduct space operations in sustainable form should play a crucial role for all states (both in terms of established space nations and emerging ones) and continue indefinitely in the future in a manner answering to equitable access to benefits of the exploration, and use of outer space for peaceful purposes, for present and future generations. Therefore nations, international intergovernmental organizations, and executive agencies but also non-governmental entities maintain their efforts to create and implement hard and soft laws, regulations, norms, and standards aiming to deal with the orbital environment and its trends that is the proliferation of space debris, the increasing complexity of space operations, emergence of a large constellation and its effects to re-entry characteristics.

The particular regulation related to space debris and re-entry, in particular, may be inferred from basic international space law, that is Space Treaties (UN).[5] As surviving fragments originating from a particular space object (usually linked to the owner) may endanger people on the ground or operating aircraft they are directly linked to the notations of the Liability Conventions 1971.[6]

Even though, despite many efforts, the binding legal consensus has not been reached yet there are many efforts coming from different organizations delivering guidance, recommendations, or technical standard aiming to preserve the space environment and shape space operation in a way minimizing space debris footprint. It is expected that nations seeking their presence in space with building up of its space capabilities following other nations example will also gradually introduce through national legislations specific norm and requirements through the licensing framework system to satellite owner/operator in all phases of satellite life.[7]

3. UN COMMITTEE ON PEACEFUL USES OF OUTER SPACE (UNCOPUOS)

One of the basic fora where the issues related to space debris and re-entries

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[4] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (The Outer Space Treaty) 1967 https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html [accessed: 20.02.2021].

[5] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (The Outer Space Treaty) 1967, The Rescue Agreement 1968, Liability Convention 1971, and Convention on Registration of objects launched into outer space 1975; https://treaties.un.org/en [accessed: 20.02.2021].

[6] Convention on International Liability for Damage Caused by Space Objects, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html [accessed: 30.03.2021].

[7] Part 450: Streamlining of Launch and Reentry Licensing Requirements; This rulemaking arose from work by the National Space Council that led to Space Policy Directive-2 (SPD-2) in May 2018, directing the U.S. Department of Transportation to streamline the regulations governing commercial space launch and reentry licensing. Part 450 consolidates multiple regulatory parts to create a single licensing regime for all types of commercial space flight launch and reentry operations, and replaces prescriptive requirements with performance-based criteria, https://www.faa.gov/space/streamlined_licensing_process/ [accessed: 02.03.2021].

are being continuously discussed since 1994 is the Scientific & Technical Subcommittee of UNCOPUOS. This forum from 2016 works on successive versions of internationally agreed non-binding guidelines for the long-term sustainability of outer space activities with its latest version issued 2019.[8] These guidelines recommend the policy and regulatory framework, the safety of space operations, rules of international cooperation, capacity-building, awareness, and scientific or technical Research and Development (R&D).

Even though the content of those guidelines is very much interdimensional nonetheless several are directly linked to the re-entry issue, i.e.: 1) take measures to address risks associated with the uncontrolled re-entry of space objects; 2) provide updated contact information and share information on space objects and orbital events; 3) improve the accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects.[9]

Based on the above guideline, re-entry, particularly hazardous objects should be closely monitored and examined in terms of associated risk and the information adequately shared between nations and international organizations to prevent or mitigate any hazards. Even though these guidelines are voluntary and not legally binding are written with the objectives to assist States and international intergovernmental organizations (individually and collectively) to prevent and mitigate risks associated with the conduct of space activities [Polkowska 2019]. In preparation and endorsement of those guidelines, the reaching of the international consensus plays a crucial role, particularly when the security aspects are involved.

4. INTER-AGENCY SPACE DEBRIS COORDINATION COMMITTEE (IADC)

As the issue of space debris has been pretty early recognized at the national level by Space Agencies and later on by the international aerospace community it has been found its attention through the creation of IADC in 1993 which was founded as a form for technical exchange and coordination on space debris matter and can today be perceived as the one of leading international expertise body in the field of space debris. The body issued IADC Space Debris Mitigation Guidelines with its latest edition from 2020.[10] IADC creates soft law necessary to fill the gap in the international standards referring to space debris. This forum is necessary to build international consensus on responsibility of states for their space activities.

The following recommendation with regards to post-mission disposal and re-

[8] Nations United. Report of the Committee on the Peaceful Uses of Outer Space – Annex II Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space (A/74/20). 2019, https://www.unoosa.org/oosa/oosadoc/data/documents/2019/a/a7420_0.html [accessed: 23.03.2021].

