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Joseph N. Pelton

New Solutions for the Space Debris Problem

INTERNATIONAL SPACE UNIVERSITY

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I wish to dedicate this book to the various talented and committed people around the world who make up the International Association for the Advancement of Space Safety. These various scientists, engineers, systems analysts, and regulatory, policy, and legal experts seek to make the world of space exploration, space sciences, and space applications safer and less exposed to risks.

This Springer book is published in collaboration with the International Space University (ISU). At its central campus in Strasbourg, France, and at various locations around the world, the ISU provides graduate-level training to the future leaders of the global space community. The University offers a 2-month Space Studies Program, a 5-week Southern Hemisphere Program, and a 1-year Master's Program related to space science, space engineering, systems engineering, space policy and law, business and management, and space and society.

These programs give international graduate students and young space professionals the opportunity to learn while solving complex problems in an intercultural environment. Since its founding in 1987, the International Space University has graduated more than 3,000 students from 100 countries, creating an international network of professionals and leaders. ISU faculty and lecturers from around the world have published hundreds of books and articles on space exploration, applications, science, and development.

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Chapter 1
Introduction

Why Space Services Are Now Vital to Global Society

Fifty years ago at the dawn of the space age, space sciences, space exploration and space applications were in their infancy. For the most part, little was known about how space might be used to achieve practical purposes and little was known about the conditions or possible use of outer space above the stratosphere. Explorer I revealed that there were the Van Allen Belts that protected the Earth from extreme Solar Storms. Early Bird in 1965 realized Arthur C. Clarke's vision of communications satellites in geosynchronous orbit and proved that a practical space industry was not only possible but highly profitable as well. Today a half century later the world is dramatically different. There are a number of videos on line known under the generic title "A Day without Satellites". These video presentations reveal many of the various ways we are today dependent on satellite networks. These videos show how we depend on satellites for air traffic control, including takeoffs and landings, for banking transactions, for credit card validation, for Internet synchronization, for television distribution, for global business communications, for a wide variety of military networking and missile targeting, for weather forecasting, for extreme storm warnings and recovery, for oil and mineral exploration, for fishing, for search and rescue and dozens of other vital services. Space systems have gone from being an exotic and new enterprise to a vital infrastructure that is central to our daily lives.

Space systems have become so very vital, that if we were suddenly denied access to our space-based infrastructure for weather forecasting and warning, for space-based navigation and timing, for civil and military communications, and for remote sensing and surveillance from space we would be in danger. We would suffer almost immediately—economically, militarily, and socially. Many of our transportation and our communications systems would go down along with our weather and rescue services and defense systems. Internet would lost its synchronization,

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credit card validation would no longer work, we would not be alerted to major storm systems, air traffic control, shipping navigation, and trucking routing services would be lost.

Unfortunately as our space-based systems have become more and more common, other factors have served to make our satellites more at risk. One risk is that of extreme solar flares and coronal mass ejections. These concerns are addressed in another book in this series entitled *Orbital Debris and Other Space Hazards*. This current book, however, returns in more detail to the problem of orbital space debris and new efforts to develop active debris removal capabilities. [Joseph N. Pelton]

The Inter-Agency Space Debris Coordination Committee (IADC) and the UN Committee on the Peaceful Uses of Outer Space (COPUOS) have developed guidelines to help reduce the creation of new space debris and aid defunct spacecraft and upper stage rockets to naturally de-orbit. Yet these guidelines are currently advisory and non-binding. These procedures, in short, are not sufficient to ensure that orbital debris build up will not continue to increase with potentially catastrophic consequences in the longer term.

Overview of the Problem

Currently there is about six metric tons of space debris in earth orbit and about 45 % of that is in low-earth orbit and polar orbits where the threat of collisions continues to increase. This process can lead to an escalating cascade of more and more debris. Today we are very much at risk of such a cascading build-up that is known as the "Kessler Syndrome". Two events in recent years have particularly contributed to orbital space debris build-up. One event was the collision of the defunct Russian Kosmos 2251 weather satellite with the Iridium 33 low earth orbit mobile communications satellite. The other was the shooting down of an old and defunct Chinese Fen Yun weather satellite by the Chinese military. Each of these events led to the creation of nearly 3,000 new tracked debris elements. Currently 22,000 of these space debris elements are being actively tracked by U.S. surveillance networks. Each of these debris elements are capable of creating major new debris, especially if they collided with another satellite or upper stage rocket. In short, without further remedial action to remove space debris from Earth orbit, the problem will continue to get worse. [NASA Office of Orbital Debris]

At some point the cascading effect of debris elements colliding with other debris elements will create deadly rings of debris that are sufficiently dense that it would not be safe to launch spacecraft into Earth orbit with a reasonable hope of not being struck by a piece of debris that would disable the satellite and the launch vehicle in such a way that they would simply add to the morass of space debris. Fortunately we are well short of this "terminal condition" that would essentially prohibit the ability to launch new operational spacecraft into Earth orbit. When Donald Kessler of NASA warned of this threat some 35 years ago, there was a minimal amount of space debris at the time. Indeed at that time the overwhelming likelihood was that natural debris from micrometeorites, meteorites, bolides, etc. constituted a much greater threat of collision with a satellite or upper stage launch vehicle. But that has now dramatically changed.

The operators of satellite networks, such as Intelsat (where the author was employed at the time) took the much more serious risks to its satellites that might be created by solar flares, coronal mass ejections, and natural cosmic debris. Thus many unsafe and indeed thoughtless practices that contributed to human-caused orbital debris continued largely unabated. This meant the on-going use of explosive bolts for the separation of staged launch vehicles, no specific efforts to de-orbit upper stages of launch vehicles, no exhaustion and expelling of fuels or explosives stored in spacecraft or upper stages of launch vehicles that could subsequently explode, and other such dangerous practices. Many space scientists continued to assume that natural objects and cosmic weather conditions would continue to be the greater risk factor for operational spacecraft. Over the decades from the 1980s, 1990s, 2000s, and now the 2010s the amount of human-launched materials has continued increase. In 1994 the UN Committee on the Peaceful Uses of Outer Space took up this problem in a serious way. This also led to a collaborative process among a number of the space agencies which became seriously engaged in trying to develop guidelines to minimize the increase of further space debris.

Several events in 2007, 2008 and 2009, however, served to escalate concerns about orbital space debris. These incidents raised concerns to a much higher level of urgency on the world stage. The first act occurred on January 11, 2007. This event was the intentional launch of a Chinese missile to destroy an obsolete polar-orbiting Chinese weather satellite, the Fen Yun 1C. A missile using an anti-satellite (ASAT) system was launched from near the China's Xichang Space Centre on 11 January and reached its target at an altitude of 865 km (or 537 miles). This unexpected event created a dangerous new ring of debris with about 3,000 trackable space debris objects. Because this event occurred at such a high altitude these debris elements will stay in orbit for a very long time. The U.S. subsequently did another anti-satellite test firing on February 21, 2008 but this intercepted a re-entering spy satellite that contained some 500 kg of noxious hydrazine fuel and thus this action was claimed to be a safety measure. All of the debris elements from this very low altitude and incoming trajectory de-orbited within 24 h of the missile hit. The key thing to note from these two events is that the higher the altitude of the missile intercept the greater the nature of the problem. This is because the debris stays in orbit much longer if created in a higher orbit. Simply put, the pull of gravity decreases in magnitude at higher and higher elevations and thus orbital decay takes much more time. [Chinese Anti-Satellite Test]

It was the Kosmos-Iridium collision in 2009 again shocked world opinion and triggered new efforts to control the build-up of human-generated space debris. On February 10, 2009, just before 1700 Universal Time (at zero degree meridian) that a very high speed and explosive collision occurred. This involved the Iridium 33 mobile communications spacecraft and the Russian Kosmos 2251 defunct weather satellite. This collision occurred at an altitude of 789 km (or 490 miles) at a location high over Siberia. This spectacular event just like the Chinese missile interception generated thousands of pieces of newly tracked space debris. Below are

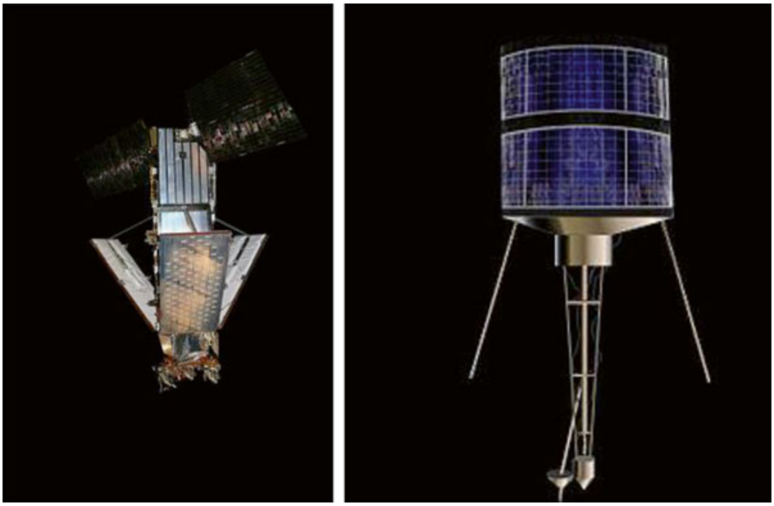

Fig. 1.1 The Iridium 33 satellite and a Russian weather satellites like the Kosmos 2251 (Graphics Courtesy of Iridium and Roscosmos)

depicted an Iridium satellite and a Russian weather observation satellite similar in design to the Kosmos 2251 (Fig. 1.1).

This random collision occurred at sufficiently high velocity to create nearly 3,000 new debris elements in low earth orbit. Thus as a consequence of the Chinese anti-satellite missile firing and the Kosmos-Iridium collision the amount of tracked debris elements increased by almost 30 %. This collision was also at high enough altitude to stay in orbit for many years as well. Dr. Donald Kessler's recent calculations project an increasing collision rate.

The international community which had been working on the issue of orbital debris renewed its efforts to establish new guidelines to control the new creation of orbital debris elements. Currently there are some 22,000 objects being tracked that are at least the size of a baseball. An object the size of a baseball may not sound like much, but a chunk of metal this size and traveling at a relative speed of perhaps 32,000 km an hour (or 20,000 miles per hour) to the impacted object has the kinetic energy of a reasonably large-sized bomb. Further there are perhaps a half million pieces of debris the size of a marble and millions of pieces equivalent in size to a chip of paint. Even a chip of paint travelling at hypersonic speeds could pierce a space suit or crack a window of a space plane.

International Efforts to Develop Guidelines to Mitigate the Creation of Space Debris

A group known as the Inter-Agency Space Debris Coordination Committee (IADC) began working on what they characterized as the "Space Debris Mitigation Guidelines" in the 1990s and came up with an initial set of guidelines in 2002.

These were then developed into a refined version in 2007. In both cases these guidelines were described as being "non-binding". Even so such standards are useful. They could and should be applied in planning space missions. The objectives of these guidelines were announced to be threefold:

1. Preventing on-orbit break-ups
2. Removing spacecraft and orbital stages that have reached the end of their mission operations from the useful, densely populated orbit regions
3. Limiting the objects released during normal operations.

The UN Committee on the Peaceful Uses of Outer Space has worked in close tandem with the IADC for over a decade to come up with unanimously agreed guidelines. And, indeed in December 2007 the UN General Assembly adopted the non-binding mitigation guidelines essentially as developed within the IADC deliberative processes. These guidelines have the following seven component parts as shown in Chart 1 below. [UN Space Debris Mitigation]

Chart 1: UN General Assembly Approved Non-Binding Guidelines on Debris Mitigation

Guidelines for the Mitigation of Space Debris

Guideline 1: Limit debris released during normal operations
Guideline 2: Minimize the potential for break-ups during operational phases
Guideline 3: Limit the probability of accidental collision in orbit
Guideline 4: Avoid intentional destruction and other harmful activities
Guideline 5: Minimize potential for post-mission break-ups resulting from stored energy
Guideline 6: Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission.
Guideline 7: Limit the long-term interference of spacecraft and launch vehicle

Today the IADC continues to work on improving these guidelines and the UN COPUOS has created a Working Group on the Long Term Sustainability of Space Activities (LTSSA). Within this working group is the so-called Expert Group B that has the key assignment of addressing orbital space debris and its mitigation. This group assignment is to work on: "Space Debris, Space Operations, and Tools to Support Collaborative Space Situational Awareness". The complete list of issues that the Expert Group B is currently addressing is provided in Chart 2 below. Space operations and space situational awareness for reasons addressed later in this book are closely related to orbital space debris mitigation activities. [Expert Group B]

Chart 2: Expert Group B Tasks Currently Under Study

Expert Group B Issues Currently Under Consideration

Space debris:

- Measures to reduce the creation and proliferation of space debris
- Collection, sharing and dissemination of data on space objects
- Re-entry notifications regarding substantial space objects
- Technical developments and possibilities regarding space debris removal

Space operations:

- Collision avoidance processes and procedures
- Pre-launch and pre-manoeuvre notifications
- Common standards, best practices and guidelines

Tools to support collaborative space situational awareness:

- Registries of operators and contact information
- Data centres for the storage and exchange of information on space objects and operational information
- Information-sharing procedures
- Topics for Discussion

On-going Inadequacies of Space Debris Mitigation

Despite the progress that has been made to develop the existing guidelines for orbital debris mitigation there remains serious ongoing problems in this area. The first and most obvious deficiency is the lack of a clear and definitive definition of "orbital space debris". The Liability Convention and the Registration Convention only defines "space objects", but nowhere is the term "space debris" clearly and broadly defined in existing treaties on outer space. In brief, there is no global agreement as to what this term means. There is no specific UN or any other international agency or institution that has legal or regulatory authority for the active removal of orbital space debris. Indeed there is no proven technology that can effectively and also cost-efficiently remove debris from orbit. Further if such a technology existed (i.e. ground based directed energy systems or in-orbit mechanism that could achieve such removal), it would very likely be characterized as a "space weapon" and has significant implications for the further negotiation of space arms control. In short, despite the now agreed non-binding UN Guidelines on Space Debris Mitigation, there is a lack of technical, legal, financial, business and institutional arrangements to undertake active space debris removal. This is clearly a real issue and problem in that despite the UN Guidelines the problem of space debris continues to become worse. The risk to spacecraft positioned in low earth orbit and especially polar orbit is especially increasing. Dr. Donald Kessler, who first identified the threat now known as the "Kessler Syndrome", has projected that on-orbit collisions such as that occurred in the case of the Kosmos 2251 and the Iridium 33 will now likely occur every decade or so and thus this problem will continue to become worse and worse over time unless active orbital debris removal can serve to mitigate these collision events and thus avert debris buildup. ["Cosmic Hazards" video, Interview with Donald Kessler]

Scope of This Book

The scope of this book is to explore the technical, legal, institutional, and financial and business aspects of the orbital space debris problem. It particularly seeks to explore new initiatives and systems that can rescue the world community from the serious future consequences of this mounting problem that could possibly limited future access to outer space. As the problem of an increasing world population, urbanization and human industrialization has given rise to major environmental problems of climate change, loss of species, desertification, and water shortages, the increasing exploitation of space to meet human goals has now given rise to the problem of orbital space debris. It is not accidental that the working group of the UN Committee on the Peaceful Uses of Outer Space that is now addressing this issue is called the "Working Group on the Long Term Sustainability of Outer Space Activities."

There are many ways that this problem might be addressed. These are broadly indicated in the seven guidelines on orbital space debris mitigation that are included in Chart 1 above. The current strong trend of thought, however, is to believe that "clean" future launches will not be enough. This is because the existing 6 tons of debris now in space (45 % in low earth orbit) will continue on an occasional basis to collide and thus build up more and more debris over time.

In short, this means that active debris removal—with a focus on the largest debris elements in low earth orbit as the first priority—needs to be given priority. Space situational awareness and maneuvers to avoid collision and perhaps the use of ground or space based directed energy systems to avoid collisions (or near conjunctions) must also likely be a part of this overall strategy to preserve long-term and save access to outer space. This combined need for debris removal as well as collision avoidance is probably essential. The activation of systems to achieve debris removal will take time, new technology, financial resources, and perhaps new institutional arrangements. Changes to current international space regulations and legal provisions will also likely be required—starting with a clear definition of space debris and agreed procedures under which debris removal can be achieved. Such changes will take time and commitment of key actors to achieve such a program of action. It took, for instance, from 1994 to 2007 (or 14 years) to get the United Nations to go from actively considering the orbital debris problem to adopting the guidelines for orbital space debris mitigation.

Key Terms

In this book there will be a number of terms used with technical or special legal or regulatory meaning. The glossary at the end of this book should be of some assistance if particular acronyms, terms or phrases are not clear. Some particularly important terms, however, will be addressed here and now.

Orbital Space Debris is defined in the UN COPUOS Space Debris Mitigation Guidelines as follows: "Space debris is defined as all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional." Orbital Space Debris is also known as orbital debris, space junk, and space waste. It includes all defunct objects in orbit around Earth. This includes everything from spent rocket stages, old satellites, and fragments from disintegration, erosion, and collisions. Normally space operators of spacecraft or their insurers decide when a space object has reached its end of life or is considered defunct. There is a danger that they wait too long to make this judgment and there is consequently not enough fuel to remove the defunct satellite to a safe orbit or power a safe re-entry into Earth atmosphere in order to burn up.

Orbital Space Debris Mitigation is a term applied to all attempts to lessen the creation, buildup or proliferation of defunct space objects. This can include the conduct of space situational awareness and tracking, maneuver or orbital change of spacecraft to avoid collisions, pacification (or de-energizing) of in-orbit spacecraft or vehicles, or ultimately the active removal of defunct of defunct space objects. It thus covers all seven of the activities included in the Mitigation Guidelines.

Active Orbital Space Debris Removal refers to all types of actions undertaken to remove a defunct spacecraft, vehicle or space object from earth orbit at the end of life or when it has been declared defunct or hazardous. This can include a wide range of activities including the following: (1) Active firing of thrusters or deploying of passive de-orbiting systems to increase atmospheric drag at the end of life for a spacecraft, or alternatively to deorbit an upper stage launcher vehicle. (2) Efforts using some form of directed energy device (either on the ground or in space) to change the orbit of a space object so that it de-orbits. (3) It can include sending up a spacecraft, device or instrument that can directly or indirectly change the orbit of a space object so that the targeted space object leaves Earth orbit either in a short period of time or on a gradual bases—but usually with the minimum objective of meeting the currently broadly agreed "25 year rule" of deorbiting space objects after their end of life. (Note: The 25 year rule is within the IADC guidelines, but unfortunately not included in the COPUOS Guidelines.)

In-Orbit Servicing: This is the type of "on-orbit" activity where changes, modifications, repairs or upgrades might be made to spacecraft already in orbit. Currently such in-orbit servicing is primarily considered to be carried out by on-orbit robotic devices that could make changes to an orbiting spacecraft. In the future this might involve human crew carrying out servicing activities.

Space Situational Awareness: This is the process of tracking—with some precision—the orbits of all space objects in Earth orbit. Space situational awareness is typically carried out by Radar (typically VHF or S band) tracking and in some cases by optical tracking. This tracking process is primarily carried out by military systems. Such military systems have a prime concern, for tracking missile attacks, but is today carried out for many other purposes including protection of valuable space assets, and seeking to avoid collisions.

Goals and Objectives

It is the objective of this book to explain the nature of currently increasing orbital space debris problems and to report, in particular, what progress is being made with regard to active space debris mitigation and removal efforts. This means that the technical systems that are being developed for active debris removal will be explored. There will also be an analysis of the new legal, regulatory, or financial mechanisms that might be employed to further the goal of space debris reduction, mitigation and removal. In addition to this prime objective, there will be supplementary information provided with regard to in-orbit servicing and space situational awareness. Developments and improvements with regard to on-orbit or in-orbit servicing can provide useful and quite parallel technical capabilities also needed to achieve active space debris removal. Close proximity tracking and precise orbital detection is critical to servicing or active debris removal. In short without tracking exactly which orbit space debris is following, active removal would not be possible. Further techniques developed for in-orbit servicing of spacecraft (or perhaps harvesting elements of a defunct spacecraft for new purposes as proposed for the Phoenix project by DARPA) can be key to the developing of new technical systems for active orbital debris removal. Indeed it is possible that some of these space activities of the future may be accomplished on a joint or at least well-coordinated basis.

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Long-term sustainability of outer space activities

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Chapter 2
Current Space Debris Remediation and On-Orbit Servicing Initiatives

Introduction

There are now quite a number of active programs around the world that are seeking to address the orbital space debris problem through remediation practices. In a few cases there are on-orbit servicing (also known as in-orbit servicing) programs that could also be utilized to assist with orbital debris remediation programs. The diversity of approach in terms of different technologies, governmentally-backed versus commercial approach, as well as differing economic models and maturity of program development is clearly quite large. Because of these quite divergent approaches, it is difficult to provide a comparative analysis of these various efforts that is systematic and consistent. The best approach thus seems is to present the various governmentally backed programs that are currently underway or planned and then to follow this with a presentation of those programs that are proceeding as private initiatives on a commercial or quasi-commercial or private institutional basis.

After these presentations are complete a summary chart will summarize these various initiatives so as to depict their source of financing, technological approach and general timetable of implementation. In Chap. 5, we well turn back to the examination of a wide range of possible new technological approaches that might be used to address orbital debris remediation that are currently at various stages of research and development. These will begin noting that there are also ground-based attempts to track and alter orbits to avert collisions and then to work up through alternative technological approaches that are more complex, or at least conceptually different than more traditional or conventional approaches.

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Governmental Backed Orbital Remediation Programs and Initiatives

The following four projects sponsored by the U.S. Government and by the German Space Agency (DLR) all feature sophisticated robotic spacecraft systems. In each case these spacecraft are designed to maneuver with high accuracy into close proximity of other spacecraft and to attach themselves to other spacecraft for repairs, augmentation, or if desired and needed, to bring about de-orbit or reposition to another orbit or to put into a parking orbit.

