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.

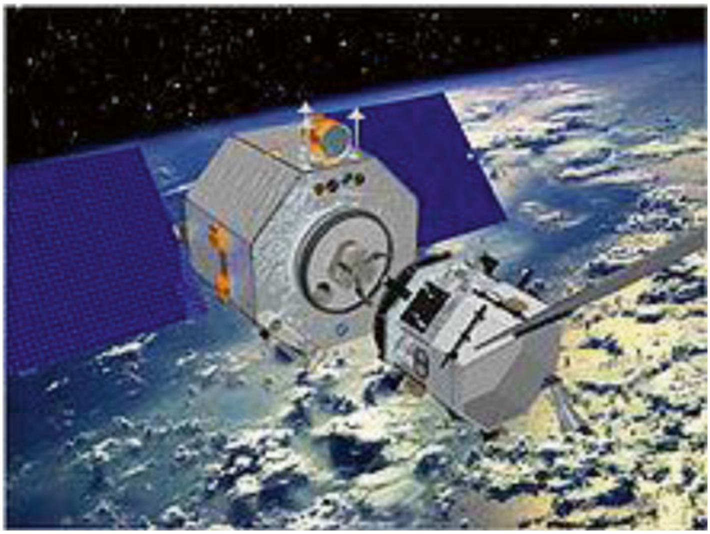

Fig. 2.1 The Astro "Servicing" spacecraft and smaller NEXTSat pictured in orbit (Graphic Courtesy of NASA)

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

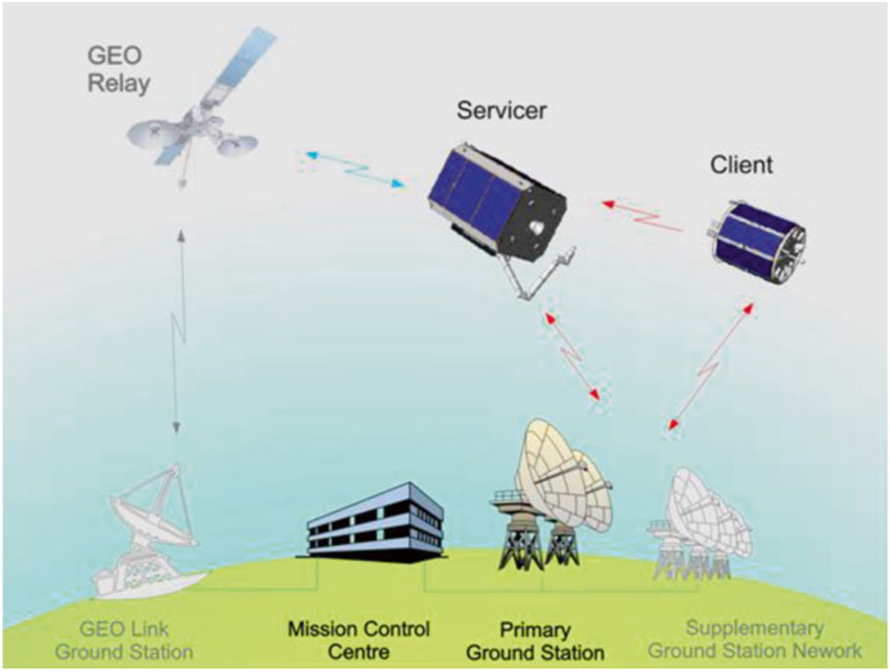

Fig. 2.3 DEOS servicer, client and ground control system (Both graphics courtesy of DLR, the Germany Space Agency)

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

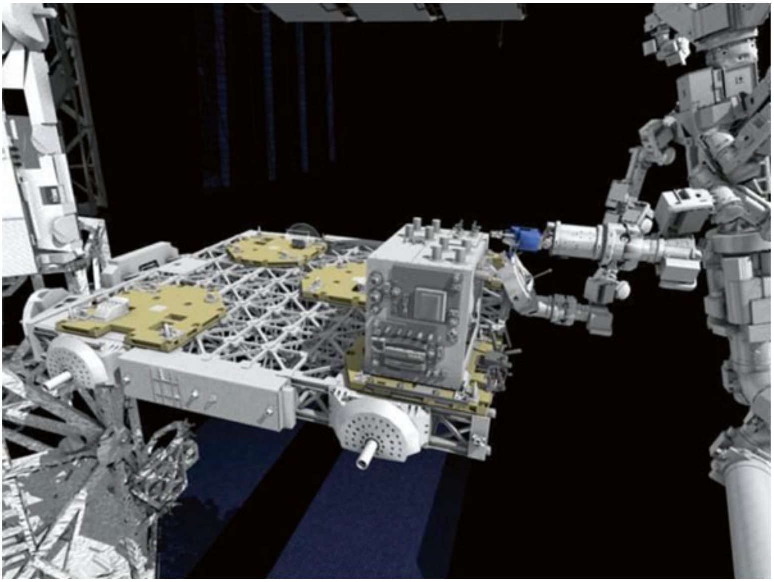

Fig. 2.4 The Dextre robotic device in tandem with the RRM was capable of a number of precision operations in space such as refueling, and orbital repairs and servicing (Graphics Courtesy of NASA)