[9] Long-term Sustainability of Outer Space Activities, https://www.unoosa.org/oosa/en/ourwork/topics/long-term-sustainability-of-outer-space-activities.html [accessed: 23.03.2021].

[10] IADC Space Debris Mitigation Guidelines, https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf [accessed: 20.03.2021].

entry for space objects passing through the LEO region has been provided.

Spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be deorbited (direct re-entry is preferred) or where appropriate maneuvered into an orbit with an expected residual orbital lifetime of 25 years or shorter.[11]

The probability of success of the disposal should be at least 90%. For large constellations, for example, a shorter residual orbital lifetime or a higher probability of success may be necessary. Retrieval is also a disposal option. If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, space debris that survives to reach the surface of the Earth should not cause any risk on the ground. This may be done by limiting the amount of surviving debris or confining the debris to broad ocean areas [Rosenkrans 2012].

Also, ground environmental pollution, caused by radioactive substances, toxic substances, or any other environmental pollutants resulting from on-board articles, should be prevented or minimized to be accepted as permissible. In the case of a controlled re-entry of a spacecraft or orbital stage, the operator of the system should inform the relevant air traffic and maritime traffic authorities of the re-entry time and trajectory and the associated ground area.[12]

5. THE U.S. FRAMEWORK

The United States has the most robust and detailed national space law and regulatory regime addressing the space activities of any nation. Many nations have modelled their laws on those of the United States [Smith 2020]. The U.S. possesses currently the most comprehensive and robust understanding of the orbital space environment through information gathered and processed by the United States military's Space Surveillance Network, which tracks over 23,000 space objects in Earth orbit. The US shares this information to allow spacecraft owner/operator to access the information, provide open access to basic services, and share the catalogue of an object in a semi-open manner. In terms of space debris policy aspects, the U.S. issued in 2018 Space Policy Directive 3 (SPD–3)[13]– National Space Traffic Management Policy and new US Space Policies[14] constitute the fundament in terms of orbital environment and re-entry.

[11] IADC Space Debris Mitigation Guidelines, https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf [accessed: 09.06.2021].

[12] IADC Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, IADC-02-01, Revision 2. 2020, https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf [accessed: 23.03.2021].

[13] White House. Space Policy Directive-3, June 18, 2018, https://www.whitehouse.gov/presiden tial-actions/space-policy-directive-3-national-space-traffic-management-policy/2018 [accessed: 02.02.2021].

[14] National Space Policy of the United States of America. December 9, 2020, https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/12/National-Space-Policy.pdf [accessed: 23.04.2021].

Within the above documents need for utilization of space capabilities to stimulate economic growth and enhance the quality of life has been highlighted. In particular, the US new space policy mentions at the first place the principle that all nations shall act responsibly in space to ensure the safety, stability, security, and long-term sustainability of space activities and to execute this principle both nationally and through international cooperation. Moreover, in the marked part of the strategy, the U.S. commits to preserving the space environment for responsible, peaceful, and safe use, and with a focus on minimizing space debris the United States aims among others referring to re-entry the most are: 1) to remain active in international policy and guidelines fora and develop adequate standards; 2) to deliver free a charge basic SSA data and services including adequate re-entry notifications and develop necessary technologies and techniques; 3) to build up an open architecture data repository (OADR) based on data coming from various sources (public and private); 4) develop in coordination with allies and partner ADR technique.[15]

6. THE EUROPEAN FRAMEWORK

The EU, ESA, and their Member States from the mid-decade of 21st century started to get more engaged in space security and sustainability. The legal framework of the EU increases its space competencies by entering into force the Lisbon Treaty.[16] In this context, the European institution and agencies have got wider competencies on space matters including space safety matters.

The issue of space debris and re-entries in Europe has been adequately tackled both in research/technologies ground and operationally by different mainly national Agencies CNES (French Space Agency), ASI (Italian Space Agency), DLR (German Space Agency), and ESA (European Space Agency) delivering different studies, tools and methods. Even though space activities led by the EU have been recognized from the early time the basic strategic document of the EU is the Space Strategy for Europe[17] which has been issued only in 2016 when several programs and the main action has been already in place.

In particular, the Space Strategy paper in third of fourth strategic goals identifies: “Reinforcing Europe’s autonomy in accessing and using space in a secure and safe environment” where among others the particular attention is paid to “ensuring the protection and resilience of critical European space infrastructure.” In that sense, European Commission recognized space debris as the most serious risk to the sustainability of space activities, confirms the continuation of work on

[15] As above: https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/12/National-Space-Policy.pdf [accessed: 23.04.2021], p. 14–15.