Orbital Express Space Operations Mission

This was a joint program of the U.S. Defense Advanced Research Projects Agency and the NASA Marshall Spaceflight Center. The Orbital Express program experiment was launched on March 8, 2007 on an Atlas V launcher. This project involved two spacecraft. The larger spacecraft was the ASTRO "servicing spacecraft" and the other was the smaller NEXTSat that served as the "client" space. This NEXTSat spacecraft was envisioned as a prototype design for future spacecraft that could be designed for in-orbit servicing. This project is relevant to active debris removal in at least two ways. One way is that proximity maneuvering in space and capture of a debris element is a critical technical aspect of active debris removal as will be discussed in Chap. 5. Secondly if it is possible to service in-orbit satellites to resupply them with fuel, batteries, and new electronics and antenna systems then the population of satellites launched into orbit can be reduced. This means less satellites and upper stage rockets that would need to be disposed of and thus would lead to the creation of less space debris.

ASTRO is an acronym for Autonomous Space Transport Robotic Operations. This ASTRO servicing satellite was almost 1,000 kg in total mass and was fueled with nearly 140 kg of hydrazine propellant. Its height and diameter were nearly 2 m. Its robotic arm allowed for capture and manual docking. During docking it was possible to transfer fuel or retrofit or augment elements of the NEXTSat target vehicle.

The NextSat target spacecraft had a mass of only 225 kg and was only about 1 m in diameter. Both of these spacecraft are depicted as flying in orbit in the figure below. [Orbital Express] (Fig. 2.1).

This joint program cost about $300 million for the design and fabrication of the two spacecraft and the Atlas V launch. This was the first such space experimental program for on-orbit servicing, although Japan in the 1990s (i.e. then NASDA and now JAXA) was able to carry out the first robotic rendezvous between two spacecraft in orbit under its experimental test satellite (ETS) program.

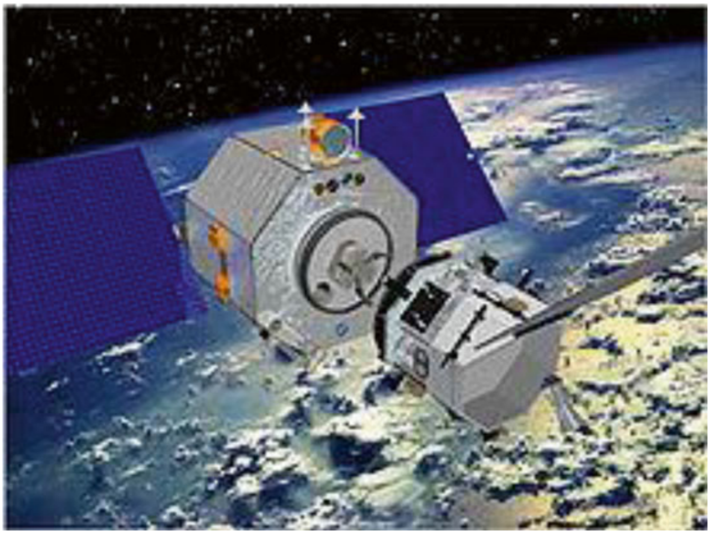

Fig. 2.1 The Astro "Servicing" spacecraft and smaller NEXTSat pictured in orbit (Graphic Courtesy of NASA)

Deutsche Orbitale Servicing (DEOS) Mission

This project of the German Space Agency (DLR), which in many ways emulates the U.S. Orbital Express program, is currently well underway. Contracts for all aspects of the mission have been awarded to Spacetech, which is the prime contractor. This development program will provide for on-orbit servicing as carried out by the so-called "Servicer" spacecraft. The specific objective of the DEOS program is to demonstrate how a defective spacecraft that is tumbling in an uncontrolled manner could be captured and suitably retrofitted so that it could resume operations rather than becoming a defunct spacecraft and thus worthless space debris. Further this mission is designed so that if the on-orbit servicing program to restore operational capability to the "Client" satellite (i.e. the name for target uncontrolled spacecraft) is not successful, then the "Servicer" (or capturing spacecraft) can link together with the "Client" and successful deorbit both spacecraft in tandem. [Deos: A Robot]

The DEOS "Servicer" spacecraft, known as the Phase A program, and the "Client" spacecraft, known as Phase B program, are both under contract to Spacetech Gmbh Immenstaad of Germany and will soon be ready for launch. Necessary ground control systems for the intended space experiments are also currently being readied for use. The Fig. 2.2 shows the robotic "Servicer" (Phase A) spacecraft, the "Client" (Phase B) spacecraft. Figure 2.3 provides an illustration of the command and control operations from the ground and the GEO relay satellite that can also be used to provide in-orbit commands. In addition to the experiments related to capturing

Fig. 2.2 The DEOS experiment

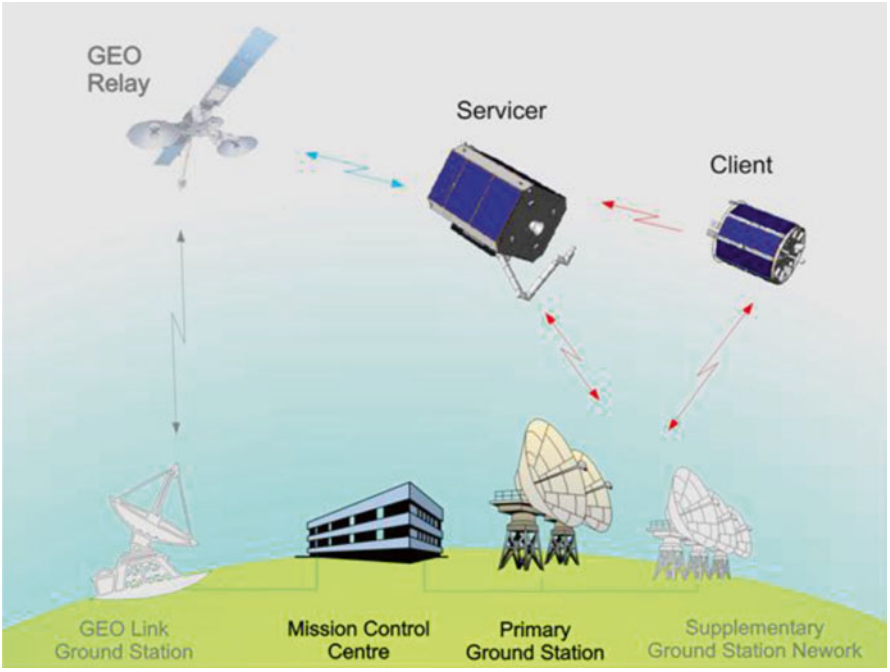

Fig. 2.3 DEOS servicer, client and ground control system (Both graphics courtesy of DLR, the Germany Space Agency)

and to coping with an uncontrolled and tumbling spacecraft the "Servicer" will also carry out refueling of the "Client" spacecraft. It will also test the ability of the Servicer to install new mechanical and electrical equipment on the Client spacecraft. A complete listing of the seven planned experiments is available on the DEOS website. [Deos Phase A]

The DEOS project is designed so that both spacecraft will be directly in communications with the ground at all times. During the special Low Earth Orbit Proximity (LEOP) experiments it is intended that there will be back up "supplementary ground station network" capabilities to provide for redundancy. The precise launch date for the DEOS Phase A and B spacecraft has not yet been set. [DEOS Phase A]

NASA Robotic Refueling Mission (RRM)

The NASA Robotic Refueling Module (RRM), on which development began in 2009, was brought to the International Space Station by the Atlantis Space Shuttle in 2011 as the last mission for the shuttle launch system. This specially designed module is about the size of a washing machine and its mass is approximately 250 kg and is shaped more or less as a 1 m cube—or about the size of a dishwasher. The RRM includes 1.7 L of ethanol that was used to demonstrate fluid transfer in orbit. The RRM contained a wide range of multi-use tools that were used to conduct a number of experiments involving the repair, retrofit, and augmentation of a hypothetical spacecraft in orbit. The RRM experiments confirmed that spacecraft that were not initially designed for refueling or in-orbit modification could be successful refueled with the type of tools that the RRM provided and the type of flexible robotic system available on the ISS through the DEXTRE.

The key to the RRM project was the use of the especially designed Canadarm 2 DEXTRE system that is capable of many complex and intricate operations that can be executed through ground commands. [NASA Robotic Refueling] (Fig. 2.4).

RRM was initially deployed on the DEXTRE's Enhanced Orbital Replacement Unit Temporary Platform (EOTP) and then after the Atlantis Shuttle departure, the RRM was installed at its permanent location on ExPRESS Logistics Carrier 4 (ELC-4). This location was key in that it allowed the RRM toolkit to be linked to ground command so that the DEXTRE system could carry out the complex RRM experiments.

Thus after the RRM module was installed on the ELC-4 platform, NASA mission controllers could operate the DEXTRE robot to retrieve RRM tools from this multi-tool module and conduct a range of servicing and refueling tasks. These experiments included manipulating, cutting and repositioning wiring and uncovering protective blankets. It also allowed the unscrewing of a variety of caps and access valves in order to transfer fluid and simulate refueling. At the end of this operation DEXTRE was able to put a new fuel cap on the fuel tank that had been

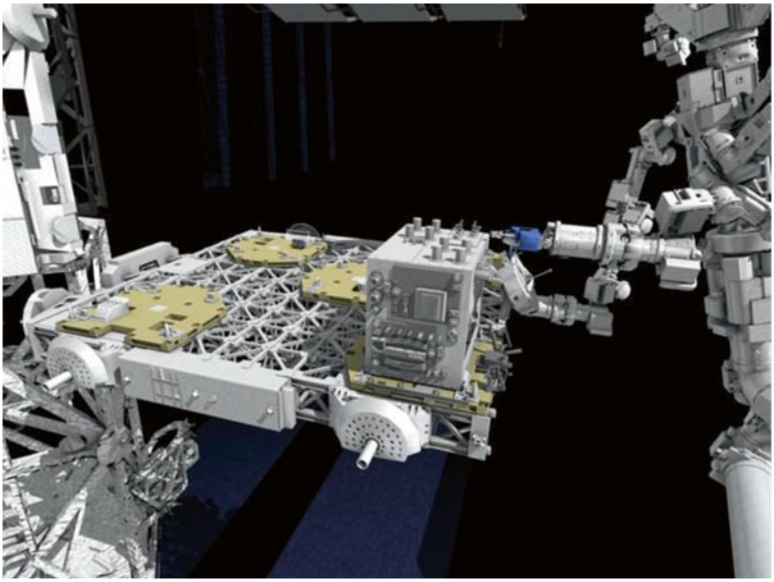

Fig. 2.4 The Dextre robotic device in tandem with the RRM was capable of a number of precision operations in space such as refueling, and orbital repairs and servicing (Graphics Courtesy of NASA)

opened. Specifically RRM tools were used to open up a fuel valve and transfer its stored liquid ethanol from one tank to another using a robotic fueling hose. [NASA Robotic Refueling]

These experiments were clearly primarily aimed at proving the viability of refueling and retrofitting satellites in orbit using remote mission controllers issuing commands from the ground. It should be noted, however, that very similar capabilities would be needed to capture a defunct spacecraft or upper stage launcher to install a system that would allow the active deorbit of selected orbit debris positioned in low earth orbit. The NASA RRM mission, since it was able to use the DEXTRE robotic system installed on the International Space Station, was able to be carried out at a much lower cost than the Orbital Express mission. It was able to carry out more detailed and intricate space repair operations than the earlier mission.

Phoenix Program by DARPA

The Phoenix Program by the U.S. Defense Advanced Research Projects Agency represents the continuing engineering and design programs of this agency in the area of in-orbit servicing and robotic construction in space. This is an extension of the earlier Orbital Express project in several ways. This program, rather than being in low earth orbit (a few hundred kilometers above the Earth's surface) is designed to carry out servicing and even space construction and operations in the much more difficult and demanding regime of Geosynchronous Orbit (GEO). This orbit, in the equatorial plane, is almost a tenth of the way to the Moon at nearly 36,000 km away from the Earth's surface. Robotic tele-commands from this great altitude are much more demanding.

This program is not only about servicing or capture of a satellite to attach a capability to move to a safe "parking orbit", but also about a whole new architecture for satellite design, assembly, and extended capability in orbit. One of the design concepts is that of modular units that could be assembled to create larger and larger capabilities over time. Perhaps most controversially is the idea that large aperture antennas or even solar arrays on defunct satellites might be "harvested" from these space debris objects and redeployed on assembled "satlets" in order to renew their use as totally reconstituted satellite systems. This would take the concept of active debris removal to a whole new level of "collecting space junk and reassembling it" into new functional spacecraft rather than de-orbiting it (Fig. 2.5).

This project, like the mythical phoenix, is designed to rise up anew from the dead and spring its wings anew, is not only extremely demanding in terms of its technological dimensions, but is also quite challenging in terms of new aspects of international space law. Does outer space salvaging translate as an exact parallel to the law of the sea? Do such concepts conjure up a vision that this would be a sort of space weapon that could act not only on a defunct space object, but also could represent a space operations vehicle that could disable the spacecraft of other nations? The Secure World Foundation has been asked by the US Government and

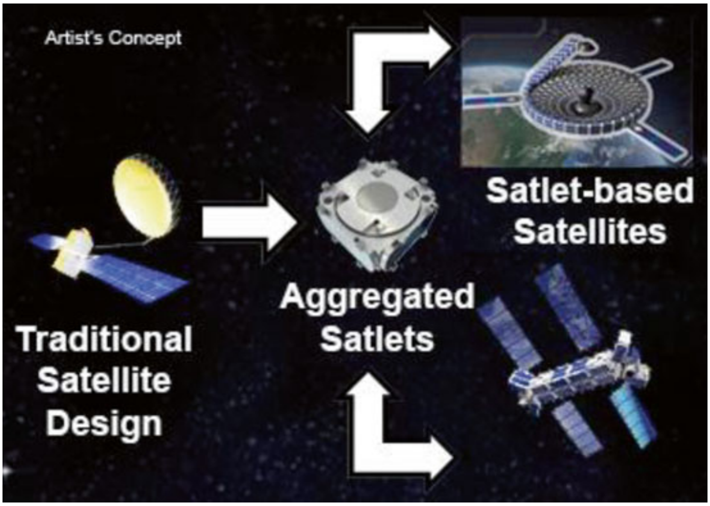

Fig. 2.5 DARPA architectural concept of aggregating Satlet modules (Graphics courtesy of DARPA)

by DARPA in particular to explore what are the legal and regulatory implications of satlets and harvesting of components such as antennas and solar arrays from defunct satellites.

Raven—The Autonomous Rendezvous Experiment

Raven is a follow on to the Robotics Refueling Mission, but in this case it is a part of the Department of Defense (DARPA) Space Test Program-Houston 5 (STP-H5) payload. It will emphasize the demonstration of a real-time relative navigation system for proximity navigation to be utilized in on-orbit servicing. The object is to allow future spacecraft to be able to autonomously mate with both prepared vehicles and those not designed for servicing. This is another joint program between NASA and the US Department of Defense. This experiment will fly on the International Space Station (ISS) and the launch date is planned for the first part of 2016.

For this experiment the DEXTRE robot will mount the so-called STP-H5 payload to an exterior platform (ELC-1) on the space station. Mission operators will subsequently use collected data related the instantaneous tracking of arriving and department spacecraft to the ISS. The goal is to improve Raven's performance in preparation for space flight on an independent robotically-controlled autonomous spacecraft.

Using the International Space Station as a test bed, the SSCO team will examine how Raven's sensors, avionics and algorithms work together as an integrated system. [Raven]

Privately Backed Orbital Remediation Programs and Initiatives

There are a number of private companies and institutions that are intent on seeking to address the space debris problem.

CleanSpace One

This is a project of the Swiss Space Center and the Federal Polytechnical School of Lausanne or the Ecole Polytechnique Federale de Lausanne (EPFL). It began with student designing a cubesat for scientific measurements with the mission to observe and map airglow—a light phenomenon found in the upper atmosphere. This project was launched in 2009 and completed its mission after several years in orbit. In February 2012 Professor Volker Gass, Director of Swiss Space Center (SSC) decided it would be desirable to try and design a small satellite capability that could track and retrieve the original cubesat.

With the support of the Swiss Space Center and EPFL the Clean Space One project was thus born. Professor Volker Gass, Director of Swiss Space Center (SSC) on this occasion stated: “Our work is guided by the principle that the person responsible for the mess is also responsible for cleaning it up. If everyone were to put their own house in order, then outer space would be neat and tidy”. [CleanSpace One]

Claude Nicollier, the first Swiss astronaut and currently Professor of Spatial Technology at the EPFL is likewise a strong proponent of this project as well and has said: “It has become essential to be aware of the existence of this debris and the risks that are run by its proliferation.” [CleanSpace One]

Current the CleanSpace One that is a small three unit cubesatellite (30 cm × 10 cm × 10 cm) is planned for launch in 2016 or 2017. Figure 2.6 shows a simulation of the CleanSpace One spacecraft overtaking the original cubesat launched in 2009. Figure 2.7 provides a schematic of the entire launch to deorbit mission.

The tracking and rendezvous for the CleanSpace One is quite complicated as shown in the attached graphics. The concept is for CleanSpace One to clamp on to the first cubesat and then they would deorbit in tandem. The graphic below is current, but the indication of 16,000 tracked space debris elements as indicated in the graphic window is no longer the latest count. As noted earlier there are 22,000 objects of 10 cm or larger now being tracked.

This project is clearly more an act of principle and public commentary than a full-scale program that will make a major contribution to the orbital debris cleanup effort. It is the removal of the largest debris elements in low earth orbit that is most

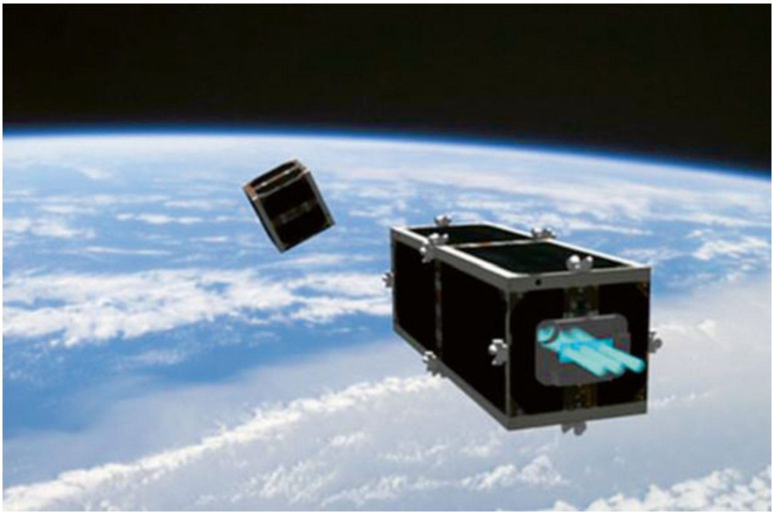

Fig. 2.6 a simulation of the cleanspace one spacecraft overtaking the swiss cubesat (Graphic courtesy of the Swiss Space Center)

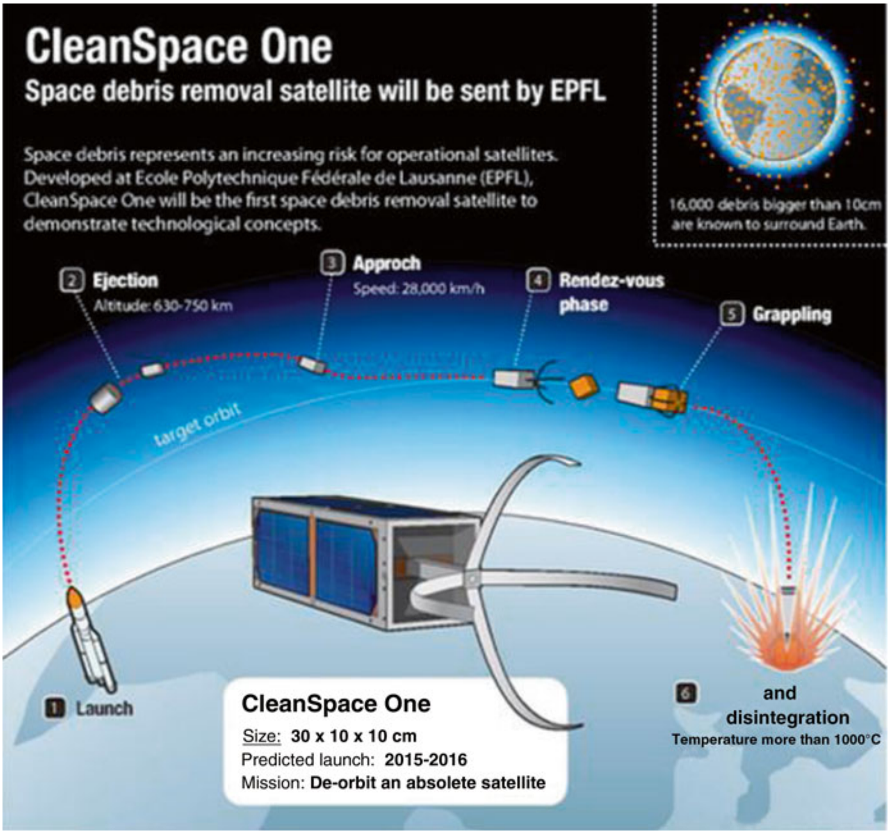

Fig. 2.7 CleanSpace one planned trajectory for deorbiting the original cubesat (Graphic courtesy of Swiss Space Center and EPFL)

critical and this effort would remove only one element out of over 22,000. The publicity that this program has generated, however, is in itself helpful. The Swiss effort to clean up their debris may well inspire other countries to follow suit. Public opinion is a key part of the effort to “clean up space.”