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

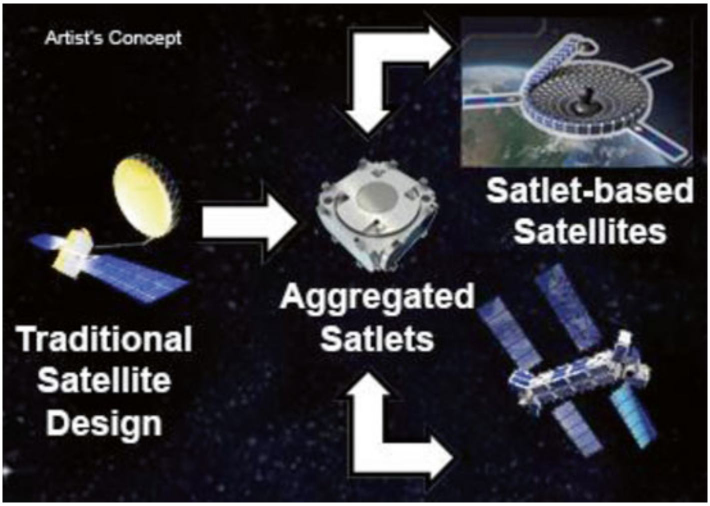

Fig. 2.5 DARPA architectural concept of aggregating Satlet modules (Graphics courtesy of DARPA)

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

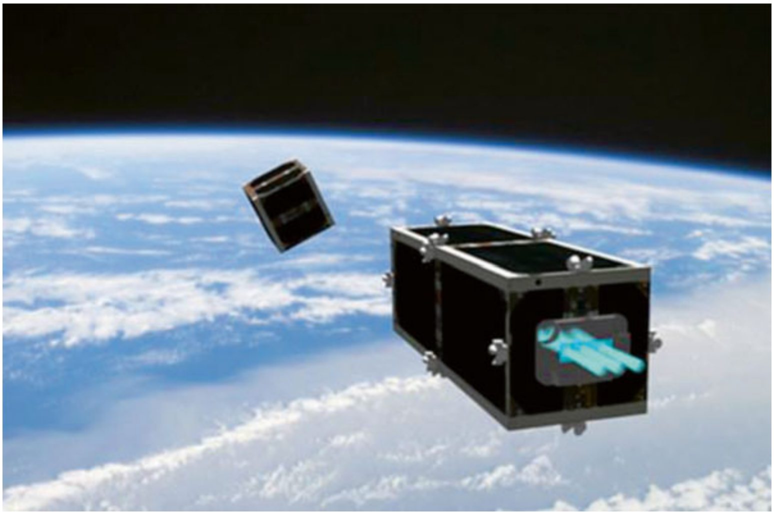

Fig. 2.6 a simulation of the cleanspace one spacecraft overtaking the swiss cubesat (Graphic courtesy of the Swiss Space Center)

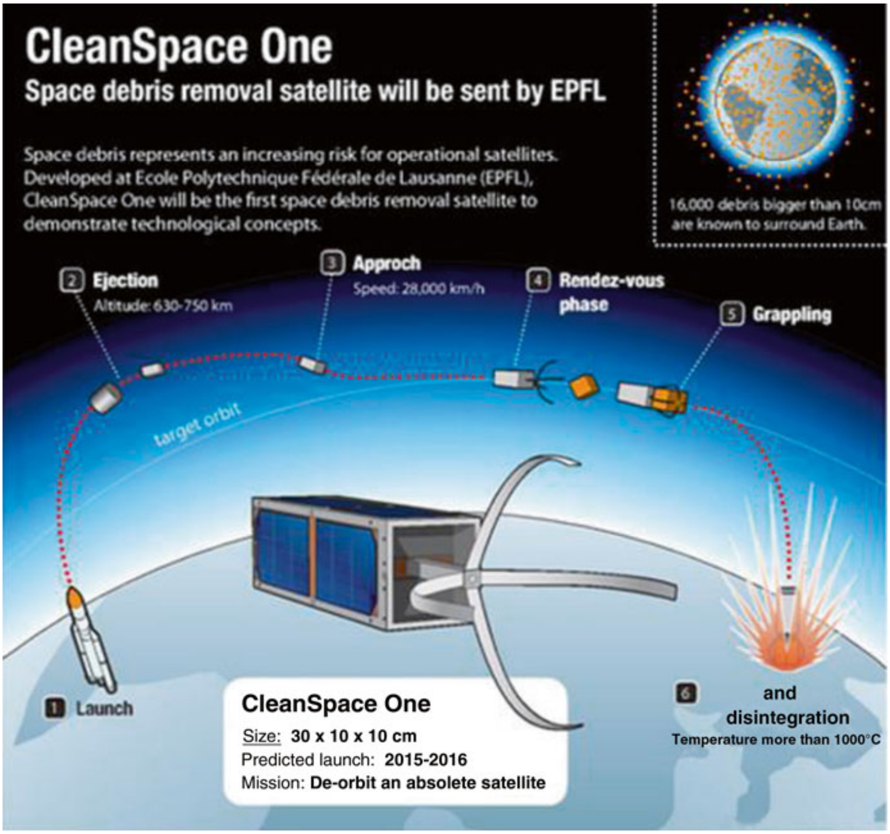

Fig. 2.7 CleanSpace one planned trajectory for deorbiting the original cubesat (Graphic courtesy of Swiss Space Center and EPFL)

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 reenter 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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