[16] Lisbon Treaty https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:12007L/TXT [accessed: 23.04.2021].

[17] DG-GROW EU. Space Strategy for Europe. 2016, file:///C:/Users/m.polkowska/Downloads/COM_2016_705_F1_COMMUNICATION_FROM_COMMISSION_TO_INST_EN_V12_P1_864471.PDF [accessed: 05.06.2020].

the implementation of the EUSST programme,[18] stressed the need to improve the performance, and geographical coverage of sensors, and emphasize the need to extend the scope to other threat and vulnerabilities (besides SST). Moreover, the European Commission stressed the need to establish partnerships in particular with the U.S.[19]

As mentioned above, European Union (EU) and its Member States started the EUSST programme before the strategy- that is in 2014 throughout Decision No 541/2014 establishing a Framework for Space Surveillance and Tracking Support.[20] Based on that decision, so-called EUSST Consortium of EU Members States has been created by pooling together existing resources of Germany, France, Italy, Spain, Poland, Portugal, and Romania to collect data, process the information, and deliver three services Collision Avoidance (CA,[21] Fragmentation Analysis (FG) and Re-entry Analysis (RE). In terms of re-entry service, it is aimed to deliver early warning of uncontrolled re-entry and estimation of time-frame and area of impact addressed mainly to governmental and national public authorities concerned with civil protection with an aim of reducing potential risk to the safety of UE citizens and mitigating potential damage to terrestrial infrastructure.[22]

The source of EU need to establish and strengthen in terms of SST (Space Surveillance and Tracking) capabilities comes from the strategic aim to build autonomy in the domain, as the increasing number of European satellite both commercial and public domain (in particular Galileo Navigation System and Sentinel Earth Observation constellations) and the risk and hazard related to space traffic on the ground (re-entries) but also to allow Europe to contribute to global burden-sharing in the domain of SSA and to enhance its position in international discussions.

Moreover from 2018 European Union works on successive regulation "Space programme of the Union and the European Union Agency for the Space Pro-

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[18] The Space Surveillance and Tracking (SST) Support Framework was established by the European Union in 2014 with the Decision 541/2014/EU of the European Parliament and the Council (SST Decision). This Decision foresaw the creation of an SST Consortium of, initially, five EU Member States – France, Germany, Italy, Spain and United Kingdom – and then eight with the addition of Poland, Portugal and Romania in 2018. SST refers to the capacity to detect, catalogue and predict the movements of space objects orbiting the Earth.

[19] EU. Space programme 2021-2027 and European Union Agency for the Space Programs – proposal. [Online] 2018–2021, https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2018/0236(COD)&l=en [accessed: 23.03.2021].

[20] EU Decision No 541/2014/EU of The European Parliament and of the Council of 16 April 2014 establishing a Framework for Space Surveillance and Tracking Support. 2014. OJ L 158, 27.5.2014, p. 227–34.

[21] NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook. December 2020, https://www.nasa.gov/press-release/nasa-releases-best-practices-handbook-to-help-improve-space-safety [accessed: 23.03.2021].

[22] EUSST. 2nd EUSST Webinar: Operations in Space Surveillance and Tracking. [Online] 2020, https://www.eusst.eu/wp-content/uploads/2020/11/EUSST_2WBR_16_11_2020.pdf [accessed: 02. 02.2021].

gramme" which among different space elements encompasses SST. In terms of services, Article 54(1)(c) defines re-entry and states that one of the services is the risk assessment of the uncontrolled re-entry of space objects and space debris into the Earth's atmosphere and the generation of related information, including the estimation of the timeframe and likely location of the possible impact. It is needed that SST services are to be free of charge and available at any time without interruption.[23]

7. INTERNATIONAL SAFETY STANDARDS

The policy documents and guidelines both international and national provide a framework for necessary action with no detailed implementation notations. That is why to adequately address issues related to re-entry there is a need to elaborate it properly through adequate technologies, regulations, behaviours and mostly norms answering primarily to the spacecraft engineering and operation. In these terms standards play an important role to improve and harmonize activities in the space sector, maintaining compatibility, interoperability, quality, safety, and repeatability. This standardization of activities is usually performed through major technical standardization bodies such as ISO, CCSDS, CEN/CENELEC, ECSS, and others.