ConeXpress Orbital Life Extension Vehicle

This project to provide on-orbit services and life extension for geosynchronous satellites is a project of Orbital Recovery Limited of the United Kingdom. ConeXpress is designed to exploit the spare capacity of Ariane-5 that exists in the conical section that is positioned under the primary satellite payload fairing structure. A launch of the ConeXpress would thus use the standard Ariane-5 conical payload adapter as its main structure. This approach allows for a launch to Geo orbit for a cost of only about 35 million euros. The approach for lifting a failed payload launch from a lower or medium earth orbit to Geo orbit would be through the use of electric propulsion which has been developed for the SMART-1 mission to the Moon that the European Space Agency successfully demonstrated. To a certain extent this concept of a mission to extend the life of a Geo orbiting satellite derives from the ESA's Robotic GEO Orbit Restorer (ROGER) studies were performed in 2002–2003. There are, in fact, many potential applications that might be utilized of the ConeXpress orbital Life Extension Vehicle. The suggested applications include:

– Orbital debris removal or life extension of a GEO or MEO communications satellite
– Orbital slot protection using Cone-Xpress in free-flying mode;
– Repositioning along the GEO arc
– Restoration of orbital inclination back to the Geostationary equatorial plane
– Creation of a second-hand satellite that has active electronics, antenna and power but lacks fuel for station-keeping
– market by using old satellites for
– Services to developing regions by recycled satellites.

The current design is that the ConeXpress Orbital Life Extension Vehicle could extend the life of a Geo satellite by up to 12 years. It has been reported by Intelsat that its reboosting the failed launch of the Intelsat 19 to GEO orbit has allowed up to $800 million in added revenues to be generated from this reclaimed satellite that would otherwise have become a large space debris element.

The ConeXpress platform is currently being developed by Dutch Space in Leiden, The Netherlands. The anticipated weight of the ConeXpress at launch would be 1,400 kg and it would be stowed on the Ariane 5 within a 2.6 m diameter and 1.35 m height conical shape and its solar power array would generate about 4 kW. Ariane-5 launch schedules currently offer several opportunities per year to make use of its otherwise-unused capacity in the cone shaped part of its launch configuration. The Cone-Xpress stack comprises the payload adapter and an extension cylinder incorporating a separation mechanism and mountings for the inner structure. The inner structure accommodates equipment such as avionics and the rendezvous and docking payload. The ConeXpress deploys its antennas, solar wings, thruster-steering mechanisms after release from the Ariane 5. It is then ready to steadily fire its electric ion thrusters that will take it on a slow spiraling orbit during what could be up to a 6-month journey to GEO. During this long transfer operation, and while preparing for rendezvous and docking with a GEO satellite, ConeXpress looks like a small conventional geostationary communication satellite with its solar panels pointing north-south.

To date there are no confirmed customers for the ConeXpress Orbital Lifetime Extension Vehicle, but it could clearly be used not only to extend the lifetime of Geo Satellites, but also to elevate them to the end-of-life parking orbit or even to dispose of a satellite at end of life. [ConeXpress]

Vivisat Mission Extension Vehicle

The ViviSat's Mission Extension Vehicle is being designed as a simpler and supposedly less risky way to create an on-orbit servicing capability. This capability is being designed so it could be employed by satellite owners to extend mission life and also help to dispose of geosynchronous satellites at end of life. It has been "advertised" as an alternative to the McDonald Dettwiller and Associates (MDA) and its Space Infrastructure Servicing (SIS) vehicle that is also described in the section below. The claim made by Vivisat is that their docking vehicle could mate successfully with a higher percentage of the nearly 500 geosynchronous satellites that are currently in orbit—or will be shortly launched—and it also can be operated at lower cost.

The Vivisat module is being designed to link up with a satellite that has depleted its fuel, but is otherwise operational and thus able to continue successful operations. An alternative application would be to rescue a satellite that had been unsuccessfully launched and not fully achieved geosynchronous orbit, but still has all of its fuel and power systems operational. In this case the Vivisat module would ferry the satellite to its intended GEO orbit location and then release it to operate normally once it had been checked out and verified as to its technical capabilities. [Vivisat]

Vivisat is a partnership with ATK and its mission extension vehicle is designed to use ATK's A700 satellite bus. The design of the ViviSat module was announced as being "finalized" in March 2012 and was thus ready for construction as visualized below. Since that time, however, no satellite operators have been willing to sign on as customers for this on-orbit type servicing. The problem related to mission extension vehicles, on-orbit services modules, and spacecraft capable of active space debris is that there is currently a lack of a firm and growing customer base willing to pay for the construction and operation of such a new type of space vehicle. [Vivisat] (Fig. 2.8).

Fig. 2.8 Artist rendition of Vivisat mission extension vehicle mated to a satellite in orbit (Graphic courtesy of Orbital ATK)

McDonald Dettwiler Associates's Space Infrastructure Servicing (SIS) Vehicle

The MDA Space Infrastructure Servicing (SIS) vehicle is advertised as one of the first operational capabilities to provide a robotics and docking system for a number of possible in-orbit operations. This system will be based on work that MDA has previously performed for NASA and the Canadian Space Agency with regard to the Canadarm 2 and DEXTRIX robotic systems as well as for various Department of Defense agencies. The SIS vehicle's robotic arm is being designed to be used for refueling, but can also be used for a many other tasks as well. This vehicle could be used to support in-orbit repairs, maintenance, or other tasks such coping with antennas or solar arrays that are stuck or did not fully deploy. It could also be for towing smaller space objects into alternative orbital locations or removal of space debris from geosynchronous orbit or other tasks.

An initial arrangement was announced in March, 2011 under which Intelsat would utilize the MDA SIS craft for in-orbit servicing of its satellites. Subsequently some 10 months later, however, Intelsat and MDA were not able to conclude specific contractual arrangements and this agreement was terminated as of January 2012. To date no other satellite operators have signed up to use on-orbit servicing or mission extension services. [MDA Terminates]

The technology for in-orbit services is now proven in a number of governmental and commercial systems, but the market that is supported by commercial operators has yet to develop. It seems likely that the systems to extend the life of satellites via in-orbit servicing are likely to develop first. This means that active in-orbit debris removal (or boost to a graveyard orbit) would likely evolve subsequently. In some instance on-orbit servicing vehicles will be used both for mission extension and but then could subsequently be used to remove spacecraft to graveyard orbits as its final mission. [Space Serving Efforts Grapple] (Fig. 2.9).

At this time ConeXpress, Vivisat and MDA are all competitively positioned to build and operate on-orbit servicing systems that could extend the life of operational satellites, move satellites to Geo orbit in the case of failed launches, recycle old satellites to new uses, or provide transport services to move Geo satellites to graveyard orbits 300 km above Geo or assist large satellites in LEO orbit to reenter the Earth's atmosphere and burn up. At this time there are no commercial operators or countries willing to sign up for these services and thus the lack of paying customers is delaying further progress in this arena.

Electro Dynamic Debris Eliminator (EDDE)

There is yet another commercial project, known as the Electro Dynamic Debris Eliminator (EDDE) that is backed by Star-Tech Inc. that is a much more ambitious and longer term project that uses a much different technical approach than any of

Fig. 2.9 Simulated image of MDA space infrastructure serving vehicle attaching to client satellite (Graphic Courtesy of McDonald Dettwiler Associates)

the other systems discussed in this chapter. This is a project that proposes to use a very long cable—several kilometers in length—to "fly in low earth orbit". This flight of a cable through the Earth's magnetic field would in theory generate electrical energy sufficient to power the EDDE. This very long but low mass device (about 100 kg) device would have manipulators at both ends that would deploy nets that would be used to alter the orbits of space debris elements. The nets from the EDDE would drag the debris into a new orbit that would allow the debris to decay and re-enter the Earth's atmosphere and burn up. Part of the EDDE's efficiency would be that it would concentrate on clusters of debris that could be addressed in relatively quick succession.

This concept that has yet to be proven in experiments does draw on the experience of tether experiments by NASA and other space agencies that have shown that long cables of significant length can indeed generate a large quantity of electrical energy. The advantage of this approach is that it is reusable since it runs on the energy supplied by the Earth's magnetosphere. Star Technology Inc. scientists have estimate that over 135 pieces of debris could be removed from sun synchronous orbit over a 3 year period by one EDDE unit. Further it is estimated that if as many as 12 EDDE units were deployed it could remove as many as 2,500 of the larger elements in low earth orbit in about 7 years. This approach that involves a craft that remains in orbit without refueling and could dispose of a large number of debris elements would clearly be much more efficient than systems that address debris elements one at a time. Clearly a robotic vehicle that mates with a debris element and then deorbits with only one defunct spacecraft or upper stage launch vehicle at a time would be very slow and economically inefficient. The one at a time approach might make sense where a very large defunct satellite is in danger of colliding with another satellite, but it does not offer a systematic solution. As noted above all of the in-orbit servicing systems now available suffer from a "business case" that lacks a clear and solid economic rationale for their use.

Chapter 5 that addresses a wide range of possible future technologies for active debris removal—including the electrodynamic energy approach—seeks to explore what some of the longer term answers might be that extend beyond the currently available technologies and systems addressed in this chapter.

Looking at Currently Available Systems on a Comparative Basis

The following chart shows what capabilities have been demonstrated or are currently under development by countries, by research institutes, labs or agencies, or by commercial enterprises. It seeks to show where the approaches are similar or different and the overall status of actual systems that have flown and been tested in space or are currently under development by governmental agencies or private aerospace concerns.

Comparative review of relevant existing governmental or commercial programs

Name of system	Country	Technical approach	Maturity & proven approach	Cost efficiency	Implementation date
Clean Space One	Switzerland	Small 3U Cubesat chaser to deorbit 1Unit Cubesat	First experiment with cubesat chaser	Low cost, but only removes a cubesat	2016–2017
ConeXpress	UK, Netherlands (with ESA support)	Robotic capture (Uses Ariane 5 cone for low cost launch) electric ion propulsion	Relative mature. Uses ion propulsion developed by ESA for Moon mission	Cost effective launch (at 33 million Euros) but one at time robotic system	Pending a contract. Could be in 2016–2017
Deutsche Orbitale System (DEOS) Servicer & Client	Germany	Servicer and Client with robotic capture for refueling, repair or retrofit, with forced de-orbit if required.	Relative mature technology. It has been shown in previous programs such as the Orbital Express	Experimental program. One at a time system but could be cost efficient for large & expensive spacecraft	Likely 2015
EDDE by Star Technology and Research (STAR) Inc.	USA	Cable to generate electrical energy from Earth's magnetosphere. Nets to drag down debris	Experimental concept with longest lead time to possible implementation, NASA awarded STAR-Tech $1.9 million R&D Contract in Feb 2012	This would be far the most cost effective solution if it proves out technically	Possibly in 2020 timeframe
McDonald Dettwiler Associates (Space Infra-structure Servicing)	Canada	Robotic mating for repair, retrofit, refueling or transport and/or stationkeeping	Relative mature technology. It has been shown in previous programs such as the Orbital Express	One at a time system but could be cost efficient for large & expensive spacecraft	Pending a contract. Could be in 2016–2017
Nasa Robotic Refueling Mission and DEXTRE Robotics Arm System	USA	Experimental system to test in-orbit refueling, repair and retrofit of satellites not designed for such retrofit or refueling.	Proven capability. Similar techniques will now be used in DEOS, ConeXpress, and MDA SIS and Vivisat	Does not apply Experimental program to test concepts. Not full scale implementation	Experiment concluded
Orbital Express	USA (NASA & DARPA)	Servicer (Astro) and Client (NextSat) robotic mating in orbit	Successful proof of concept	Experimental program. One at a time system but could be cost efficient for large & expensive spacecraft	Experiment concluded
Phoenix project	USA (DARPA)	Will implement robotics and proximity maneuvering proven in Orbital Express and NASA RRM	Feasibility and definition of scope of activities still being defined. Many robotics & docking, systems proven	Experimental program but could be very cost effective way to recycle defunct satellites	2016 onwards
RAVEN	USA (DARPA) Using ISS DEXTRE	Will test real-time tracking of space vehicles to create autonomous navigation	Will fly to ISS in first half of 2016 for testing. Space Test Program-H 5	Experimental program. Builds on Orbital Express, RRM programs.	2016 onwards
Vivisat Mission Extension Vehicle	USA (partnership of ATK, US Space and Vivisat)	Will implement robotics and proximity maneuvering proven in Orbital Express and NASA RRM	Many proven technologies in robotics, proximity maneuvering	One at a time system but could be cost efficient for large & expensive spacecraft	Pending a contract. Could be in 2016–2017

Other Key Infrastructure for Coping with Orbital Space Debris

Finally it needs to be noted that all of the above systems must ultimately depend on accurate and real time updates that provides the latest orbital parameters of space debris. Close proximity navigation to mate with a defunct space object must thus begin with precise space situational awareness. Currently the U.S. Air Force operates precise radar tracking systems that relies on a VHF radar system known as the Air Force Space Surveillance System (AFSSS) very high frequency (VHF) radar tracking system that operated continuously from 1961 up to the present. Even though it has been upgraded steadily over time it has less precise tracking capabilities than a much more precise S-band radar system that will likely be implemented sometime around 2018. In 1980 the U.S. Air Force system was tracking about 5,500 objects. Today, with augmentation and space-based tracking spacecraft that figure is around 22,000 with the ability to track low earth objects about 10 cm or larger in diameter.

The new S-band U.S. Air Force Space Fence, now likely to go on line in about 3 year's time, is a much more extensive geographic installation and uses much higher frequencies with much smaller wavelengths. This allows it to detect much smaller microsatellites as well as more minute debris particles than the previous systems.

The Space Fence is designed to operate using what is called a "net-centric architecture". This means that the system will be capable of detecting and tracking much smaller objects in low/medium Earth orbit (LEO/MEO). It will also be able to integrate the capabilities of the Space Fence with in-orbit tracking abilities and optical tracking systems that are also being added to the space tracking network. This system was earlier planned to become operational in 2015, but budgetary concerns and technical development issues have pushed it to a date of December 2018 or perhaps later. [USAF's Space Situational Awareness]

The purpose of the space tracking system as operated by the U.S. Air Force is defined to be:

- **Detect, Track, Identify, and Differentiate Among Space Objects**. The current radar system and the new S-band Space Fence are the key elements for this purpose by spacecraft and optical tracking capabilities augment this capability.
- **Threat warning and Assessment**. The key reason for the operation of this multi-billion dollar facility and supporting network is to create the ability to detect potential or actual attacks (especially of missiles) as well as to monitor the space weather environment effects, monitor space system anomalies as well as track space debris that can threaten critical space infrastructure such as the International Space Station.

In addition to these two vital functions, the operators of the U.S. Air Force space situational awareness program are also charged with assessing the performance of U.S. and foreign space assets and their operation and intended purposes in what might be called "space-related intelligence". Finally this operation seeks to integrate all data obtained from all sources so that threats of all types can be analyzed and appropriate alerts given. The new US Joint Space Operations Center Mission System (JMS) that supports all U.S. defense forces will have overall responsibility for data assessment and creation of threat alerts.

In addition to space assets that support tracking capabilities, a recent agreement was announced on August 25, 2014 with Australia to develop a new optical space object tracking site in Western Australia that will support both governmental and commercial customers concerned with space debris threats. This new facility will be constructed and operated by Australia's Electro Optic Systems Pty Ltd. The site will use a combination of lasers and sensitive optical systems to detect, track and characterize man-made debris objects. [Lockheed Martin and Electro optics]

Other space tracking systems are operated by Russia, the European Space Agency, and other military units, but the U.S. facilities are the most sophisticated and comprehensive capability and are the most extensively relied on facilities for orbital space debris tracking.

Conclusions

Currently the great preponderance of programs that have actually flown in space—or are under active design, construction or corporate planning—are all oriented toward on-orbit servicing of spacecraft and attempt to extend the useful lifetime of spacecraft operated by commercial concerns—especially in the communications satellite sector. The current systems for on-orbit services, however, also represent the only capabilities now available that might be used to rescue defunct satellites, to place them in super synchronous orbit or to mate with them and force their de-orbit. In Chap. 5 we will examine new concepts that are seeking to develop new and more innovative ways to achieve active debris deorbit. The motivation is to find new technological approaches that could be much more cost effective than systems that address the removal of debris elements on a one at a time basis.

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Chapter 3
Exploring New Approaches and Solutions to the Orbital Space Debris Problem

Introduction

The legal definition and status of orbital space debris is problematic in a variety of ways. As already noted, all human crafted items launched into space are known as "space objects" as specifically defined in the Liability Convention and generally conceived in the Outer Space Treaty. [Treaty on Principles] But orbital space debris, in contrast, has no agreed international definition. Nevertheless "defunct space objects no longer in use" is a practical definition that is often used. Such a legally agreed definition becomes quite important in such circumstances as when the provisions of the "Liability Convention" come into play. [Convention on International Liability]

The collision of the Iridium 33 and the Kosmos 2251 spacecraft is a specific case in point. If the Kosmos 2251 satellite had been clearly and unambiguously defined as orbital space debris that was officially designated as defunct and uncontrolled while the Iridium 33 had been designated an active and operational space object, then the collection of liability damages from this collision would have been much easier to resolve if formal claims had been made.

There is a further definitional problem under the "Outer Space Treaty" and the "Liability Convention" that places the responsibility for any accident that occurs as a result of a space collision not with the offending "space object" nor even the "operator or owner of the spacecraft". The responsibility for paying liability claims, under these ratified UN agreements only go to the "Launching State"—and exclusively so. Yet, there is ambiguity here in that there can be more than one "Launching State". The language that defines the Launching State sets forth a threefold definition in Article VII of the Outer Space Treaty and Article I (c) of the Liability Convention. The Launching State is defined as a State that launches or procures the launching of an object into outer space, or from whose territory or facility an object is launched. In some cases the "Launching State" can be a single nation, but it is possible for four or more countries to be somehow involved. France for instance

J.N. Pelton, *New Solutions for the Space Debris Problem*, SpringerBriefs in Space Development, DOI 10.1007/978-3-319-17151-7_3

operates a launch facility in Guyana and launches Russian launch vehicles from this facility for many different customers from different countries that procure services to place their spacecraft into orbit. Sea Launch that operates out of the United States Long Beach California launches from the High Seas in the Pacific Ocean near Kiribati. The Sea Launch consortium is owned by four companies from Norway, Russia, Ukraine, and the United States but is incorporated in the Cayman Islands. [Sea Launch]

There is now a Registration Convention that sets forth the requirement for registration of all launches into outer space and identifies what the process is when more than one Launching State is involved. This is specified in Article II of the "Convention on the Registration of Objects Launched into Outer Space" as follows:

> "2. Where there are two or more Launching States in respect of any such space object, they shall jointly determine which one of them shall register the object in accordance with paragraph 1 of this article, bearing in mind the provisions of article VIII of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, and without prejudice to appropriate agreements concluded or to be concluded among the Launching States on jurisdiction and control over the space object and over any personnel thereof.
> 3. The contents of each registry and the conditions under which it is maintained shall be determined by the State of registry concerned." [Registration of Objects]

With this background in mind, it should be clear that the active removal of space debris has a number of challenges. The legal issues that are involved are addressed in detail in Chap. 6.

This chapter is more specifically concerned about what incentives can be given to nation states, satellite owners and operators, and those who launch spacecraft to minimize orbital space debris at the time of launch and to remove debris from orbit at the end of life or when a spacecraft or upper stage launch vehicle becomes defunct.

Launching States currently take a risk of incurring a large liability when undertaking active removal of a spacecraft or deorbiting an upper stage launcher. According to Article III of the Liability Convention, in the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable if the damage is due to its fault or the fault of persons for whom it is responsible. If there is a collision while these removal processes are under way the "Launching State" may be held liable for the crash. If on the other hand, they simply leave their satellites in orbit, once it is successfully launched, it is difficult to prove that any collision that may occur is due to their fault, hence holding them liable. The current Guidelines for the Mitigation of Space Debris under Guideline 6 urges all concerned that they: "Limit the long-term presence of spacecraft and launch vehicle orbital stages in the Low-Earth orbit (LEO) region after the end of their mission". But these guidelines are non-binding and the incentives "to do the right thing" either on the part of private satellite operators or even the Launching State are currently simply not present. Since it does not seem likely that the current provisions of the Outer

Space Treaty or the Liability Convention will soon be amended, the question becomes what can be done instead to encourage active orbital debris removal. [Space Debris Mitigation]

Current Problems with Space Debris and Creating New Incentives to Facilitate Debris Removal

The classic case in economics is the problem of the light house. All ships at seas benefit from light houses. These facilities help ships to avoid running aground or perhaps even risking a puncture and sinking into the ocean. Yet no one ship owner wants to pay for a lighthouse individually. Thus governments build lighthouses and pay for them through taxes and usage fees imposed on ship owners. Air and water pollution is much the same. No individual wishes to pay for the clean-up of air and water pollution all on their own. Instead governmental regulations are created and enforced by taxes and clean-up fees. There are also fees, and fines against offenders. The case of orbital space debris pollution is even more difficult because outer space surrounding Earth is in the global commons and not under the control of any one nation and not subject to taxing authorities. Clearly if there were a way to collect revenues to pay for active orbital debris prevention or removal this would assist a great deal. The problem of space debris is clearly complicated by the lack of enforceable regulations, the lack of a revenue source to cope with the problem and lack of an entity that is globally accepted to impose sanctions, fees, or enforce other remedial actions. Yet the problem of mounting orbital space debris remains along with the cascading effect which means that high velocity debris will continue to generate additional orbital debris. Nor is any treaty or convention-mandated solution to this issue on the horizon. Thus, the question becomes what can be done?