In terms of SSA/STM, the ISO could be recognized as the most active standardization body issuing particular ISO norms (non-binding as all ISO standards) which take into consideration in-depth issues related to re-entry among others through the following norms are applicable: ISO 27852:2016 Space systems – Estimation of orbit lifetime, ISO 16164:2015 Space systems – Disposal of satellites operating in or crossing Low Earth Orbit, ISO 16699:2015 Space systems – Disposal of orbital launch stages, ISO 24113:2019 Space systems – Space debris mitigation requirements, ISO/TS 20991:2018 Space systems – Requirements for small spacecraft, ISO 27875:2019 Space systems – Re-entry risk management for unmanned spacecraft and launch vehicle orbital stages taking into account that certain of them are adopted also at European levels, such as ISO 24113 by ECSS.[24]

The ISO standards, among others, refer to the EOL of the spacecraft and its disposal in LEO. According to it LEO satellites supposed to re-enter into should remain casualty expectancy below 1 to 10,000 (surviving fragments risk to injure or kill a person on the ground if the object re-enter 10,000 times). In this case, the object may gradually decay if that process will be shorter than 25 years, If the risk overpass the threshold, the object should be directed to an uninhibited area with minimal risk to people.

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[23] ESA's Annual Space Environment Report: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf [accessed: 02.02.2021].
[24] International Standards Organisation (ISO). Space systems – Estimation of orbit lifetimes, ISO TC 20/SC 14 27852:2016. 2016, https://www.iso.org/standard/68572.html [accessed: 24.03.2021].

At the moment to answer to above-mentioned norms, there are different software packages, usually available free of charge, enabling in particular spacecraft designer, owner, and operator modelling of various aspects of re-entry from orbital lifetime prediction to the assessment of the risk to people on the ground. Even though those packages attempt to answer to the multitude of different aspects of the re-entry in particular cases significant differences may occur. Among those different packages there it is worthy to mention: Orbital Spacecraft Active Removal (OSCAR) tool, Survival And Risk Analysis (SARA) and Spacecraft Atmospheric Re-Entry and Aerothermal Break-Ip (SCARAB) of ESA AGI STK have also orbital lifetime calculation (analytical model) from the contraction of the orbit due to atmospheric drag such as AGI STK , Object Re-entry Survival Analysis Tool (ORSAT) and Debris Assessment Software (DAS) of NASA Orbital Debris Program Office, or Semi-analytic Tool for End-of-Life Analysis (STELA) and DEBRISK of CNES.[25]

It is necessary to add that the variability of actual solar activity contributes to the uncertainty of any long-term orbital lifetime calculation regardless of the tool used. Moreover, in the case of elliptical orbit with apogees in LEO, there is a need to take into consideration solar-lunar perturbations. In terms of fragmentation of re-entering objects available software frequently render different results due to many uncertainties and fidelity of modelling.

8. RE-ENTRY AND RELATED RISKS

Each day different space objects perform re-entry e.g. debris, rocket stages, satellites re-enter Earth's atmosphere where usually burn up posing eventually a marginal risk to people, aviation, or infrastructure on the ground. Those objects enter the denser layers of the atmosphere with a speed of over 28 000 km/h at about 120 km of altitude. As usual, over the year there are only a few very large objects re-entering the atmosphere, such as heavy satellites. More frequently they are have rocket bodies or standard satellites re-entering the atmosphere typically once/twice a week or two catalogued objects twice a day.[26]

The process of re-entry constitutes of the following phases: entry into denser regions of the atmosphere, atmospheric heating due to air resistance, increase of load to the melting point, and release of major parts (at altitude approximately 78 km) leading in the majority of cases to its destruction. If fragments survive the re-entry (typically in the case of large satellite, or compact design, or particular materials) they fall vertically from around 30 km altitude with possible horizontal added velocity coming from winds. Therefore, the cloud of fragments may have tens of kilometres wide and hundreds or even thousands of kilometres long. Each fragment falls at various speeds depending on its aerodynamic and mass chara-

[25] Space Debris User Portal, https://sdup.esoc.esa.int/ [accessed: 23.03.2021].

[26] ESA. Reentry and collision avoidance, https://www.esa.int/Safety_Security/Space_Debris/Reentry_and_collision_avoidance [accessed: 06.06.2020].

cteristic. In most cases, it is estimated (if no further information was available on construction), that the mass of re-entry is approximately 10–40% of the satellite dry mass (reaching ground). The likelihood of hitting the surface depends on entry angle, shape, dynamics (e.g., tumbling), and material composition of the re-entering object.