Transparency and Confidence Building Measures

The issue of orbital debris has been actively on the agenda of the UN Committee on the Peaceful Uses of Outer Space for essentially two decades—starting in 1994. Cooperation with the Inter-Agency Space Debris Coordination Committee (IADC) has produced the Guidelines on Space Debris Mitigation adopted by the UN General Assembly in 2007. This is, however, not the only UN initiative in this area. The UN Office of Disarmament Affairs (UNODA) has set up a Group of Governmental Experts on Transparency and Confidence-Building Measures in Outer Space Activities as directed by the UN General Assembly. This GGE was asked to address space-related issues in terms of disarmament and coping with space issues in terms of national defense issues.

The GGE in its report of July 29, 2013 identified six explicit areas where the development of Transparency and Confidence Building Measures would be desirable and should be pursued. The fifth recommended area suggested that efforts should be made to establish "norms of behavior for promoting spaceflight safety such as launch notifications and consultations that aim at avoiding potentially harmful interference, limiting orbital debris and minimizing the risk of collisions with other space objects." [Report of the Group of Governmental Experts]

It is sometimes assumed that consultations related to civil space activities are much less contentious and difficult than negotiations related to defense-related matters. This is simply because of the highly sensitive and strategic nature of military and national defense issues. In this area, for instance, experts have rather universally recognized the mounting problem of space situational awareness and the dangers that space debris or re-entering space craft could be mistaken for a missile attack with tragic consequences. In this case, the concern about such consequences works in favor of initiatives to clean up orbital debris. The logical thought process is that if leading space faring nations (who are also typically those with space missile defense systems) could agree on a norm of behavior related to minimizing space debris, space collision avoidance, and active space debris removal this would also assist with improved missile defense. Military officials certainly wish to avoid false perceptions of missile attacks. From this perspective, "best practices with regard to debris removal" would be a benefit to everyone concerned. If for starters there could be an agreed "norm" with regard to space debris (and its active removal) this would be a net positive rather than some sort of zero sum game. In short it is generally agreed among the military space practitioners in the U.S., Russian, Europe, China, India and Japan, as reflected in the GGE Report, that progress on the orbital debris problem and space collisions is highly desirable. From this perspective, if a norm of behavior could be developed and broadly observed over a period of time, it would almost be as good as a new space treaty to this effect. Certainly it appears highly desirable if the UN Working Group on the Long Term Sustainability of Space Activities would stay in touch with the UNODA and the GGE recommended initiatives to devise possible steps forward. These could, in fact, be based simply on "Transparency and Confidence Building Measures" as agreed by key space faring nations. These agreements or norms would presumably apply to space debris minimization, launch notifications, and even plans for active debris removal. Joint discussions that involve both civil and defense space agencies in moving forward on orbital space debris could prove helpful in a number of ways.

Expanded Recognition of the Role of Private Entities in the Outer Space Arena and New Approaches that Transcends the "Launching Nation" Conundrum

Today the world of space activities is dramatically different from the time that the Outer Space Treaty and the Liability Convention were agreed. In the early days of space it was only governments in terms of Defense Ministries or civil space agencies that launched spacecraft or missiles. Private enterprise was not a part of the equation. In almost a half century the world of space activities has dramatically changed.

Today about half of all launches and spacecraft are related to commercial activities, student or university projects, or private international institutions. Organizations like Bigelow Aerospace are deploying private space stations. Private aerospace companies are developing launch systems to ferry astronauts to and from the International Space Station (ISS). There are ventures such as the SpaceShip Corporation and XCOR pursuing private suborbital flights, and other ventures such as Launch One, Stratolauncher and Reaction Engines are developing commercial launch systems that are able to lift different classes of satellites to orbit at ever decreasing costs. [Joseph N. Pelton and Peter Marshall]

Companies not only arrange to buy and launch satellite systems, but they also buy and sell in-orbit satellites and trade space systems freely around the world. The initial Outer Space Treaty and the Liability Convention that held (and still holds) that the "Launching State" was responsible for a spacecraft even after it has been bought and sold commercially by companies from entirely different regions of the world does not seem to make sense, yet this indeed reflects the current realities in terms of space-based activities and associated liability provisions.

The problem is far clearer than the solution. One approach would be for Launching States to not agree to launch until there was binding contract to cover not only due diligence, related to orbital space debris at launch, but also strict contractual terms and conditions that cover the right to sign off on any subsequent sale of satellites and provisions for end of life disposal arrangements. There could also be a separate deorbit system installed on satellites that would remain under the control of the Launching State, regardless of any sale of the satellite and would be exercisable at a prescribed time unless formally agreed to by the Launching State. The bottom line is that the division of responsibilities between private commercial concerns on one hand and governmental entities on the other needs to be reappraised. This is true with regard to all space transportation and on-orbit systems in general and orbital debris mitigation provisions in particular. As there is continued movement toward "New Space" commercial activities the urgency only increases. The increasing risks related to space debris only increases with time. The importance of this reappraisal will thus become more and more apparent.

Financial Incentives and Funds to Address Orbital Debris Issues

There have been a number of proposals made as to improved ways to address space debris issues. These include the creation of a new international agency, perhaps modeled on the initial incarnation of the Intelsat Consortium, or a new international convention or agreement devoted to orbital debris. Ultimately, as is the case with many international problems and issues, the key to the orbital debris problem is closely related to money and the need for funds to address this issue.

It has been suggested that one solution would be for all space missions, in addition to the purchasing launch and mission insurance, should be required, under national or regional regulation, to put a small percentage of the project into a debris mitigation fund. This fund would compensate innovative space entities that develop the needed new technology that could remove defunct spacecraft and upper stage launch vehicles from working orbits. It has been calculated that for a much smaller percentage of the mission costs than is currently devoted to launch insurance, it would be possible to create a financial mechanism that could reverse the process of debris build up and also generate a range of new and innovative technologies that could spur new types of space applications. [J. N. Pelton, A Global Fund]

By using the space insurance model and financial incentives it is believed that many new response mechanisms would be developed and that they would prove more efficient and cost effective than other approaches. Such an approach would be lower in cost, faster, and more effective than the creation of a new international agency. It certainly could be accomplished much faster than through a process of negotiation of a new treaty or convention that requires near unanimous international consensus. Indeed the “financial insurance model” can be implemented on a national or regional basis and grow as more and more countries agree to sign on to this process. Indeed just one country passing a “model national space law” could change space history. This law would only need to mandate an “orbital space debris insurance fund” going forward. Such a bold step, if joined by other forward looking countries could usher in a new era in space safety and allow human society reclaim its long term ability to leave this planet and use the heavens for science, exploration, and a wide range of essential applications.

The Way Forward

In the short term it seems apparent that individual countries will need to utilize technology currently developed (as outlined in Chap. 2) to remove the largest and most dangerous space debris in low earth orbit on a one at a time basis. Currently only the Launching State can remove its own defunct satellites from orbit unless it is going to be accused of deploying a Weapon of Mass Destruction and committing an act that would likely be deemed an act of war. Likewise using a directed energy system to change the orbit of a satellite of some other country would also be seen as an act of aggression. It has been suggested that a country that is the Launching State for a particular defunct satellite might be given access to another countries technical capacity to divert the orbit of this satellite in order to avoid a collision and also in this manner avert an international incident.

It has been suggested that if the ten most dangerous debris elements were removed each year, even if employing technology that removes only large defunct spacecraft at a time, that progress on proliferation of space debris could at least be initiated. But this is just an interim step. The new approaches that are discussed in Chap. 5 can develop much more efficient and cost effective ways to remove a much larger volume of space debris. Clearly there is also a need to address the institutional, regulatory and legal issues that are initially presented in this chapter and discussed in more detail in Chap. 6.

Conclusions

The intricacies of the orbital space debris issues are enormously complex. There are difficulties everywhere. The current guidelines for mitigation are modest, incomplete, and non-binding. The problem of debris build-up continues to grow worse due to the cascading effect that comes with the 6 tons of debris, with tens of thousands of these debris elements being in sizable chunks, that are constantly colliding and creating yet other new debris elements. One collision involving large objects can generate thousands of new debris elements. Efforts just to remove ten large debris elements, using current technology are quite expensive. And yet even this minimal effort can help stabilize the ongoing build-up of debris elements. All of the players in this ongoing play entitled something like: “The Rise of Orbital Space Debris”, need to continue to work to find new solutions. This means a concentrated effort to address these issues by all of the space agencies, the military and defense space programs, the Inter-Agency Space Debris Coordination Committee (IADC), the UN Committee on the Peaceful Uses of Outer Space, the Working Group on the Long-Term Sustainability of Space Activities, the UN Office of Disarmament Affairs and the Group of Governmental Experts on Transparency and Confidence Building Measures. The interesting new dimension would be if others such as the space insurance agencies, satellite and launch vehicle manufacturers, and the scientific and astronautics community should join into these discussions with innovative new ideas and suggestions. The stakes of not solving the problem of space debris are sufficiently high that a crash effort (pun intended) to solve this problem is now imperative.

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Chapter 4
Examining the Case for Active Orbital Debris Removal

Introduction

For some time the problem of increasing orbital debris has been clearly understood to be a potential menace to the future sustainable use of space. Dr. Donald Kessler, the father of the concept of the so-called "Kessler Syndrome", has recently written that even with the 25 year rule for removal of debris after the end of life of spacecraft and the voluntary, non-binding rules adopted by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) are insufficient. He believes space debris will continue to accumulate just due to collisions among existing debris. He has particularly noted the danger that comes from the potential collision of large pieces of debris. Dr. Kessler has indicated that "in the region between 700 and 1,000 km, events such as the Iridium/Cosmos collision can now be expected to occur at a rate of about once per 10 years. If the 25-year rule is not followed, then the frequency of collisions will increase more significantly over time. These collision rates can be expected to increase for hundreds of years and end only when there is a significant decrease in the number of massive debris objects within this altitude band." [Kessler] Although the low earth orbit bands, and especially the polar low earth orbits are of the most urgent concerns, there are also increased concerns about other orbits as well.

Clearly Dr. Kessler and others with expertise in this area have indicated the need to concentrate on removing large objects from low earth orbit and especially in the areas of Earth orbit that are particularly crowded. Today a great deal of attention is being devoted to considering how technical methods might be devised that could serve to remove the largest elements of space debris from low Earth Orbit and do so with technical efficiency, at low cost. Further this might be accomplished by a variety of means that might include governmental or military programs, commercial activities or projects, or perhaps by some new institutional arrangement that would still be considered consistent with international legal arrangements or accepted

J.N. Pelton, *New Solutions for the Space Debris Problem*, SpringerBriefs in Space Development, DOI 10.1007/978-3-319-17151-7_4

codes of conduct. This chapter examines the various possible strategies whereby active space debris might be accomplished and the relative effectiveness of these approaches in terms of a viable economic business case.

Factors Involved in Building a Business Case in Favor of Remediation

The key questions that currently surround the orbital debris issue are the following: How bad is the current situation? Will it get worse in the near future? Are there reasonable methods to address the orbital debris issue in terms of collision avoidance techniques that can be operated effectively from the ground until on-orbit systems can be developed for active removal? Are their reliable and effective means to achieve active debris removal using innovative space-based systems on the relative near term horizon? And if there are such means can they be carried out cost-effectively and reliably? And then there are the institutional, business and regulatory issues and questions.

Who should be "authorized" or "enabled" to conduct such operation? Should there be additional controls imposed on yet to be launched space missions to mitigate future debris? Should such additional controls include a separately commandable active deorbit systems and perhaps especially developed procedures involving small satellite launches? In terms of a broader concern with the sustainability of space should their also be controls related to rocket launches that relate to pollution of the stratosphere? Finally there is the question of whether those who engage in active debris removal should be governments, an authorized international entity or entities, or perhaps commercial entities working within some form of legal or regulated mechanism? The answers to these questions obviously will have a large impact on the business case for active debris removal and the cost of such operations—whether these relate to removal, prevention or the effective creation of a future sustainable space environment.

In addition to these prime questions there are also ancillary questions as well. These include such questions as: Who decides what is actually designated as space debris and whether it can be removed within the constraints of existing space regulations and practices? If some of the mechanisms that remove space debris can be considered "space weapons", would such active removal processes be considered "illegal" under the Outer Space Treaty or other space conventions and regulations? If the government that is considered the "Launching State" controls the equipment and processes associated with the removal, then does this mitigate against defining such equipment or systems as a space weapon? Would this be true regardless of whether this is a space-based instrument or a ground-based instrument? If the technology developed for space debris removal can also be used for other purposes such as on-orbit servicing does this also help bolster the business case for active debris removal in a sufficient manner so as to make such operations economically viable?

The discussion of these questions are divided into the following sections: (a) Intermediate Actions to Address Orbital Debris Collision Avoidance Using Ground-Based Systems; (b) The Business Case for Governmental Action to Exclusively Engage in Debris Removal; (c) The Business Case for a Globally Designated international Entity to Engage in Active Orbital Debris Removal; (d) The Business Case for Private Commercial Entities to Remove Orbital Debris under Some Form of International Structural Guidelines, Global Funding Mechanism or Insurance Financed Operation; (e) Business Case Based on Breakthrough Technologies. In each "case discussion" the technical, financial, operational and economic aspects will be considered, but the prime focus will be on economic viability.

(a) Intermediate Actions to Address Orbital Debris Collision Avoidance Using Ground-Based Systems

There are currently ground based laser and directed energy systems that can be used to divert the orbits of space debris elements that are projected to collide with spacecraft, the International Space Station (ISS), or other large space objects that are in low earth orbit. Alternatively it is also possible to maneuver spacecraft or space stations with thruster systems to seek to avoid collision with passive debris objects that have no control mechanisms. The use of ground initiated maneuvers to create a slight diversion to avoid an in orbit collision, however, represents only a temporary solution for a problem that could become more and more likely to occur. As noted in the introduction to this chapter the current projection is that a major collision in low earth orbit can now be expected once a decade. This type of ground-based initiated maneuver, however, can be cost effective in that no dedicated launch must be undertaken. Further the registered "launching country" could be asked to be directly involved in this type of orbital debris diversion to avoid the collision and by this direct involvement by controlling the pulsed directed energy might perhaps minimize concerns that such activity would be considered improperly undertaken without legal consent.

Such a diversionary activity, although it might be successful and relatively low cost, still poses several problems. One problem is that the diverted orbit might result in a space collision at a later date with another space object and thus the maneuver could lead to a future adverse liability claim. Secondly there could be a miscalculation and the diverted orbit for the targeted debris could actually create a space collision that might have otherwise not occurred. The participation in the orbital diversion might rather ironically lead to the very result which was being sought to avoid. Telesat maneuvers to avoid the so-called out of control Galaxy "Zombie sat" were successful, but the calculations had little tolerance for error and the Telesat officials decided to take a calculated risk that were fortunately successful.

Satellite operators have thus been able to maneuver satellites by firing jets to avoid collisions such as the elaborate maneuvers that were carried out by both SES of Luxembourg and Telesat in seeking to avoid the Galaxy satellite of the Intelsat fleet while still maintaining service. [Selding]

The use of high energy lasers or directed energy beaming systems to divert the orbit of a piece of orbital debris of irregular shape and size and to hit exactly the right spot with the exact degree of inertial force is a difficult and still largely unproven technique. Most fundamentally, such maneuvers to divert orbits are really "stop-gap" measures that do not really provide a longer term solution—just short term relief.

And if orbital diversion via laser beam energy is an unproven technique it is a step further to consider the possible use of directed energy to burn up and remove elements from orbit entirely. Currently there is research underway as to how directed energy systems could be used to destroy or divert an asteroid from hitting planet Earth, but such techniques are still in early days of experimentation. Further such a very high energy system would undoubtedly be considered a "space weapon". In this case, there are not only technical, operational and financial considerations but quite serious legal and regulatory issues to sort through as well. Clearly these issues will continue to be researched, but for the next few years, it is reasonably safe to say that ground-based directed energy systems represent a complex of issues to be solved. Only with more experimentation and some clear precedents based on viable tests will these types of ground-based methods move ahead. Currently, there is a wide-spread consensus that such ground-based solutions form only a temporary type solution and that active in-space solutions will ultimately be needed. The key, of course, will be the development of improved space-debris procedures that will assist to decrease new space debris build-up.

(b) The Case for Governmental Action to Exclusively Engage in Debris Removal

The complexity of the task associated with orbital debris removal tends to point toward either governmental space agencies or a new international intergovernmental agency being set up under a new global treaty arrangement to accomplish this daunting feat. The many challenges include:

- The huge amount of orbital debris that has now formed in low, medium and geo orbit.
- The complexity of the missions needed to remove space debris from orbit without engendering a collision and the creation of more debris.
- The high cost of such activities with no existing commercial market associated with it.

The issues here are obviously complex in that they involve financial and economic considerations, the need for governmental subsidies or underwriting, and the feasibility of a new global set of international agreements to address a concerted effort to remove orbital debris, and more. The fact that the Inter-Agency Space Debris Coordination Committee (IADC) reached agreement on procedures to minimize the creation of new debris and also has signed on to a continuing effort to address the issue of orbital debris removal is a positive sign as to the willingness of space faring nations to work for solutions in this area. The fact that the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) unanimously agreed to voluntary procedures that were closely akin to that adopted by IADC is a further positive sign. Finally, the current COPUOS Working Group on the Long-Term Sustainability of Outer Space Activities is now addressing orbital space debris and extreme solar weather as core issues in their studies.

The membership of the IADC and COPUOS are comprised entirely of governmental representatives. Any agreements reached within these bodies are by definition intergovernmental in nature. Yet despite these efforts at governmental agreement on space debris, the current situation does not seem likely to result in international agreements covering orbital space debris or providing explicit sanctions to active debris removal. No new space treaties or conventions have been reached since the five international agreements were negotiated and agreed in the late 1960s and 1970s. The expense of creating a new international agency to undertake debris removal, the potential interference that might occur with regard to missile defense and orbital tracking systems, and a number of other practical factors all argue against a new wide-spread agreement that would lead to the formation of a new international agency to address this problem. Even the most severe threats to the entire planet of extreme solar weather events and asteroid and comet strikes have only resulted in modest agreements to form a new International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG).

The history of the last 10 years thus seems to indicate that action related to active orbital space debris removal will thus end up with national governments taking action, or governments supporting, underwriting or subsidizing private aerospace enterprises to address this effort. Current activities seem to indicate a pattern of some countries looking to national space agency to undertake action for this purpose, while other countries—particularly the United States and to a lesser extent Europe—are supporting private initiatives. Perhaps the most important national governmental effort to establish a process and improved legal regime to minimize space debris has come from the French Space Operations Act (FSOA) of 2008 and 2010.

The various programs described in Chap. 2 are today essentially national governmental programs with virtually all of the funding coming from governmental space agencies. Even those commercial ventures such as the Electrodynamic Debris Eliminator (EDDE) are essentially dependent on governmental support.

The conclusion that seems most plausible and likely is that most of the initial funding for active orbital debris removal will come from governmental funds. These development programs may be derived from either national defense budgets to respond to the threat of debris impairing missile defenses and missile launch detection systems or to protect military space assets. Or they may come from national space agency programs based on a number of needs. These expenditures could be based on the need to sustain vital governmental space programs such as those conducted by the U.S. Defense Advanced Research Projects Agency (DARPA) (Fig. 4.1). Another important supplemental source of funding, however, could come from national governmental legislative mandates that impose new requirements on non-governmental programs. The requirements of the French Operations Space Act is a case in point.

This Act now requires industry to meet a number of stringent requirements in the post 2020 time frame in order not to create new debris, have the capability to de-orbit all spacecraft, and to invoke sanctions if these conditions are not met. There are even more stringent requirements that could potentially be enacted by national legislation in the future. One such proposal is that future spacecraft that are launched into orbit would have to have a separately command-able de-orbit system with an

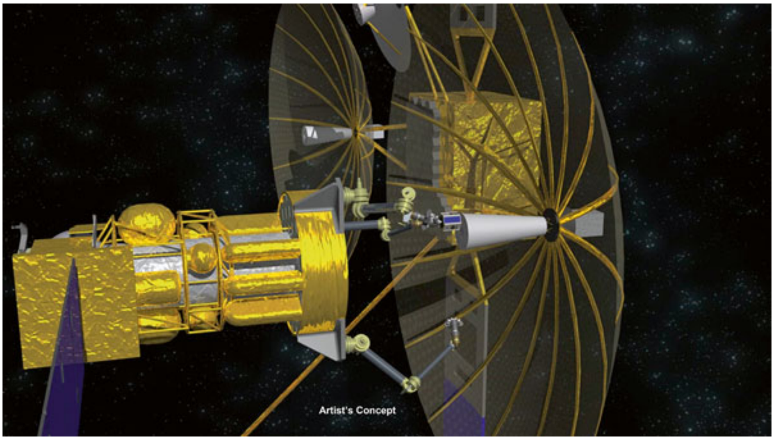

Fig. 4.1 Conceptual illustration of DARPA Phoenix on-orbit servicing vehicle (Graphic Courtesy of DARPA)

independent fuel supply to accomplish de-orbit or to place the spacecraft into a safe parking orbit.

These type "fail safe deorbit" proposals have as yet not been taken up and would likely be resisted by industry. It is important to note that these actions appear likely be undertaken as national legislation that other nations might follow but not require an intergovernmental type agreement or treaty arrangements. The important point to note here is that national legislative action could serve to "switch" the business case from an exclusive-type governmental debris removal program that would be funded by taxes to a program whereby industry would at least fund themselves as a substantial part of the debris prevention and active end-of-life debris removal programs. In short new national legislature could serve to create a new commercial market for orbital debris removal systems.

(c) The Business Case for a Globally Designated International Entity to Engage in Active Orbital Debris Removal

There have been a number of proposals with regard to how the United Nations system or other international arrangements could be made to engage in an active space debris removal program. One of the proposals championed by the Executive Director of the International Association for the Advancement of Space Safety (IAASS) is to create an organization akin to the Intelsat Organization when it was an intergovernmental organization that would be charged with active debris removal. The analysis of this proposition has indicated that before this step was taken there would need to be a preliminary demonstrated debris removal programs to verify relevant technology. The analysis has also indicated that amendment to the current Space Liability Convention might also be required since currently only designated "Launching States" are liable for any accidents involving space objects. The new international entity would be charged with the responsibility to remove debris, but without being relieved of liability if an accident should occur.

Currently there are a number of difficulties with the "business case" associated with this proposed arrangement should this approach be adopted. International organizations are difficult to create and fund and even more difficult to dismantle once formed. There are currently a wide range of space safety related issues that are pending consideration in the global space community. These issues include the regulatory and legal arrangements for the oversight of commercial space tourism travel, hypersonic travel in the so-called "protozone" or "subspace" whereby space planes might fly. In the future there could also be hypersonic space planes that follow suborbital arcs for intercontinental transportation, operation of high altitude platform systems and dark sky stations that would also occupy this "protozone" high altitude region, as well as robotic flights above commercial air space. All of these new "protozone" or "subspace" services will require some sort of safety regulation.

There are also concerns about radiation exposure and stratospheric pollution due to rocket launches and commercial space travel. Currently these discussions involve the possible future roles and responsibilities of the International Civil Aviation Organization (ICAO), the International Telecommunication Union (ITU), the World Health Organization (WHO), the World Meteorological Organization (WMO), and the United Nations Environmental Programme (UNEP). In light of this current set of space safety regulatory issues, it seems unlikely that yet another new international agency to address just the space debris issue could be agreed and put into place.

On top of these very pronounced policy and regulatory concerns, there is the future financial and economic set of issues to consider as well. There would be legitimate questions as to whether such a new space debris organization under the auspices of the UN or another international intergovernmental organization would be more cost efficient, have access to the key technology, research, tracking systems, and financial resources to carry out these operations in a cost-efficient manner. And if it was created and carried out its mission successfully it would be difficult to shut down if it accomplished its task, or if it was found that a totally new technology associated with a space elevator, electro-dynamic propulsion, or electric propulsion rendered a space debris organization obsolete.

The lack of any new major space treaties or significant new international agreements related to space being agreed since the 1970s—almost a half century ago—seems to suggest that such a new international agency for space debris will not be agreed any time soon. Further the business case based on either national governmental programs or commercial initiatives seem to promise more cost effective and agile programs than the creation of a new international entity charged with this responsibility. The liability issue alone might render the business case for an international entity void.

(d) The Business Case for Private Commercial Entities to Remove Orbital Debris under Some Form of International Structural Guidelines, Global Funding Mechanism or Insurance Financed Operation.

The systematic reduction of orbital debris provides potential benefits to various users of outer space. These include commercial providers of space applications services (remove sensing, mobile, fixed, and broadcasting telecommunications satellite services, space navigation, etc.) plus military and governmental satellite networks, and indeed the general public and a host of businesses that depend on space-based activities. The problem is that these various groups benefit from debris removal in widely divergent ways. A further issue is that different orbits (LEO, Polar Constellations, MEO and GEO) are affected to differing degrees and by different classes of users. In light of these complexities a simple formula whereby all users of space would pay into something like an insurance fund that represented a small portion of their space-related investments would not easily work out because of these various differences. The two prime areas of commercial interest, however, are low earth orbit (where the most congestion occurs and especially in high-latitude polar constellation orbits) and in GEO orbits (where upper stage rocket stages are crossing this orbit at high relative velocities). Since the GEO equatorial orbital belt is such a narrowly defined region, just one collision of this kind would have very severe consequences.

A possible solution that might address active space debris removal efforts, at least in these two most critical bands might be the creation of a space debris removal fund that operated much the same way as that used for commercial space insurance protection against launch failures. One type fund would be created for low earth orbit launches (with insurance premiums being perhaps 3.5 % of total mission value) and thus employing a metric similar to that used for launch insurance coverage. The other type fund for GEO launches would be a more modest 1.5–2 % of total mission value. The objective of the first fund would be to remove at least five large debris elements from the LEO orbit each year and the objective of the GEO fund would be to remove one to two under stage rockets or other large debris elements that cross the GEO belt at high angular velocities.

If at all possible such an economic mechanism or fund should be brought into place as soon as possible. This is simply because the problem continues to worsen. These funds could be established over time in an "organic manner" with countries forming such a fund on a national basis—or perhaps for Europe as a region. This type of national, regional—and in time ultimately universal—"space debris insurance fund" could be formed by space actors for the specific purpose of funding the systematic removal of the largest debris elements from LEO and GEO orbits (Pelton, "Possible Institutional…).

The creation of such funds could represent a pro-active "forward looking" approach to financing a solution to the problem rather than seeking a "backwards-looking" approach to addressing space debris formed in the past when no financing mechanism was in place.

The money to capitalize this type of space debris fund would be collected prior to all launches and would be capitalized through these insurance funds. These funds would be collected for a period of perhaps 25 years but would have a sunset provision on the premise that significant mitigation of orbital debris could perhaps be successfully accomplished over this length of time. A trend line that reflected less and less debris over time would be a possible objective rather than complete elimination of debris.

Such a fund (or network of funds) would be formed by means of a specific assessment paid into a designated bank account, or space insurance company, or some other designated entity or entities prior to launch. This fund would apply to all those deploying spacecraft into Earth orbit—or if on a national or regional basis—would apply to all launches from that country or region. Perhaps in time even organizations launching satellites beyond Earth orbit would also pay into the fund but at lesser rate. After each launch there could also be a small rebate assuming it was a certified as a clean "debris-free" launch as independently verified. Such a clean launch would require that the upper stage rocket would be actively de-orbited and no residual debris created (Pelton, "Possible Institutional…, 2015).

When a space craft reaches its end-of -life and is then actively de-orbited or successfully placed in a graveyard orbit there could also be a further rebate. The size of the rebate for a "clean launch" and "successful disposal" would be specified at the time the fund(s) were established. The rebate formulas could be updated over time at suitable intervals. Over half of the payments into the fund, however, would also be retained to compensate those entities involved in removing "officially designated" debris from orbit or moving defunct space objects to a graveyard orbit.

The prime purpose of the national, regional (or hopefully, in time, a universal) space debris fund(s) would be to compensate those entities "licensed under an appropriate regulatory framework" to remove debris from earth orbit. It is possible that a small fractional part of the fund could also help fund activities related to operating systems to avoid collisions, but this would not be a part of the original mandate for the insurance funds for debris removal (Pelton, "Orbital Debris…," 2012).

This licensing process for entities designated to undertake orbit debris removal or collision avoidance activities might, for example, be formally assigned to the United Nations Office of Outer Space Affairs or in time spelled out in a new international space convention after the concept had proven in practice. Clearly there would be many details to be worked out, such as perhaps initial national funding, that would kick-start the capital financing for the debris removal process. The biggest issues to be resolved would be to determine how the process of licensing entities would actually work. This would likely require for the issuance of a United Nations' designated "license" to designed entities with proven capabilities to accomplish active deorbit mission. This process might also simply be performed by national governmental space transportation agencies. The key would be to create a process where governmental enities or private commercial concerns would somehow receive an authorization to undertake the specific removal process for individually designated debris elements. There would also need to be some form of new interpretation of the "space liability convention" to allow the debris removal operation that was fully sanctioned by the designated "Launching State". This might require the creation of an international liability fund to be established to cover any liability claims that might result over the time of the 25 years or so in which the space debris removal funds were active.

Further there is the specific issue of small satellite-related debris. There is a threshold issue of whether there should be a minimum payment related for small or nano-satellites. It is hoped that in time there would be a new international agreement (or at least code of conduct) reached concerning small satellites, their registration processes, passive or active de-orbit capabilities, minimum altitudes to meet the 25 years de-orbit rule, their relationship to the overall orbital debris problem, and so on.

One might make specific arrangements for such small satellite launches by offering 3 options. Option one would be for a passive deorbit capability at end of life for launches at or below a specific altitude that would meet the 25 year rule. Option two would be an active de-orbit capability at end of life that would also meet the 25 year rule regardless of altitude. Option three would be for the small satellite to fly as a multi-mission vehicle with deorbit capabilities or on board a space station with subsequent controlled return or de-orbit. These arrangements might mitigate the need to pay into the orbital debris removal fund for LEO launches (Jakhu and Pelton 2014).

Payment into this fund would for the most part "seem and feel" to satellite operators and governmental space agencies conducting space operations very much like buying launch insurance for a spacecraft mission. Indeed the fund could possibly be administered by launch insurance companies. These payments would be different in that it would only represent perhaps about a third or less of the "net cost" associated with purchasing launch insurance, after rebates for clean launches and ultimate de-orbit. Rebates might eventually return perhaps 30–40 % of the money originally paid into the fund. Further, the projected end date for the fund would establish a very real goal for accomplishing "a largely space debris-free world" over a 25 year period (Pelton, "Possible Institutional.").

The creation of this fund and the rebate payments would reverse the current incentives that, if anything, actually "encourage" the increase of orbital debris. Under current space law the "Launching State" not only lacks an incentive to remove their space debris from orbit they actually face substantial financial penalties if the removal process somehow adversely affects another space object and create liabilities for which they are compelled to pay. The owners and operators currently have incentives to use station-keeping fuel to extend satellite lifetime, rather than to deorbit a spacecraft. In short, almost all of the incentives work the wrong way to reduce space debris (Listner 2011).

The payments into the fund are considered to be modest in comparison to the costs of postponing the removal process, since the cost of removal will only spiral upward. If the Kessler syndrome stage is ultimately reached and debris continues to cascade out of control the cost of active debris removal might truly soar into levels that might involve trillions of dollars (U.S.) ("Space Junk Problem").

If one considers this wide range of payments for launch insurance, the threat that orbital debris represents to all future space activities, and the cost of debris removal, it can be reasonably argued that a modest payment into an orbital debris fund would be modest and certainly not excessive. This seems even more reasonable when consideration is given to the process of rebates after a clean launch and a further rebate when spacecraft are deorbited. Such a fund would create all the incentives to clean up the space debris problem, eliminate the formation of new debris, and help to transfer the problem from establishing liabilities for space debris accidents to solving the space debris problem. The reasoning provided in favor of this option in this section provides the rationale for what seems to be the optimum business case for addressing the orbital debris problem at least for LEO and GEO orbits. This approach creates incentives for developing the most cost-effective debris removal processes, provides financial rewards for not contributing to new space debris, and allows nations or regions the latitude to organically develop funds that would grow in size and, in time, become a universal fund that perhaps could "break the back" of this problem over a 25 year period. Finally it would give incentives for national governments, commercial aerospace and space insurance entities and the United Nations to work together to address this problem without the explicit need to create a new intergovernmental space treaty or convention.

(e) Business Case Based on Breakthrough Technologies

The problem with attempts to create commercial, economic or regulatory solutions to problems involving outer space, or for that matter any area involving the rapid development of technology, is the mistaken assumption that the *status quo* will continue. The allocation of frequencies by the International Telecommunication Union, and even the naming of spectral bands, has never adequately anticipated the advance of new technologies. Today's Extremely High Frequency (EHF) bands range from 30,000,000,000 Hz to 300,000,000,000 Hz versus what was once thought to be the top of the frequency allocations heap and given the today's inapt name, the Ultra High Frequency (UHF) band. The UHF band at 300,000,000 Hz to 3,000,000,000 Hz covers a range of frequencies that are 100 times lower than the EHF band or 10 times lower than the so-called Super High Frequencies. In most English lexicons, the progression would most likely be "extremely", "super" and "ultra", rather than the reverse. Time and time again regulations such as speed limits, standards for pollution or safety, and so on, have been outstripped by new technology and conditions created by not anticipating the consequences of an innovation.

It is certainly hoped that technology related to space safety, orbital debris removal, planetary defense against asteroids and extreme solar weather, and so on, will make major gains in coming decades. Thus any attempt to define the solution in terms of a particular technology, or even the use of rocket technology, will likely be self-defeating. In future years the use of "electro-dynamic propulsion" or perhaps even the development of a space elevator or tether technology may provide a much more efficient and cost-effective way to address the problem of space debris and deployment of vital space infrastructure (Fig. 4.2).

In light of the dominant role that technology will likely play in space systems, the key to the orbital debris issue seems to be to allow for the maximum amount of technological flexibility and to create both positive financial incentives to minimize the formation of new debris and economic consequences for a lack of action to address this problem. In some cases there can well be serendipity that will aid the cause. The develop of new systems to provide on-orbit servicing (i.e. replacement

Fig. 4.2 Artist conception of a space elevator (Graphic Courtesy of NASA)

of batteries, refueling of propulsion tanks, and even installing new antenna systems) could also lead to improved systems for orbital debris removal. This might be particularly so in terms of having a single space mission be able to accomplish the de-orbit of many different space debris elements rather than just one. Flexible, as opposed to static institutional and financial arrangements, would seemingly be crucial to finding the most lasting and enduring solutions to space debris and perhaps space and stratospheric pollution issues as well.

Conclusions

This chapter has sought to address various approaches that might be taken to address the mounting problem of orbital space debris creating—particularly in low earth orbit as well as in the GEO orbital arc. A number of different institutional, economic, financial and regulatory approaches have been considered in terms of the overall feasibility. This type of business case analysis suggests that there could be a number of possible solutions. Some of these solutions that might involve national and regional governmental agencies, private commercial organizations and international institutions (and particularly the UN, its specialized agencies, and the Committee on the Peaceful Uses of Outer Space and the Office of Outer Space Affairs in Vienna) are not necessarily mutually exclusive. New national and regional space legislation and initiatives such as the creation of an insurance fund for active orbital debris removal might prove to be a possible way forward. But even these national initiatives, to be successful, will need international institutional support to transform from partial solutions, to a model of behavior and action that is more universally followed and thus become a coherent solution that is supported on a worldwide basis. The activities of the Inter-Agency Space Debris Coordination Committee (IADC) has provided some of the most important world leadership to address this important issue to date and perhaps the future discussions and agreements within the IADC can consider some of the options set forth in this chapter.

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Chapter 5
New Technological Approaches to Orbital Debris Remediation

Introduction

Efforts to develop active space debris removal projects currently underway were described earlier in Chapter 2. Virtually all of these projects relied on the current state of space technologies. Many of these currently envisioned projects involve sending up a robotic spacecraft that can attach itself to a selected element of orbital debris such as a defunct spacecraft or upper stage rocket launcher and then deorbiting the debris along with the capturing spacecraft. Today, in some instances both the target and the capturing robotic spacecraft are launched as part of the effort to develop an active deorbiting capability and to avoid concerns related to liability claims. There are clear and apparent problems with this approach in that it is extremely expensive, slow and deliberate, and inefficient by almost any index of effectiveness. This chapter explores a number of technical approaches that have been identified as potentially viable that would ultimately be far more effective, achieve de-orbiting more rapidly and effectively, and thus logically cost far less than the one-by-one active de-orbit missions.

These technological approaches can be divided into a number of different categories as follows: (a) Ground based approaches to active debris removal or collision avoidance; (b) Passive de-orbit systems that can be deployed at end of life; (c) New types of active de-orbiting systems that could be mandated to be included that are separate from the regular positioning and orientation capabilities of spacecraft; (d) Innovative active de-orbiting systems that can assist with the removal of many debris elements in a single mission. These might also use different propulsion systems than conventional chemical rocket thrusters; (e) Improved technical means for locating orbital debris for removal by efficient proximity navigation and mating.

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Key Trade-Off Considerations: Innovative Technology vs. Maturity, Reliability and Precision of De-Orbiting System Design

The conventional approach of one-by-one robotic capture of defunct satellites is one that has been demonstrated on a number of occasions and involves minimal risk of de-orbiting the wrong spacecraft. Ground-based systems might be more cost effective, but there are issues of high power particle beam or laser systems being considered space weapons systems and there are also concerns about the accuracy of their targeting systems and potential error. Many of the newer technological approaches discussed in this chapter are likely to be more cost effective, but these are new and largely unproven capabilities. It could take a number of years for these new methods to reach technological maturity. Such new systems need to be proven to be reliable and indeed able to accurately remove debris from orbit. The most secure way to achieve future debris removal might be to mandate active (or passive) removal systems that are separate and complementary to conventional positioning and orienting thruster systems for station-keeping. Such an approach would entail mandating separate and fail safe de-orbiting capabilities. One particularly challenging issue that will perhaps require the greatest amount of new technical capability is the problem of upper stage rocket launchers that transverse the geosynchronous orbital plane and threaten active or defunct satellites at accelerated relative velocity and dangerous relative angles of incidence.

Review of Alternative Technological Approaches

Ground-Based Systems

Ground-based systems can provide important capabilities in addressing orbital debris issues. The first type of capability involves irradiating a debris object that is threatening a collision with another orbiting element in such a way as to slightly change the debris object to avoid impact. This could be a laser-based tracking system or a particle beam projection system that is continuously focused on debris object prior to an impending collision. At orbital speeds even a change of an orbital period by a tiny fraction of second can be sufficient to avoid a collision. There have been innovative suggestions that the officially registered owner of the debris element could have their own operators control the beam projections to alleviate concerns that these systems would be deployed militarily against their own space assets. Such types of ground systems would not constitute active debris removal but simply debris collision avoidance. These temporary measures to avoid major collisions are important steps to undertake until more permanent solutions can be found and undertaken.

Much high powered particle beam weapons or even very high powered laser systems, however, could, in fact, provide active debris removal. It has been proposed that a beamed or directed energy system could be positioned on the International Space Station and from this location it could systematically remove debris from low earth orbit through the use of such a strategically advantageous location. [Lubin and Hughes 2014]

Directed energy systems might well be developed for a range of other capabilities. The logic of developing a super intense beamed energy system could well be used to change the orbit of a potentially hazardous asteroid so it could be captured by the gravity of the sun or perhaps over time entirely break up and disintegrate into harmless pieces of a potentially hazardous asteroid. Such a beamed energy system or super intense laser beam system might also be used for strategic purposes or even to power a spaceship drive system. [Lubin and Hughes 2014]

These ground based systems are clearly most effective to deploy in the case of low earth orbit spacecraft and especially for debris which are orbiting only a few hundred kilometers from the Earth's surface. The ability of ground based systems to address the removal of debris from medium earth orbit, from geosynchronous orbit or defunct upper stage launch vehicles in 12 h transfer orbit is technically challenging and probably not financially viable nor practical under the current terms of the Outer Space Treaty and the Liability Convention. Finally, the use of ground-based systems to create orbital changes for such debris elements, rather than saving the situation, could increase the risk of a collision and not be able to effectuate removal. Currently these ground-based approaches have not been practically demonstrated to be reliable and effective.

Passive De-Orbit Systems

The deployment of passive de-orbit systems at end of life represents the most economical means to ensure the longer-term deorbit of low earth orbit satellites. A number of different concepts have been conceived and tested that at the end of life for a small satellite that could be deployed to create a significant amount of atmospheric drag and thus hasten de-orbit. These concepts include inflatable balloons, inflatable tube membranes (ITMs), suspendable tethers, or solar sails. Essentially these are all rather simple and easily deployable drag systems that are designed to increase the rate at which the de-orbiting process occurs. Such systems are really appropriate and effective for small satellites at relatively low orbits, i.e. under 800 km or so. Such mechanisms can accelerate the rate of de-orbit and allow small LEO satellites to meet the current standard of de-orbit within 25 years. [Rasse]

Satellites that larger in size with deployable solar sails of a larger cross section could use their arrays to assist de-orbit at the end of life. Solar sails have been used to accelerate the de-orbit of the NASA Fastrac satellite. This approach has also been utilized in the CANX-Drag Sail which is a project of the Canadian Government. [Grant Bonin et al.]. This approach of deploying a reasonably large, but very low mass solar sail was also utilized in the case of the European Union Protec 1-2015 program ["Passive Means."]. A large number of university programs in the United States, Europe and other parts of the world have also developed similar capabilities.

These are typically designed for low earth orbit and quite small satellites. When these passive systems are deployed the cross section that creates atmospheric drag can be significantly increased and thus accelerate the de-orbit time and thus make de-orbit two to three times more rapid. There are today some new chemical and electronic thrusters of sufficiently small size and mass that they could be used to assist in the de-orbit of some small satellites or to work in tandem with passive de-orbit systems. The smallest cube satellites, nano-satellites, or so-called femto-satellites will for the most part decay simply due to gravitational effects, especially if they are deployed at 400 km altitude or below.

There are sufficient numbers of these very small satellites now being deployed—and in some cases without formal registration and at altitudes above 400 km. In these instances their deployment can be considered a problem. Solutions to this problem might include flying experiments on the International Space Station and thus not becoming free-flyers. Another option would be to designing "consolidator" satellites that could be the host for a number of small experiments and then deorbit in a controlled burn. In the case of the "host" or "consolidator" satellite they might not only provide thrusters for de-orbit but could also provide a common power supply and perhaps other services common to the small experimental packages that fly in common. National action that provides very clear registration procedures and perhaps imposes fines for not registering small satellites might also be considered. Ultimately there will need to be a review of the 25 year de-orbit rule to see if that is adequate to depopulate low earth orbit at a sufficiently rapid rate. Certainly international agreement to require a 20 year rule for removal of spacecraft from the protected LEO and GEO orbits would be a step forward in seeking to reduce debris in orbit.

It needs to be particularly noted that these passive systems work well for low earth orbit satellites, particularly when Solar Max activities serves to balloon the Earth's atmosphere to higher altitudes but that these systems are not as effective in higher LEO orbits and do not work in any way for medium earth orbit or geosynchronous orbit since they are well above the Earth's atmosphere.

The Prospect of Mandating New Types of Fail Safe End-of-Life De-Orbiting Systems

Another new concept that has been suggested to address the orbital debris removal issue is not so much a new technology, but a new approach to end-of-life processes. This is the proposal that there should be a de-orbit thrusters system that is separate from a spacecraft's regular orientation and station-keeping systems that could also be separately commanded. This capability would, in effect, provide a fail-safe de-orbit system. This idea is not likely to be greeted with enthusiasm by spacecraft owners and operators in that it could involve a separate telemetry and command system, an additional fuel tank, and additional fuel. Conceivably this de-orbit capability could be an ion thrusters system that would make the system lighter in mass.