Since around 70% of the Earth's surface is covered by water, the re-entry event is distributed, and relatively rare it happens that re-entering objects will land on the ground with relatively low probability and most lands on the water never be retrieved. Even though the likelihood of injury related to re-entry is low it is not negligible. Because of it the predictions of re-entry and associated risks rise in importance and demand. However, the predications have inborn uncertainty as tracking data usually scare and re-entry phenomena complex (dependant among others on object shape, material, orientation, uncertain atmosphere mo-delling, and solar activity). To even better model and predict re-entry there is a need for adequate physical and geometric representation of all components of the object considering flight dynamic, aero, and thermal dynamic in principle heating and melting processes.

Uncertainty of these events goes down with time, but even 25 hours before the event the error may be at a level of few hours. As that object travels with a velocity of around 28,000km/h it implies that the last trajectory may result in an uncertainty of several thousand kilometres on Earth's surface what makes civil protection services difficult to react.

9. RISK ASSESSMENT

In the case of LEO orbit, the spacecraft designers should consider in particular the terminal phase of its life and associated risks to be prevented or minimized. Besides of design phase also in terms of re-entry, the operator of the system should inform the relevant Air Traffic and Maritime Traffic Authorities of the assumed time and trajectory and the affected ground area. As satellites re-entry, they disintegrated but some debris may survive the heat of re-entry and go down through the atmosphere bringing various kinds of risks which may be divided into "primaries" and "secondaries."

The primary risk is related to direct harm to people on the ground through kinetic impact. As far as the secondary risk is concerned it is related to potential indirect human casualties through impacting infrastructures, such as a building, industrial plant (e.g. chemical), or a hit to the aircraft in flight directly influencing people safety on board. The other category of risk comes from the environment of the polluting substances on board the spacecraft (e.g. toxic, radioactive) or influencing the high atmosphere pollution coming from massive vaporization of material in the atmosphere related to routine maintenance of large constellation satellites (replacement of satellites).

CONCLUSION

As the re-entries risk may be typically reduced by either decrease of re-entry frequency or re-entry survivability, the main action must include the extension of satellite lifetime or broader utilization of "the design to demise" approach. Besides object-related approach, it is necessary to work out adequate "re-entry answer" through civil protection services to people on the ground or aircraft operators of those events (e.g. recommendation to stay in buildings).

Even though there is no international legally binding legal framework to regulate the issues of re-entries nonetheless current international efforts manifested by the set of guidelines and recommendations (such as LTS) are fortunately progressively transferred into national regulation and satellite licensing systems.

To maintain this process within the international community there is a necessity to continuously update and distribute knowledge related to re-entries related risks and hazards through adequate bodies such as UNCOPUOS.

As the new space accelerates, those guidelines must be to be revisited and fine-tuned periodically to better reflect the challenges related to the orbital environment, its trends, and re-entries associated risks in particular. It is mainly concerned with the increase in the number and variety of satellite operators (the issues of best practice universality) and large constellation development (the issue of fine-tuning technical licensing requirements).

To support those actions, at the international and internal level, there is a need to develop very detailed standards based on adequate models and simulations in particular to better work out atmosphere and space weather models, ADR manoeuvres, re-entry physics, or "the design to demise" techniques. Moreover, the proliferation of large constellations bringing the obvious benefits to societies must be studied to better understand and estimate related risks with regards to re-entries. Those studies may significantly differ from the existing ones because of the scale and consequently different approaches to mitigation actions. On the one side, such aspects of re-entries of a large number of satellites and its effects on aircraft traffic safety must be better elaborated. Moreover, also less classical aspects as the "green" re-entries approach must be considered as widely as a large number of re-entries may influence Earth's atmosphere pollution and climate (e.g. massive vaporization of aluminium and its effects on the warm of the atmosphere or degradation on ozone layer) as the re-entering mass may get increased from 8 to 32 times.[27]

In this context besides regulatory and standard issues, there is also the problem of verifying and executing them – e.g. verification of disposal regulations and reentries activities usually through monitoring of re-entries activities and proper, timely transfer of re-entry data and information among concerned parties. By that,

[27] See www.spacenews.com. Aerospace Corp. raises questions about pollutants produced during satellite and rocket reentry. [Online] 11 December 2020, https://spacenews.com/aerospace-agu-reentry-pollution/ [accessed: 06.06.2021].

it is required to broaden observation and prediction capabilities with adequate data and information exchange to create more precise re-entry services and deliver necessary assistance in case of emergencies. That is why the delineation of military SSA from civil Space Traffic Coordination/ Space Traffic Management (STC/STM) is required.

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