Nevertheless this sort of fail-safe deorbit system might add 5 % or more to the mass budget for a spacecraft. This would initially be for low earth orbit satellites, but the additional capabilities related to MEO and GEO satellites and there redeployment to graveyard parking orbits might presumably come into play at a future date.

To accomplish this “guaranteed de-orbit” D-Orbit of Italy has developed and is now promoting the future use of a new product which they have designated as a Decommissioning Device (DD). This is a unit which as now designed includes a solid propellant motor and a control/command unit. The advantages of this product would be that it is completely autonomous even if the satellite is defunct, and that it is fully compliant with ESA and NASA safety standards. D-Orbit claims that there would no single point of failure except for the solid fuel motor and that it would be guaranteed to be reliable for more than the lifetime of the satellite and that it would be scalable to adapt to different types of missions. This guaranteed de-orbit system could be designed with a timer set for a period of time well passed the planned operational life to provide additional margin against failure. It could also use a chemical thruster or even an ion thruster either to make this system “cleaner” or to reduce the mass of the fail-safe system. [Antonetti et al.]

As interesting as this proposal is from the perspective of likely limiting the buildup of space debris there are a number of factors to consider. These factors include: (1) this would be a partial solution and as now designed would only be for the de-orbit of low earth orbit satellites. There could, of course, be similar systems designed to raise the orbit of geosynchronous satellites; (2) this type of program would not assist with upper stage rocket motors and other debris elements unless this program was expanded in scope; (3) it would be too large of a system to assist with nanosatellites; (4) it would be a very “expensive” program for commercial satellite operators in terms of a major lost operational capacity and the associated opportunity costs—even if this were just an orbit raising system to deploy to graveyard orbit and used a separate ion thruster; and (5) solid fuel rocket motors although they are quite reliable, are also environmentally more polluting than liquid fuelled rockets. Further the potential future use of electric ion systems, although slower and with less thrust, could be more efficient in terms of reduced overall mass penalties that would be added to the mission and certainly would be less polluting. In short the design of fail-safe systems to raise geosynchronous satellites to super GEO might well find ion-thrusters optimum in terms of imposing the minimum mass penalty.

New Technical Concepts for Active Removal Systems for Orbital Debris

Robotic Capture and De-Orbit

The range of technical approaches that might be used to remove orbital debris are quite diverse and the innovative concepts continue to grow and diversify. The main-line approach which a number of aerospace companies and space agencies are now proceeding involves a basic strategy of sending up a robotic satellite to attach to a debris element and then de-orbiting the composite system. The various projects that are being developed with this type of capability were reviewed in Chapter 2. These developments are on one hand conceived as a way to remove major debris elements from low earth orbit and on the other hand they are seen as a possible mechanism for capturing operational satellites and servicing them by providing new batteries and fuel. The most exotic concept in this regard is the idea that grappling robotic spacecraft with the ability to capture defunct satellites might "harvest" antennas or other re-usable components in space and redeploy them on a new space system. This "harvesting" spacecraft concept is unique in that it is primarily designed to operate at GEO altitudes and thus be able to rendezvous with application satellites in geosynchronous orbit.

The one at a time approach to active debris removal, which is currently the prime approach under development, has the major disadvantage of being extremely expensive, time consuming, and ultimately inefficient. The only exception at this time is the Electro-Dynamic Debris Eliminator which has been provided funding by NASA for prototype development by Space Technology and Research (STAR) Inc. Thus this innovative approach is addressed in both Chapters 2 (existing programs) and Chapter 5 (Future technology).

Spacecraft with Multiple De-Orbit Kits

This proposed approach that provides a variation on the above theme with the intent of being much more efficient and less costly involves a capture spacecraft that was capable of attaching to a number of defunct satellites one after another and attaching to each one a "de-orbit kit". The idea behind the "de-orbit kit" is that there is a concentration of debris in the range of 600 to 2,000 km altitudes that could be addressed by a robotic spacecraft that could attach de-orbit units. One such concept is to equip a robotic spacecraft with a number of "remotely operated semi-self-attaching de-orbiter modules". These units would be deployed via a robotic arm which is fixed to the delivery satellite chassis. Detection of the targeted debris elements would be carried out using a photon camera/sensor attached to kit-deploying satellite and a sanctioned data base provided by the Inter-Agency Space Debris Coordination Committee (IADC), the UN Office of Outer Space Affairs or other appropriate sources such as information provided by the launching country of record.

As proposed by the research team at the Indian Institute of Technology. It would be possible to use different modules for the chaser spacecraft and detachable "de-orbit kits." It is also anticipated that "modules may include the communication system used for communicate between ground based station, satellite system and de-orbit kit." These modules would also need to include some sort of electrical power system (that would most likely be solar cell panel arrays and lithium-ion batteries), an orbital intercept and thrust control system, plus an altitude determination and control system. There would also likely be either a robotic arm or tether linkage system plus a number of “de-orbit kits”. It is anticipated that this “kit” would include a GPS system, computer control and communication modules plus a propulsion module, or tether, encompassing net or a deployable passive de-orbit system such as an inflatable balloon or solar sail or inflating foam to create atmospheric drag. [Kaushal et al.].

Tether-Deployed Nets

One of the most common concepts consistently put forward for de-orbiting of debris envisions that a net would be draped over the derelict satellite or upper stage rocket so as to create substantially more atmospheric drag. This is the technique anticipated by the EDDE system described below. This approach has most exotically been described as the RUSTLER system for “Round Up of Space Trash—Low Earth orbit Remediation”. Despite the frequency with which there have been references to tether-deployed nets as a de-orbit mechanism this approach has only be simulated on computer models and not actually demonstrated in actual practice. [Hoyt, R.]

Glues, Adhesives, Foams and Mists

A less complicated version of the deployed nets would be to deploy a satellite that would be capable of shooting at close range adhesives, epoxies, foams or mists on to the surface of the debris object. Some have envisioned what might be called very sticky balls or expanding balloon like foams. These balls might be constituted from epoxies, resins or foaming aerogels. Once these adhesives are attached to space debris objects they would expand in volume and in time alter the debris orbits so that they would eventually degrade and presumably burn up in the Earth’s atmosphere**.** [Kushner] A variation on this theme would be spaying of mists on the debris spacecraft or defunct rocket stage so that the mists would freeze and create orbital drag. Again although these various ways of shooting or spaying materials onto debris elements have been simulated and modelled they have not actually been tested in space. The concept in all cases is that a remotely controlled dispenser satellite would be designed so that it could be positioned close to derelict space objects. The dispenser satellite then would then shoot glue balls or spray gas mists or expanding foams so as to create new atmospheric drag on the debris element. This would serve to help de-orbit smaller orbital debris. This type of system would, however, be for just low earth orbital debris and smaller debris elements and not for higher orbits and larger space debris. [Kushner]

Terminal Tape or Tether

In addition to tether systems or nets to create drag there have also be proposals to attach to debris what is call a "Terminator Tape". This tape would have an adhesive to cling to the satellite and then it would be deployed just like a gravity gradient antenna to create the maximum gravitational pull. The longer the tape, the greater the gravitational attraction. It would also create some atmospheric drag as well. Again this would be an approach suitable only to low earth orbit satellites [R. Hoyt]

Space Harpoon System

The concept of a space harpoon system as opposed to a robotic grasping system would appear to have several advantages. The proximity of the "chaser" satellite would not need to be nearly as great and thus minimizing the risk of on-orbit collision. Also the "connection" to derelict space objects, whether an upper stage launcher, space craft or other type debris, can be in any shape or size. Finally a harpoon system connection can be connected to a free-flying propulsion system that allows a repetitive process to initiate the de-orbit of multiple satellites rather than a single debris element. There are, of course, alternative de-orbit systems that could be attached to the harpoon tethers such as a passive net system that could create atmospheric drag as opposed to an active propulsion system that could be a chemical rocket system or ion thrusters. Prototype systems have been conceived with a four harpoon deployment mechanisms, but in theory the number of harpoons could be much larger.

Use of an Ion Beam to De-Orbit Debris

Ion beam projection systems represent yet another means to steer debris into a de-orbiting mode. Such an ion beam could be focused on a debris object over a period of time so that it would steer the targeted space debris to a controlled de-orbit. This technique is being studied by the European Space Agency, NASA, and the Japanese Space Agency (JAXA). Some of these studies are focused on high-powered lasers, others on ion beams, and other higher powered particle beams that might be developed as part of a planetary defense system against potentially hazardous asteroids. [Claudio Bombardelli et al.]

There are concerns about the use of such mechanisms in space since they could be seen as anti-satellite weapons and as such may be considered to be contrary to Article 4 of the Outer Space Treaty. One solution to this issue, that has been recently proposed, is that the country that is recorded as the "Launching State" would be given control of the laser or particle beam ionic stream for the de-orbit operation.

Systems Using Electro-Dynamic Systems and the Earth's Magnetic Field as the Propellant

Large-Scale Orbital Debris Cylinder Using Electro-Dynamic Propulsion

Many technical analysts who have considered improved and more cost effective means to remove debris from low earth orbit have come up with the idea of using the Earth's magnetic field as a means to generate electricity so as to drive systems that would conduct the debris removal function. These analysts suggest that using chemical rockets with robotic devices to clamp on large debris elements and bring them down one by one is simply too slow, too inefficient and too costly. A number of these critics of using conventional chemical rocket systems propose that systems that use tethers to generate electricity or perhaps even a large metallic chamber or ring that also trails metallic tethers would be a much more efficient and cost effective approach. Bharat Chaudhary has proposed the idea of deploying in low earth orbit a large Metallic cylindrical orbiter. This concept suggests that debris could simply fly through the cylinder with the result that LEO debris would have its velocity slowed sufficiently that the debris would thereafter tend to de-orbit. This design concept suggests that a stronger electrical field could be generated by attaching both solar cells and tethers to the flying disposal cylinder. It is suggested that resulting reduction in speed would be sufficient so that the debris objects would rather quickly descend towards Earth. Debris slowed in this manner would in reasonably short periods of time burn up on coming in contact with the atmosphere, except in the case of the very largest debris elements**.** Although this is a clever concept, there are many practical questions to be addressed. These include what would be the optimal size of the cylinder? How would one be able to guarantee that there would not be collisions between the cylinder and debris elements and what would be the specific avoidance mechanism? And would the design actually be a cylinder, a circular wire grid or some other more suitable geometry? [B. Chaudhary]

Electro Dynamic Propulsion Systems for Space Debris Removal

There are other concepts that suggest the electrical-generating capability of the Earth to power an orbital debris removal mechanism. The alternative ideas is to create a more targeted system that would provide a "passive vacuuming" of space as discussed above. There are suggestions that one could utilize the Earth's magnetic field to generate electric propulsion to create a new electro-magnetic "space tool" that could search out and remove debris.

At least two quite different variations on this approach would be possible. The least ambitious means would be to have a conventional satellite with chemical propellant that would maneuver in low earth orbit to simply attach tethers to multiple satellites to help de-orbit derelict space objects. This may or may not include an electric ion thrust motor along with the tether to accelerate the de-orbit process. This approach by relying on conventional chemical rockets could likely be designed more quickly and this effort mounted in the not too distant future. [Pearson, Jerome et al.] and also see [Hoyt, R.]

A much more ambitious technological approach would attempt to create a large scale electro-magnetically driven device that would undertake this type of operation for potentially hundreds of orbital debris pieces. This system, as noted in Chapter 2, has been given the name of an Electro Dynamic Debris Eliminator (EDDE). The scale of these systems would be quite large (i.e. kilometers in length), but the mass would be small. This is because it will use tethers to generate electricity so there is no need for chemical propellants. This device would be quite long, although the modules that could be commanded would be compact and few in number and most of the EDDE would be the tethers that connect solar arrays together (Figs. 5.1 and 5.2).

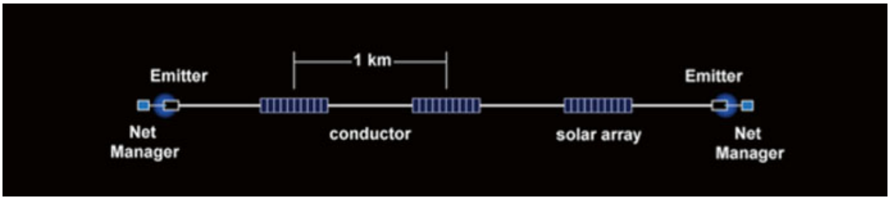

Fig. 5.1 The Schematic design of the overall EDDE system (Graphic courtesy of STAR Inc.)

Fig. 5.2 The EDDE Net manager at end of tether system (Graphic courtesy of STAR Inc.)

The main aspects of the EDDE would be the following: (1) It would be quite low in mass even though it would be about 4 km or so in overall length, and thus relatively easy to launch into low earth orbit in a stowed configuration; (2) In theory it could be maneuverable to virtually all inclinations, including polar orbits, in low earth orbit; (3) The combination of power from solar cells and from the tether flying through the earth's magnetosphere would generate enough electrical power to move the EDDE from location to location without the need for chemical propellants. (4) The deployment of low mass nets onto debris elements would create sufficient atmospheric drag to remove the orbital debris over time with a "net manager" being positioned at each end of the EDDE device; (5) One EDDE spacecraft would be designed with the objective of being able to remove over 100 space debris elements from low earth orbit in about 3 years' time. The developers of this project have ambitiously estimated that 12 EDDE spacecraft over a 7 year period could remove nearly 2,500 space debris objects and leave only smaller debris elements in low earth orbit. (i.e. all debris weighing under just a few kilograms)

This approach sounds very attractive in terms of its not requiring chemical propellants to operate, its ability to remove a very significant debris elements, and its purported ability to remove debris in an environmentally clean way with maximum economic efficiency. Yet major questions still remain. The most important questions are whether this type of technical concept can actually be proved to work as proposed and whether legal, regulatory and liability issues and concerns surmounted. In February 2012 NASA awarded Star Technology and Research (STAR-Tech Inc.) a $1.9 million contract to develop this technology. The legal concerns will be explicitly addressed in a later chapter.

Key Technical Challenges Related to Active Debris Removal

There are several key technical challenges related to active debris removal. These challenges need to be addressed in parallel since these are in many cases complementary capabilities and involve different technologies and system capabilities. One need is the ability to locate and rendezvous or achieve close proximity with debris elements that are derelict in orbit. This means close conjunction without a destructive collision. A second need is to create a de-orbit mechanism that quickly or over time effectuates the de-orbit process for low earth orbit. A third need, which has received the least attention to date is to develop ways to link to debris in higher orbits (i.e. MEO or GEO or highly elliptical transfer orbits) so as to reposition them into a safe parking orbit. The DARPA Raven and Phoenix mission is currently the most relevant project of this type. The development of a capability to provide in-orbit servicing of GEO satellites is closely parallel to the needed capability to rendezvous with a derelict object in GEO orbit and then remove this space debris to a safe parking orbit or in the case of a GEO transfer orbit achieve safe deorbit. A fourth need, that is not so widely agreed, is the extent to which large debris elements need to be brought down in a controlled manner to avoid collision with aircraft or avert potential damage or loss of life on the ground. This is clearly very desirable but difficult to do. Most spacecraft or launch vehicles burn up, but the largest objects can make it through re-entry.

Strategies for Location and Rendezvous of Debris Elements

Although most of the debris elements that constitutes the greatest problem are not a huge distance away from the earth's surface, i.e. typically between 200 km and 1,000 km, the debris is travelling at very high velocities and locating the precise derelict space object and manoeuvring to close proximity without crashing into it at a high relative speed is one of the greatest technical challenges. Some of the steps to help in this regard are simple and straightforward while others require great technical sophistication. In terms of identification there have been suggestions that all space objects should have reflectors applied to them to assist with their location. These identification systems could also have something like a bar code identifier or an RFID. As of yet no internationally agreed procedures for clear identification and ease of rendezvous have yet to be accepted in practice [NASA Office of Space Servicing Office]

There has been a great deal of experience acquired in using optical sensors and docking systems in space. Japan has carried out early experiments in deep space and NASA and participants in the International Space Station have acquired a good deal of experience with docking and capturing spacecraft with the Canada arm. In the past decade the following efforts to accomplish in-orbit activities in space, commonly known as rendezvous and proximity operations (RPO), have been carried out with the results noted below:

The U.S. Air Force XSS-11 mission in 2005 accomplished a close proximity inspection of several satellites with success but did not attempt a docking.

- The NASA DART spacecraft in 2005 attempted an autonomous rendezvous with defunct spacecraft known as MUBLCOM satellite with only partially successful results since there was a slight collision.
- The U.S. Defense Advanced Research Project Agency spacecraft named the Orbital Express demonstrated in 2007 the ability to carry out on-orbit refuelling and servicing of another spacecraft.
- The Swedish Space Corporation PRISMA successfully demonstrated the ability of two microsatellites to fly in close proximity formation.
- The Chinese SJ-12 in 2010 maneuverer close to the SJ-06F spacecraft for reasons thought to be close proximity inspection [Weeden et al.]
- The Raven project in 2016 will aid with the ability to undertake rendezvous and proximity operations.

In addition there are operational low earth orbit satellite constellations such as the Iridium satellite system that is flown as a global network with operators constantly in control of the network. In the early days of operation in the late 1970 when the system was first deployed several “cockpit” errors occurred in terms of network configuration mishaps, but in recent years successful formation has been maintained and no such problems have occurred.

Currently there is a great deal of research work being concentrated on in-orbit servicing by NASA and other space agencies. It is clear that if a servicing spacecraft can be moved into position for on-orbit servicing that the same technology could be used to address active debris removal.

Various Types of De-Orbiting Technology and Systems

The previous parts of this chapter have outlined a wide range of new de-orbiting mechanisms that might be used to assist with the removal of debris from orbit. These techniques can be divided into the following categories: (1) passive elements such as balloons, sails, inflatable vanes, etc. that can be installed on a satellite or spacecraft before launch into low earth orbit and that can be deployed at end of life by command or even a pre-set timer; (2) passive de-orbit systems that can be attached to a spacecraft, upper stage launch vehicle or other debris element on-orbit to hasten its deorbit due to atmospheric draft and perhaps additional gravitational pull (i.e. terminal tape). (These include tethers, nets, glueballs, expanding foams, mists, epoxy materials, etc.) Most of these systems involve the use of chemically-fuelled rockets but some systems have been proposed that could use solar cell and electro-dynamic energy derived from the geo-magnetosphere to provide propulsive power. (3) Active removal propulsion systems that attach to derelict objects and pull them into a new orbit that hastens descent or lifts a geosynchronous spacecraft into a safe super GEO “parking orbit”. These can be a captured satellite that brings the debris element down or it can be a more complex spacecraft that attaches a propulsion kit that can actively bring orbital debris down but perhaps less rapidly. Although the tracking and rendezvous requirements are more complicated, these kits could also theoretically be used to elevate a defunct GEO spacecraft to a safe location above the geosynchronous orbit as noted below. (4) Thus the fourth approach, which applies primarily to spacecraft in higher orbits, is the activation of spacecraft propulsion systems and station-keeping thrusters that place a defunct satellite into a “graveyard orbit” where “dead satellites” can remain for millions of years without doing damage to active satellites. MEO orbits are the most difficult to remove since it takes far more power to either bring them down into a de-orbit path or to raise them sufficiently to go super synchronous.

A variation on this theme would be de-orbit units that have separate command and control systems that would be responsible for end-of-life orbital repositioning or de-orbit. Research into all of these capabilities is needed. In the active debris removal arena, the first initiatives may simply be capture and de-orbit systems that work on one piece of debris at a time, but ultimately methods will be developed to bring multiple debris elements down with a single mission. Great emphasis is place on attacking debris in low earth orbit but improved procedures for MEO and GEO debris must be addressed as well.

Finally there is one other concern to consider. This is the problem of upper stage launchers that are designed to boost a geosynchronous satellite into a highly elliptical (or cigar shaped) transfer orbit that does not quickly degrade from its perigee encounter with the Earth's atmosphere. These large scale space objects can cross the Clarke orbit path at relative speeds of many thousands of kilometres and unlike spacecraft in GEO orbit that are traveling with the rotation of the Earth at relatively similar speeds, these upper stage rockets are ascending or descending at dangerous velocities. This particular issue has not been considered in any depth because most vehicles that perform this task do degrade in a matter of weeks because the atmosphere drag at perigee is quite considerable. Unfortunately just one such collision with a large application satellite would generate a large amount of new debris that would be quite dangerous to all satellites in the relatively narrow Clarke orbit. This problem therefore needs careful study.

A variation on this theme would be an active act of terrorism. In this case one might launch a relatively small rocket around the moon with a payload that was simply a container of nails and nuts and bolts. This rocket launch could be orbited around the Moon into achieve a retrograde orbit travelling in the exact opposite direction and speed of geosynchronous satellites and set off an incredibly dangerous chain reaction of debris that could put the entire belts of over 300 operational geosynchronous satellites at risk.

Controlled De-Orbiting Systems that Can Avoid Collisions

The bulk of small satellites that degrade in altitude and eventual de-orbit simply burn up in the atmosphere on re-entry and constitute no harm. There are two concerns about orbital debris that should be addressed in looking to the future. One concern is that new commercial applications are now being developed for the so-called protozone, which is the area above commercial air space (nominally 21 km) and the area below outer space (nominally above 100 km). These applications include high altitude platform systems (HAPS), drone or auto-piloted aircraft freighters, hypersonic transport, space tourism, and dark sky stations. These various vehicles, operating within the protozone could in time be at risk from debris before it is entirely consumed. In addition larger debris elements sub-orbital craft could collide with aircraft or even people or facilities on the ground. There have been serious proposals for independently controlled and fail safe de-orbit systems that could ensure deorbit operations that could be, in essence, auto-piloted down to guarantee that debris could come down in a fully safe manner so as to avoid dangerous collisions. New national space safety provisions such as the provisions of the French Space Operations Act that will come into full effect as of 2020 could well hasten actions to create specific controlled de-orbit capabilities. (Gaudel et al.)

Conclusions

The technology to accomplish effective and cost-efficient removal of orbital debris has still to be accomplished with any degree of competency. There are today a number of quite different approaches to solving this problem. Some are closely linked in positive ways, while others are clearly in competition with alternative systems and technologies. Here are the main strategies currently underway:

(a) Methods and guidelines to prevent the creation of new debris such as the voluntary guidelines developed by IADC and the UN COPUOS.
(b) Improved tracking programs for space situational awareness such as the so-called S-Band radar space fence and the increased sharing of data as to on-orbit earth orbiting vehicles such as the Space Data Association and as recommended by the UNODA Group of Governmental Experts.
(c) Increasing efforts to install passive de-orbit mechanisms on LEO satellites to engender de-orbit at end of life to meet the 25 year de-orbit objective.
(d) Research to develop effective ground-based laser or directed-beam devices that can change the orbits of satellites or space objects so as to avoid collisions or change velocities so as to de-orbit over time.
(e) Development of a variety of space-based on-orbit systems to carry orbit debris down to Earth in a controlled manner, or to create additional atmospheric drag or gravitational pull to de-orbit debris over time.
(f) Development of systems to cope with defunct spacecraft, launchers or other space debris elements in MEO and particularly GEO to move them out of harm's way and into parking orbits as opposed to de-orbiting them.
(g) Explore if on-orbit servicing vehicles, particularly for GEO orbit could serve a dual purpose of debris removal from geosynchronous orbit.
(h) Consider threats to geosynchronous satellites from defunct rockets in transfer orbits or destructive payloads placed in a retrograde Clarke orbit that would endanger all satellites in this narrow but highly useful band.

At this time there are a number of elements that are creating barriers or difficulties to solving the orbital debris problem. These factors include the fact that procedures to avoid the creation of new debris are voluntary and are not backed by specific sanctions or financial incentives or other type rewards. Likewise the current UN Liability Convention does not provide incentives for debris removal and indeed are believed by some to work to discourage launching nations of record to remove debris. There is today no clear-cut international actor in charge of regulating orbital debris removal nor technology designed for active debris removal that has been clearly demonstrated to be effective and cost efficient. There is essentially no reward or incentive to develop such a removal technology or system. Until these conditions change, the solution to the orbital debris problem and its active removal will remain a problem. On top of all of these practical and regulatory problems, there is the additional concern that many of the technologies that could potentially be deployed to remove space debris from orbit, could also be considered to be “space weapons”. Some of the technology could perhaps be seen as being banned under the UN Outer Space Affairs Treaty—especially if it involved technologies that could be equated to being a weapon of mass destruction. Until many of these issues are resolved clearly, the development of active removal procedures will likely lag behind and thus allow the orbital space debris problem to grow. This is another reason why on-orbit servicing will likely lead the way. Finally, the current emphasis is being placed on low earth orbit systems where the greatest problems lie. In the not too distant future, efforts to address orbital debris in medium earth orbit and GEO orbit must become an area of focus as well.

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Chapter 6
Legal Challenges Related to Active Orbital Debris Removal

Introduction

There are currently several sources of international regulatory control and pertinent legal instruments related to orbital debris and its removal. Three of these sources are currently existing international instruments of law, namely the pertinent original principles of international law devised before the Outer Space Treaty was agreed within the United Nations system, the Outer Space Treaty of 1967, and the subsequent Liability Convention of 1972. In addition to these three established sources of international law there are practices of space faring nations and model national laws that define practices for a particular country, but which can also help establish customary practice for other countries as well. Currently there are a number of problems that need to be addressed to facilitate the opportunity for either active orbital debris removal or for activities that would impact the orbits of space objects in attempts to prevent orbital collisions or minimize the likelihood of such collisions. These problems which can be characterized as current challenges to active orbital debris removal include the following:

1. First of all there is a need for a clear definition of what might be considered orbital debris and the specific means and processes that can be used to distinguish a "space object" from what can be characterized as a "space debris element". This distinction which does not currently exist in international law must be clear and unambiguous to all entities who might be involved.
2. A second priority is whether a mechanism might be established to transfer liability from the initial "launching state" to another entity. This involves a number of sub-points such as whether liability can in consistent practice over time be transferred to a "non-state" such as a private entity, an international organization, or a consortia that might include corporations, international organizations and states. There is also the question of whether the launching state could transfer its "ownership" and "launching state status" in terms of liability to another entity and how this could be formally done and whether this could be done multiple times.

J.N. Pelton, *New Solutions for the Space Debris Problem*, SpringerBriefs in Space Development, DOI 10.1007/978-3-319-17151-7_6

3. There are a number of derivative points of precise process and clear understanding of obligation for those involved with the launch, operation and disposal of space objects/space debris. These include such points: (a) as what could be considered "due diligence" related to the launch of space objects and the subsequent handling of space debris and its removal from orbit; (b) fulfillment of duties and obligations with regard to registration and processing of both "space objects" and the ensuing "space debris elements"; (c) the definition of "due diligence" and "duty of care" with regard to the launch and operation of space objects, the disposal of space objects and/or space debris elements. This obviously involves clarity of definition as to how, when, and why a space object (whether a satellite, a launch vehicle stage, or residual parts) somehow makes the transition to become space debris.
4. Further there is a need to consider a better definition of "fault" with regard to liabilities, especially when there might be operations such as space debris removal or alteration of an orbit to prevent collision, or placing of space debris into parking orbits.
5. Finally there is new issue with regard to operations above commercial space but below conventional understanding of outer space. This so-called Protozone or sub-space arena (i.e. above 21 km and below 100 km) is where a great deal of new activity is currently being planned. These activities might include such things as dark-sky stations, ionic engines flying small payloads to low earth orbit, rocket launches from stratospheric launch platforms, hypersonic transoceanic flights, robotic freighters, and sub-orbital flights. There is particular concern about sub-orbital flights (whether for space tourism or hypersonic transportation). This is because these activities are judged to pose the greatest danger of collision that may occur within the Protozone. Currently there is no agreed oversight regulatory body for this increasingly busy area.

The purpose of this chapter is to address all of these regulatory and legal issues and suggest the most urgent areas that need to be addressed to cope with the growing orbital debris problem and to establish an effective legal regime under which active orbital debris removal might be undertaken in coming years.

The Current Sources of International Law in This Area and Supplementary Sources of Regulatory Support Involving Orbital Debris Issues

The international law of space is quite compact—especially when it comes to the subject of space objects and space debris. The formal international space law that exists in this area was drafted over a relatively short period between 1963 and 1972 and as such does not take into account much that has changed about outer space activities over the last four decades. It is these instruments, however, that set forth who has jurisdiction over space objects (and thus space debris) and what liabilities that these objects can incur.

Essentially there are three prime sources. First there was the 1963 Declaration of Legal Principles. This was followed with the 1967 Outer Space Treaty that evolved from the consensus discussions within the UN Committee on the Peaceful Uses of Outer Space (COPUOS). (It is notable that as of 1 January 2014, the Outer Space Treaty had been ratified by 103 States and signed by 25 signatories including all space faring nations and thus it is the most pervasive in its global acceptance and as such constitutes what might be called a firm basis of "customary international law".) [UN Office of Outer Space Affairs]

Finally there is the so-called Liability Convention of 1972 and it is this last provision that is today the most controversial. Following a decade of negotiations, the so-called Liability Convention was adopted by the UN General Assembly. This Convention, elaborates upon Article VII of the Outer Space Treaty that addressed the liability issue. This Liability Convention was unique in that it imposes on the "launching state" an absolute responsibility to provide reparation for damages even in the absence of wrongful conduct by the launching State and does not take account of the fact that the launch might be for another country or a private company located somewhere else around the world, or that the spacecraft that incurs the damage might have been sold to another party entirely. In short this Liability Convention is considered today to have many logical shortcomings and it is this source of international law that is considered to be flawed and stands in many ways as a barrier to active orbital debris removal. [Nicholas Matte]

In addition to these sources of international law there is also UN General Assembly Resolution 1721 (XVI) adopted in 1961 that called upon all States launching objects into orbit or beyond to furnish information promptly to the Committee on the Peaceful Uses of Outer Space, through the Secretary-General, for the registration of launchings. This has transitioned into the Convention on the Registration of Objects Launched into Outer Space that entered into force in 1976 and currently has 62 Parties and 4 Signatories as of July 2014 (Fig. 6.1).

In addition there is the Inter-Agency Space Debris Coordination Committee (IADC) that has developed consensus guidelines to minimize the creation of

Fig. 6.1 The UN general assembly—the prime body to create outer space law (Graphic courtesy of the United Nations)

Fig. 6.2 The inter-agency space debris coordination committee (IADC)

additional space debris. The IADC has 13 member agencies that include those of the major space faring nations and European Space Agency (ESA) and has four working Groups that address related issues. The IADC guidelines with minor modifications became the basis for the voluntary guidelines agreed within the UN Committee on the Peaceful Uses of Outer Space (COPUOS), and then endorsed by the General Assembly in its resolution 62/217 of 22 December 2007. [Inter-Agency Space Debris Coordination Committee] (Fig. 6.2).

There are also other helpful regulatory sources that go beyond these UN instruments. Perhaps most notably a number of space faring nations such as the United States and France have adopted national space laws or exacting administrative processes that are quite specific in terms of addressing such issues as legal liability, due diligence to limit the creation of orbital debris, and to set guidelines such that launched space objects must de-orbit within 25 years after mission completion or be placed in suitable parking orbits. In this regard the French Operation Space Act is perhaps the most explicit and serves as model of other national laws for space faring nations. Because there have been no major new treaties related to outer space developed for many decades, the development of these other more informal types of agreements helps to establish international norms of behavior related to space that have evolved in more recent years.

The Major Deficiencies and Legal and Regulatory Issues That Exist with Regard to Orbital Debris and Its Removal

Clearly there are many challenges to be overcome in terms of finding cost effective, safe, and technically efficient ways to remove space debris from orbit or even to find effective ways to maneuver space craft to avoid collisions. But, there are likewise a number of problems and challenges to establishing space law and regulations that allows the cleaning up of space to proceed in an efficient manner without creating political, strategic, or liability claim problems as the removal of space junk takes place. As already noted it is the Liability Convention that because of unfortunate definitional problems and the lack of latitude in being able to transfer liabilities that creates the largest legal barrier to efficient orbital debris removal. There are problems that start with the lack of definition of "space debris elements" (in contrast to an all-encompassing term which is space object). There are also problems in terms of defining what is the extent and nature of jurisdiction and control that applies to a launching state. Further there is a lack of clarity with regard to the relationship that applies to a launching state, a state that registers a launch under the UN Convention, and the entity that actually "owns, operates or controls" a space object. There are certainly a number of terms that would benefit from better definition, particularly terms and concepts that may have changed in meaning or effective process over the last 40–50 years. These terms include active or unintentional alteration of orbits, transfer of ownership and liability, the recognition of both nation states and non-nation states as launching entities, actors, owners and operators in space. Also concepts such as due diligence and duty of care, and fault and liability with regard to space related activities could also be usefully defined and updated with exacting defined meanings.

Unfortunately an amendment to the Liability Convention or a new Liability Convention that clarifies these terms and provides for new and more appropriate liability provisions seems unlikely at this time. This means that either model national space laws or voluntary guidelines that all or most space faring nations accept may have to represent the practical step forward in this area. Although the main concern here is space assets and possible damage to space assets by one country or organization by another, care must also be taken to address legal or regulatory or liability issues that could arise if damage or harm comes to property or humans from space objects that are either deorbiting or are being launched into space. In the following sections these various legal and regulatory issues and definitions are addressed.

Difficulties with Definitions (Orbital Debris, Alterations of Orbit, Jurisdiction and Control, Transfer of Ownership, Nation States and Other Space Actors, Liability, Fault, Liability and Fault: Plus Due Diligence and Duty of Care)

Space Object versus Space Debris: Article VIII of the Outer Space Treaty provides that: "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." (Article VIII of the Outer Space Treaty).

The IADC has defined space debris as "all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional." This definition was adopted by the UN COPUOS. Similarly, the European Space

Agency has defined space debris as: "all non-functional, man-made objects, including fragments and elements thereof, in Earth orbit or re-entering into Earth atmosphere." Nowhere in the 1963 Declaration of Legal Principles, the 1967 Outer Space Treaty, or the 1972 Liability Convention, however, is any distinction made between functional and non-functional space objects. According to Article VIII of the OST, a State Party on whose registry an object launched into outer space is carried shall retain "jurisdiction and control" over such object while in outer space or on a celestial body. This includes not only launched operational spacecraft, but upper stage rockets, dead satellites, and even residual rocket and satellite parts. According to Article VII of the same treaty, a State Party that launches or procures the launching of an object into outer space, and each State Party from whose territory or facility an object is launched, is internationally liable for damage by such object or its component parts. Under the Liability Convention, such liability shall be absolute for damage caused on the surface of the Earth or to aircraft in flight, and be conditioned on fault for that caused elsewhere than on the surface of the Earth to a space object or to persons or property on board. As of now, nothing changes when operational space objects become non-functional and thus space debris. A start for the world space community would be a universally agreed definition of space debris.

Jurisdiction and Control: One of the reasons for a differentiation of a "space debris element" from a "space object" would be the presumed ability to transfer jurisdiction and control of a launched space object to another entity for the purpose of removal, lowering of its orbit to facilitate orbital decay or orbital parameter change to avoid a collision. The word jurisdiction of course has one meaning and control, especially for a non-functional space object (or space debris) quite another. Thus devising new language other than jurisdiction and control would also add greater precision to whether the intent is to cover "legal responsibility and liability" (i.e. jurisdiction) or whether the intent is to cover efforts to control a non-functional space object. This could have several practical implications. One suggestion with regard to changing an orbital parameter to facilitate de-orbit or collision avoidance, is that there could be a collaboration between the entity having "jurisdiction" over a non-functional space object and an entity with the technology to bring about the orbital change. This orbital variation might be via such means as a laser pulse or directed energy system. One concept would be to provide the entity with jurisdiction for the space object with the control of an energy system that would affect the orbital change.

Transfer of Liability Versus Transfer of Jurisdiction and Control: Today under existing space law there is no mechanism to transfer jurisdiction, control or liability of a space object regardless of whether it is functional or non-functional. Many have argued that such a condition creates exactly the wrong incentives to address the orbital debris problem and reduce orbital debris congestion and thereby reduce the threat of orbital collisions that would create yet more orbital debris. Clearly the problem, in part, stems from language in the Outer Space Treaty (1967) and the Liability Convention (1972) that did not anticipate the coming complexity of space activities. The possibility of private entities (i.e. non-State entities) launching, owning, operating, and buying and selling spacecraft was not anticipated. The current international legal environment suggests that a revision of space treaties and conventions currently in force is not likely to occur soon. Thus other recourses such as model space laws, agreements about codes of practice in space, and discussions and agreements within the Inter-Agency Space Debris Coordination Committee (IADC) or the Committee on the Peaceful Uses of Outer Space (COPUOS) may help define the meaning of these key concepts. Such non-treaty provisions might still be able to help define "space debris", the meaning of "jurisdiction" and "control" of space objects when non-functional, and whether there could be a transfer of "jurisdiction", "control" or "liability" with regard to such non-functional space objects. One subject that has been discussed in various forums is the creation of an orbital debris removal fund that could not only provide the means to undertake orbital debris removal, but also be used to cover the liabilities associated with debris removal. [Pelton]

Liability and Fault—Due Diligence and Duty of Care: The normal situation in law is that liability in a given situation is governed by where the fault lies and whether the entity at "fault" has exercised due diligence or undertaken appropriate duty of care to minimize risk to a reasonable standard. Under the Liability Convention the liability for launching States of a space object exists regardless of whether or not some other State, private entity or subsequent owner or owners have taken "ownership" of the spacecraft or space object and has created the fault or damage to property or individual. This seemingly illogical condition is nevertheless the existing international law and it clearly stands as a barrier to active orbital debris removal or programs that could minimize the creation of new orbital debris. In short the wrong incentives now exist to minimize orbital debris. Owners and operators of space objects that are other than the launching State currently have no special obligation under existing international law to exercise due diligence and duty of care to minimize orbital collisions or orbital debris buildup. Fortunately, they could be held liable under existing and pending national space law. Further as operators of space activities they may very likely have business reasons to avoid such results. In short the biggest problem is that existing international law does not create incentives to "clean up" orbital debris. A global fund that helps to pay for cleanup of orbital debris and becomes the first line of payment in case of an accident involving orbital debris removal occurs, could be one possible solution, especially if supported by national space laws enacted by space faring nations. [Pelton, "A Global Fund."]

Regulatory Responsibility and a Lack of Responsible Agency

The legal challenges and issues related to active orbital debris removal go beyond just the language in the Outer Space Treaty of 1967 and the Liability Convention of 1972. The other major problem is that there is no clear regulatory agency that is in charge of space safety, traffic in outer space, and other concerns. The International Telecommunication Union (ITU) coordinates the allocation of frequencies on Earth and in near to Earth space. The World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP) are responsible for atmospheric and meteorological concerns. The World Health Organization (WHO) is responsible for health standards related to such issues as radiation. Currently the International Civil Aviation Organization (ICAO) is beginning to examine the extent to which the Chicago Convention might be extended to cover coordination of space traffic control and management related to space transportation perhaps even up to GEO orbit. Currently there is no regulatory agency concerned with regulating and controlling space debris even though the UN Committee on the Peaceful Uses of Outer Space is the entity that has ultimately achieved agreement on voluntary procedures to minimize the creation of additional orbital debris. These procedures are currently voluntary and there are no enforcement provisions and certainly do not provide a regulatory basis for such activities as active orbital debris removal or the establishment of a fund to cover active debris removal or possible compensation for liabilities that might arise. [Jakhu and Nyampong] and [Sgobba, Jakhu et al.] Until some form of international regulatory framework is formed it seems unlikely that substantial progress can be made with regard to a coordinated approach to active orbital debris removal.

National Defense and Defensible Actions

In the area of international law there is always a good deal of complexity in that one provision in an instrument might well be trumped by another. National defense and "defensible action" is consistently invoked to justify national state actions in a great many of UN developed legal instruments and treaties. The regime of fault liability, which applies to damage caused elsewhere than on the surface of the Earth, as provided by Article III of the Liability Convention, requires the victim of the presumed wrongful act to prove the fault of the offending State. In contrast to that, the regime of objective responsibility found in Article II, which applies to damage caused by space objects on the surface of the Earth or to aircraft in flight, invokes responsibility as a sole consequence of conduct contrary to an international obligation. Yet Article II also permits the State to invoke defenses that may be available under international law to absolve itself from the responsibility. Fault responsibility must therefore be distinguished from causal responsibility. Thus the obligation to compensate arises only from the causal link between the action and the damage.

This means that a nation that employs an action to undertake active orbital debris removal or to change the orbit of a space object and can demonstrate that such action was undertaken as an act of national defense may be able to prove that this was not a wrongful act and thus was not at "fault" under the provisions of the Liability Convention. [Brownlie]

The Special Issue of the Protozone

The main focus of this book is on the problem of orbital debris which is largely concentrated in low earth orbit. Currently about 2.75 metric tons of the orbital debris in Earth orbit is in close proximity to the planet out of the total space debris of about 6 metric tons. This low Earth orbit is much more densely collected together and thus represents a much greater chance of collision. This is why much greater attention is paid to low Earth orbit debris even though debris such as upper stage rockets near GEO orbit is clearly also a major concern.

There is a further concern that needs careful attention in coming months and years as we see an increase in activities in the zone above normal commercial air space (i.e. above 21 km) and below the area that most nations consider the start of outer space (i.e. below 100 km). (Note: This translates into above 13.167 miles and below 62.5 miles). For years there was little activity in this "protozone" or "sub-space" area, but in recent years there has been an increase in actual or proposed use of this region. Activities include high altitude platforms for telecommunications and remote sensing, "dark sky stations" for scientific experimentation and possible staging to support low thrust ion engine flights to low earth orbit from these dark sky stations, sub-orbital space tourism flights, intercontinental hypersonic transportation flights, and robotic freighters across oceans that could move freight at lower cost and with substantially lower labor costs. This protozone region does not pose a space debris issue because gravity would deorbit all but lighter than air objects relatively quickly.

The problems for the "protozone" are nevertheless many fold. The challenges include space traffic management and control, potential crashes between objects potentially moving at high velocities relative to each other, stratospheric pollution of this very fragile atmosphere, and frequency interference. This is an area that also needs attention and it is not clear whether the International Civil Aviation Organization (ICAO), International Telecommunication Union (ITU), the World Meteorological Organization (WMO), the UN Environmental Programme (UNEP), or the World Health Organization (WHO) would have the greatest concerns and regulatory oversight responsibilities for the protozone. Despite this possible ambiguity the greatest amount of attention in the last few years has been focused on the ICAO responsibilities for air safety, which is seen as the driven regulatory concern at this time. There is clearly a need to consider the mounting applications for the protozone and many risks and dangers that can arise from having no clear-cut regulatory authority established for this region with all of its expanding new applications. [Pelton, "New Integrated Global…"]

Conclusions and Recommendations

The legal challenges related to active orbital debris removal as outlined above are both numerous and also not prone to easy solution. The obvious answer of amending the Outer Space Treaty of 1967 and the Liability Convention of 1972 is actually quite unlikely. The most promising areas to address the mounting problem of increasing orbital debris would: (a) model national space laws that contain appropriate penalties for violations and incentives for debris removal; (b) discussions between the space agencies on this subject, particularly within the Inter-Agency Space Debris Coordination Committee (IADC); (c) consideration of new and more current definition of key terms as discussed in this chapter and especially within the UN Committee on the Peaceful Uses of Outer Space and its Working Group on the Longer-Term Sustainability of Outer Space Activities; and (d) discussions within various space forums as to codes of conduct for the pursuit of space applications and development and debris removal. An idea of some logic is the creation of a global space development and orbital space debris removal fund that could be used to remove debris from space under licensing processes provided through the UN Office of Outer Space Affairs. Such a fund could in theory be used in case activities related to orbital debris removal led to some form of liability claim. A good start in this area would be discussions as how to define key terms and concepts that relate to today's realities in space. These realities are that private entities are engaged to a variety of space activities, that space assets are transferred from one entity to another, and that removal of space debris (i.e. non-functional space objects) or altering the orbits of space objects to avoid collisions are activities that are mutual benefit to everyone. That is to say that space faring nations, commercial space operators, space defense systems and everyone who anticipate the future exploitation of space would benefit from an improved legal regime. Such a regime should encourage the active removal of space debris from orbit and an improved legal and financial framework that could facilitate the prevention of collisions of space objects, create incentives for debris removal, and cover on a "no fault basis" the cost of liabilities in the event damages are somehow incurred in space.

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Chapter 7
New Ways Forward: A Program of Action for Orbital Space Debris

Introduction

In today's increasingly complex world it turns out that most problems and issues are interdisciplinary in nature. Unfortunately, most of the tools and processes we have available to address these issues are often geared to a single discipline or capability. The issue of orbital space debris is no exception. In order to address the best way forward to remove space debris from orbit, or to prevent it from occurring, requires a wide range of capabilities, including at least the following.

- **Technology**: Navigation and orbital mechanics, propulsion and launch systems testing, docking, guidance and avionics systems, computer simulation and modeling, relevant information and communications technology (ICT) systems, design, simulation and testing of space situational awareness (SSA) systems.
- **Management**: Strategic planning and scheduling, contracting, back-up arrangements, operation of space situational awareness (SSA) systems, and intelligence assessment and strategic data analysis.
- **Risk Minimization**: Quality control, safety standards, insurance coverage.
- **Finance and Capital Planning**: Mission financing, cash flow analysis, trade-off and cost-benefit analysis, competitive bidding contracting policies.
- **International Relations and Legal and Policy Analysis**: A new level of adherence to international guidelines for debris mitigation, negotiation of new provisions to limit creation of new debris, seeking agreement on new liability provisions, financial and legal arrangements to create incentives to engage in active debris removal, consider military and defense implications of new international agreements.
- **Strategic Planning**: Consideration of short term costs of debris mitigation versus longer term costs of being denied access to space or loss of critical space infrastructure.

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- **Environmental Issues**: Assessment of the environmental impact of different types of active orbital debris systems versus their costs and cost effectiveness, comparative impact of use of liquid-fueled, solid-fueled or electrical-ion propulsion.

In order for progress to be made there is a need for at least two things. One key objective, of course, would be an agreed international goal-oriented action agenda. The second key asset would be interdisciplinary teams with a wide range of expertise that would be available to work with all of those addressing the problem and seeking the needed new solutions. The community of interested parties is quite broad. It clearly includes space agencies and defense-related ministries; relevant governmental agencies dealing with the international relations in this area; the various United Nations bodies dealing with disarmament and the peaceful and sustainable uses of outer space; aerospace, space-applications and space transportation companies; and perhaps most significantly the insurance and risk-management industries and a wide range of economic interests that now have a significant dependence on space-related infrastructure.

An Action-Oriented and Goal-Directed Agenda

An action plan needs a number of clearly defined goals across several substantive technical, operational, regulatory and legal areas. It also requires the involvement of aerospace, insurance and financial corporations, national governments, and various types of organizations that includes professional groups, research organizations and universities, non-governmental organizations and intergovernmental organizations. Many of these objectives should and indeed will be pursued in parallel. Some of the specific elements of such an action plan include the following:

(a) Strengthening of guidelines for Mitigation of Orbital Debris. This might involve new requirements for passive measures to accelerate end-of-life deorbit for small satellites, or mandatory requirements for de-orbit systems that would be separately installed and operated from the orbital control systems that are used for station keeping on application satellites and perhaps similar deorbit systems even for upper stage rocket motors as well.
(b) Development of new more efficient and cost effective technology for debris removal.
(c) Development of insurance arrangements and/or financial incentives for debris removal.
(d) Creation of model laws.
(e) Development of provisions related to orbital debris that are defined in "codes of conduct", transparency and confidence building measures, etc.
(f) Creation on a "de facto basis" of new procedures that cover registration of space objects, duties and responsibilities of private entities designing, launching, deploying, operating and owning space systems, and liability provisions through insurance and other risk-mitigation initiatives.

The key entities for defining and achieving many of the goals may most likely be space faring nations and pertinent entities such as the Space Data Association, the Inter-Agency Space Debris Coordination Committee (IADC) or NGOs such as the Secure World Foundation (SWF), the Davos World Economic Forum, or the International Association for the Advancement of Space Safety (IAASS). Perhaps the greatest progress will be achieved when consensus is reached among space faring nations. This might be reflected in model laws that are backed by more than one spacefaring nation or it might achieve through proposed codes of conduct that have broad backing. In another context entirely, progress might be made when issues of liability or financial incentives create new levels of risk reduction for those that might actually pursue active debris removal. An organization such as the Secure World Foundation, or the McGill University Institute of Air & Space Law, which is undertaking a major project on Global Space Governance, might indeed seek to define such an action agenda, based on the seven goal areas as noted above. This initiative should not only address ways to produce less new debris in low and medium earth orbit and its removal but also address ways to clean up the geosynchronous orbital arc as well. Finally it should be noted that military and defense related agencies and actors are key players in all aspects of this problem. They thus need to be actively involved in terms of space situational awareness (SSA) systems, ground based systems that could change orbits to avoid a collision, active space debris removal, and regulations involving the definition and potential use of space weapons.

Interdisciplinary Support Systems to Support Progress in Debris Mitigation and Active Debris Removal

Experts with regard to different types of propulsion systems, experts in radar and optical tracking, experts in computer modeling and simulation, experts in directed energy beam systems, experts in orbital mechanics, experts in various types of space applications and their economic and strategic importance, experts in international law and regulation, experts in insurance and risk management, experts in drafting national space legislation, and experts in international relations and United Nations forums and their procedures. This is a preliminary list of just some of the types of experts that need to be involved to devise workable new procedures that could help ameliorate the growing space debris problem in Earth orbit. It is difficult to assemble all these types of expertise and even more difficult to assemble these capabilities into an effective interdisciplinary team that can objectively examine the problem and potential solutions and help develop new concepts, technical systems, and legal and regulatory systems that actually work to reverse the steady build-up of space debris. Yet this is the type of expert interdisciplinary help that is needed to move forward and to make progress in this difficult area. It is not an exaggeration to state that this problem now threatens the future of all space activities unless effective and definitive action is taken soon.

The potential dangers of the Kessler Syndrome actually denying future access to space must be taken seriously. To date only “band aids” have been applied to a dangerous problem that needs much more serious remedial solutions.

Conclusions

The nature of the problem posed by space debris has become clearer and clearer in recent years, but the serious new solutions needed to sustain longer term access to space have not yet been identified, let alone put in place. The truth of the matter is that international space law is still a weak and difficult regulatory system that often has limited impact on national or even business interests. An international treaty or convention that has been ratified by a national legislature has the impact of national law. But, in truth, such treaties and conventions are often hard to enforce and can often be interpreted in a variety of ways.

Strict national laws with sanctions and penalties for non-conformance that are put into place due to perceived economic or political interests would be key to the future. Such strong national laws would clearly be a much stronger instrument if and when it could be put in place. The recent involvement by the Davos World Economic Forum and the greater recognition by defense agencies that orbital debris issues are a problem for the reliable launch and targeting of defensive missile systems as well as the accurate detection of incoming missile attacks both can help to support new solutions to the increasing orbital debris threat.

There is not any one element of the above seven point action agenda that represents a “silver bullet” that will provide complete and long-term solution to the orbital debris problems. In fact, new technology, new national laws and regulations, new guidelines to reduce the creation of new debris, new definitions that facilitate active debris removal and places new explicit responsibilities on private space operators and owners will all help to alleviate space debris problems going forward. The large membership of the UN Committee on the Peaceful Uses of Outer Space and its diverse political make-up makes it very difficult to achieve consensus agreement. This means that other mechanisms such as the IADC that brings most of the key space agencies together or the Space Data Association that brings many of the key satellite operators together may provide the forums in which the initial core agreements might be worked out and the first core understandings reached. Once this initial understanding has been achieved the subsequent consensus within COPUOS may then be achievable.

A good deal of the problem is that technical research and breakthroughs and political consensus do not necessarily operate in synch. It could well be that after years of discussions to achieve international political consensus on a particular process, that new technology or a new systems approach might change the equations entirely. The greatest challenge of all thus remains to seek interdisciplinary processes that combine the best technical, operational, financial, risk-management, legal, and regulatory answers to the complexity that orbital space debris constitutes.

Chapter 8
Top Ten Things to Know About Active Debris Removal

All that one needs to know of the orbital debris problem and the concerns it raises for those engaged in space activities is the story revealed by looking at the images revealed over time that shows the accumulation of space debris surrounding the Earth in low, polar, medium and geosynchronous orbit ever since the 1970s. Each year the number of debris elements and the mass of debris elements has continued to rise—and ineluctably and steadily so (Fig. 8.1).

So what we should do about this problem and what are the most important take-aways from this book. Here are the top ten points to consider.

1. **There is a strong technical, economic, and operational link between space systems being developed to provide for on-orbit servicing, refueling and lifetime extension and systems that could be deployed for active orbital space debris removal.** This synergy needs to be considered as an advantage because R&D in this area can be supported and funded from both perspectives. These dual applications should be leveraged so that on-orbit servicing and active debris removal serve to feed on each other and create technical and operational advantage for both applications. In short there will be more financial resources available because of this synergy.
2. **The first priority should be to strengthen all aspects of the orbital debris mitigation guidelines to make them more binding and complete and effectively-oriented to all types of Earth orbits.** This is because the creation of less debris in the first place simply translates into less debris to remove at a later date. Also the emphasis should not be exclusively on end-of-life removal of low earth orbit and polar orbit satellites but removal of all debris or repositioning them into graveyard orbits that do not pose a potential damage to future space activities.
3. **There is a need for improved liability and less restrictive provisions on active debris removal.** Indeed the key is to provide new and better operational, financial, or insured risk incentives to pursue pro-active ways to remove debris for Earth orbit.

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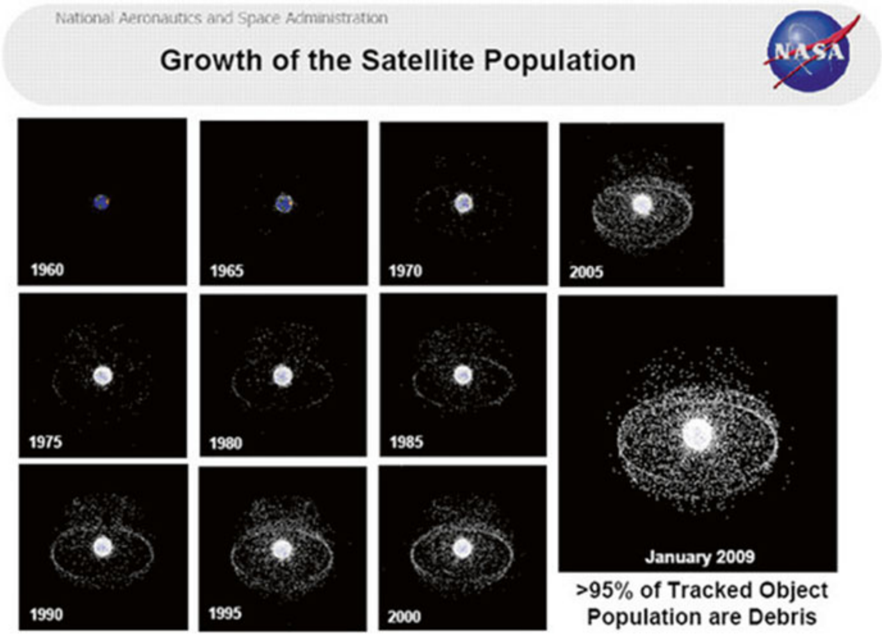

Fig. 8.1 The dramatic increase in orbital debris over time (Graphic courtesy of NASA)

4. **One way that might create new incentives for debris removal and financial advantage to those pursuing active debris removal systems would be to involve the insurance and financial services industry in an active way.** These industries could help develop new business models to incentivize active debris removal and allow "new space ventures" to provide innovative solutions to this now almost intractable problem.
5. **Private space actors (i.e. owners and operators and private launch operators) need to be formally recognized as part of the legal space community in relation to space debris and pertinent regulatory reforms related to international space law**. One of the largest current problems related to orbital debris is that a significant portion of space launches and defunct spacecraft are financed, launched and operated by private space industry. Despite this role and status, private entities are not recognized in the context of the Outer Space Treaty, the Liability Convention and key legal definitions related to "Launching States". This deficiency needs to be addressed and modified in international space law with pertinent de facto space regulations and practices. This particular issue needs to be addressed with some urgency, not only because of space industries, but because of student cubesats, private research institutes and other non-State actors.

6. **We need a number of key new definitions related to "Space Debris", "Registration of Space Objects" and "Launching States".** There are key deficiencies related to registration of space objects and a lack of penalties for non-conformance. Further there is a need to improve in the definition of "Launching States" as well as new legal definitions for "space debris" and in the specification of "private spacecraft owners and operators" as well as private space launcher entities.
7. **Model Space Laws, Transparency and Confidence Building Measures, and Codes of Conduct are all key tools of potentially great effectiveness**. The great weakness in international space law and regulation is the lack of binding provisions and penalties and enforcement provisions. There need to be other mechanisms to provide incentives for space faring nations and indeed all relevant space actors to take responsibility for their actions. The solution most likely to be found in today's "status quo" international community (where no new space treaties are likely to be adopted) would be through the creation of strong "model space laws" or administrative provisions at the national level that are enforceable through fines, revocable deposits, or other penalties for non-conformance. The French Space Operations Act (FSOA) of 2008 and 2010 as well as exacting NASA administrative procedures are a useful start in this direction. Closely related to new "model space laws" would be relevant new agreements in the area frequently referred to as "soft law". This could be in many forms such as Transparency and Confidence Building Measures that are often employed within the defense and military domains. These agencies need to be actively involved in this arena. We also need to seek other new soft law mechanisms such as newly proposed "codes of conduct" or broadly agreed "rules of the road" or in this case new "rules of the spaceways"
8. **Involve all key forums and agencies.** International governmental organization, national governments, space agencies, professional groups, foundations, research groups and universities, non-governmental organizations, and others need to become actively committed to solving the problem of space debris. It is important to pursue legal and regulatory reforms related to debris mitigation and active removal within all relevant forums. These include the UN Committee on the Peaceful Uses of Outer Space (COPUOS), the UN Office for Disarmament Affairs, the International Astronomical Union, the Committee on Space Research, as well as professional organizations such as the International Association for the Advancement of Space Safety (IAASS) or non-governmental organizations (NGOs) such as the International Academy of Astronautics, the Secure World Foundation or the McGill University Global Space Governance study.
9. **New and innovative technology to support active orbital debris is truly critical.** We need significant advances to be made in the technology to remove orbital space debris from orbit in the next few years. This new technology should serve to make removal much more reliable, efficient and cost effective. Unless technological progress is made, many of these sought legal or regulatory

reforms will produce little progress. In short funding and financial incentives to develop the new and innovative space debris removal techniques are of vital importance.

10. **Raise awareness of the orbital space debris threat to a much broader audience.** The final thing to note is that a much greater and empowered audience of political and economic leaders needs to become aware of the dangers that currently increasing amounts of orbital debris brings to vital space infrastructure, national defense, and the global economy. Recently groups such as the Davos World Economic Forum have set up a committee on space commerce that has acknowledged these types of threats. The Group of Governmental Experts on Transparency and Confidence Building Measures of the UN Office for Disarmament Affairs has likewise recently acknowledged the threat and need to make progress in this area. Yet much more needs to be done to raise awareness to a broader community with the power and financial clout to put more force behind these efforts.

Glossary of Terms and Acronyms

AFSSS	Air Force Space Surveillance System
ASAT	Anti-satellite missile programs
ASTRO	Autonomous Space Transport Robotic Operations. This was the name given to the servicing vehicle in the Orbital Express project. Also see NextSat
ATK	This is the short name for Alliant Techsystems. This a corporation that covers a wide range of aerospace competencies including solid motor rockets, space robotics, and space plane systems
Canadarm and Canadarm 2	Robotic manipulator arms developed by MDA and CSA for the Space Shuttle and the ISS
Clean Space One	This is a Swiss experimental project
Client Satellite	This is the satellite that is captured by a servicer satellite for purposes of refueling, repair and maintenance, and upgrade
CNES	The French Space Agency
ConeXpress	The name of the orbital life extension vehicle to providing servicing capabilities to satellites being developed by Orbital Recovery Ltd. of the United Kingdom and Dutch Space
COSPAR	Committee on Space Research. This is an international collaborative body that considers all aspects of space research
CSA	Canadian Space Agency
DARPA	Defense Advanced Research Projects Agency
DD	Decommissioning Device that would provide a fail safe way to de-orbit defunct satellites from LEO at end of life
DEOS	Deutsche Orbitale System

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DEXTRE	The Dextrous Manipulator developed by McDonald Dettwiler Associates as part of Canadarm 2. Also see its other official name: Special Purpose Dexterous Manipulator (SPDM)
DLR	The acronym for the German Space Agency
D-Orbit	Company of Italy that is developing “fail safe” systems to de-orbit LEO satellites at end of life
EDDE	Electro-Dynamic Debris Eliminator
EOTP	Enhanced Orbital Replacement Unit Temporary Platform which is a key capability on the International Space Station for carrying out experiments
ESA	European Space Agency
ETS	The Japanese Experimental Test Satellite series to test telecommunications, broadcasting, mobile communications and space robotics capabilities
ELC-4	ExPRESS Logistics Carrier 4 (ELC-4) which is used for staging on the International Space Station
FSOA	The French Space Operations Act of 2008 and 2010
GEO	Geosynchronous Earth Orbit
GGE	Group of Government Experts
HAPS	High Altitude Platform Systems. This is the term that the International Telecommunication Union has applied to very high altitude stabilized platforms used for telecommunications or other purposes. An altitude of about 21 km would be typical for such platforms
IAASS	International Association for the Advancement of Space Safety
IAA	The International Academic of Astronautics
IAC	International Astronautical Congress
IADC	The Inter-Agency Space Debris Coordination Committee
IAF	International Astonautical Federation
IAU	International Astronomical Union
ICAO	The International Civil Aviation Organization
ICT	Information and Communications Technology
ISS	International Space Station
JAXA	The Japanese Space Exploration Agency
JMS	This is the United States’s. **J**oint Space Operations Center **M**ission **S**ystem (JMS)
LEO	Low Earth Orbit
LEOP	Low Earth Orbit Proximity
LEV	Life Extension Vehicle. This is term used by ConeXpress for their on-orbit servicing vehicle
LTSSA	the UN COPUOS Working Group on the Long Term Sustainability of Space Activities

MDA	McDonald Dettwiler Associates of Canada
MEO	Medium Earth Orbit
MEV	Mission Extension Vehicle. This is the term that Vivisat uses for its on-orbit servicing vehicle
NASA	The National Aeronautical and Space Administration
NextSat	This was the name given to the “Client” satellite in the Orbital Express experiment funded by NASA and DARPA. The idea was that “NextSat” would represent the future modular designed satellites that would allow for efficient on-orbit servicing
Orbital Express	This was a joint NASA and DARPA project to demonstrate in-orbit
ORL	Orbital Recovery Ltd. This is the British firm that is developing the ConeXpress Orbital Life Extension Vehicle (CX-OLEV)
OST	Outer Space Treaty
Project Phoenix	This is the project of DARPA to develop the capability to provide on-orbit servicing as well as the harvesting of parts from in-orbit defunct satellites
Protozone	This area that is also referred to as Sub-Space or Protospace is typically thought of as being between the ceiling for commercial air space (up to 21 km) and below the normally accepted start of outer space (at 100 km). This area between 21 and 100 km could potentially be used for robotic air freight, space tourism sub orbital flights, hypersonic, intercontinental air transportation, dark sky stations, and high altitude platform stations (HAPS)
RCPM	Remote Power Control Modules
ROGER	ESA’s Robotic GEO Orbit Restorer
RPO	Rendezvous and Proximity Operation
RRM	Robotics Refueling Mission. This was a project by NASA to study a number of intricate refueling, repair and retrofit operations on an on-orbit mission
RROxiTT	Remote Robotic Oxidizer Transfer Test. This test was part of the Robotics Refueling Mission experiments carried out on the ISS
SDA	The Space Data Association
Servicer Satellite	This is a satellite that is able to conduct on-orbit services to a satellite. It could also be used for transport services to move a satellite to a new orbit or to de-orbit it at the end of useful life
SIS	Space Infrastructure Servicing. This is name that MDA uses for its on-orbit servicing vehicle

SMART-1	This was the ESA Moon mission explorer that used electronic ion engine propulsion. This ion engine.... propulsion is the be used in the ConeXpress robotic service vehicle
SPDM	Special Purpose Dexterous Manipulator (also see DEXTRE which is how it is also known
SSA	Space Situational Awareness
SWF	The Secure World Foundation
TCBMs	Transparency and Confidence Building Measures
UN COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UNEP	United Nations Environmental Programme
UNODA	United Nations Office for Disarmament Affairs
VHF	Very High Frequncy 30–300 MHz spectrum range
Vivisat	A project developed with the support of the ATK Corporation to develop on-orbit servicing capabilities
WEF	The World Economic Forum that meets in Davos, but which has many committees constituted around the world that address specific regional and function areas, including outer space affairs
WHO	World Health Organization
WMO	World Meteorological Organization

About the Author

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