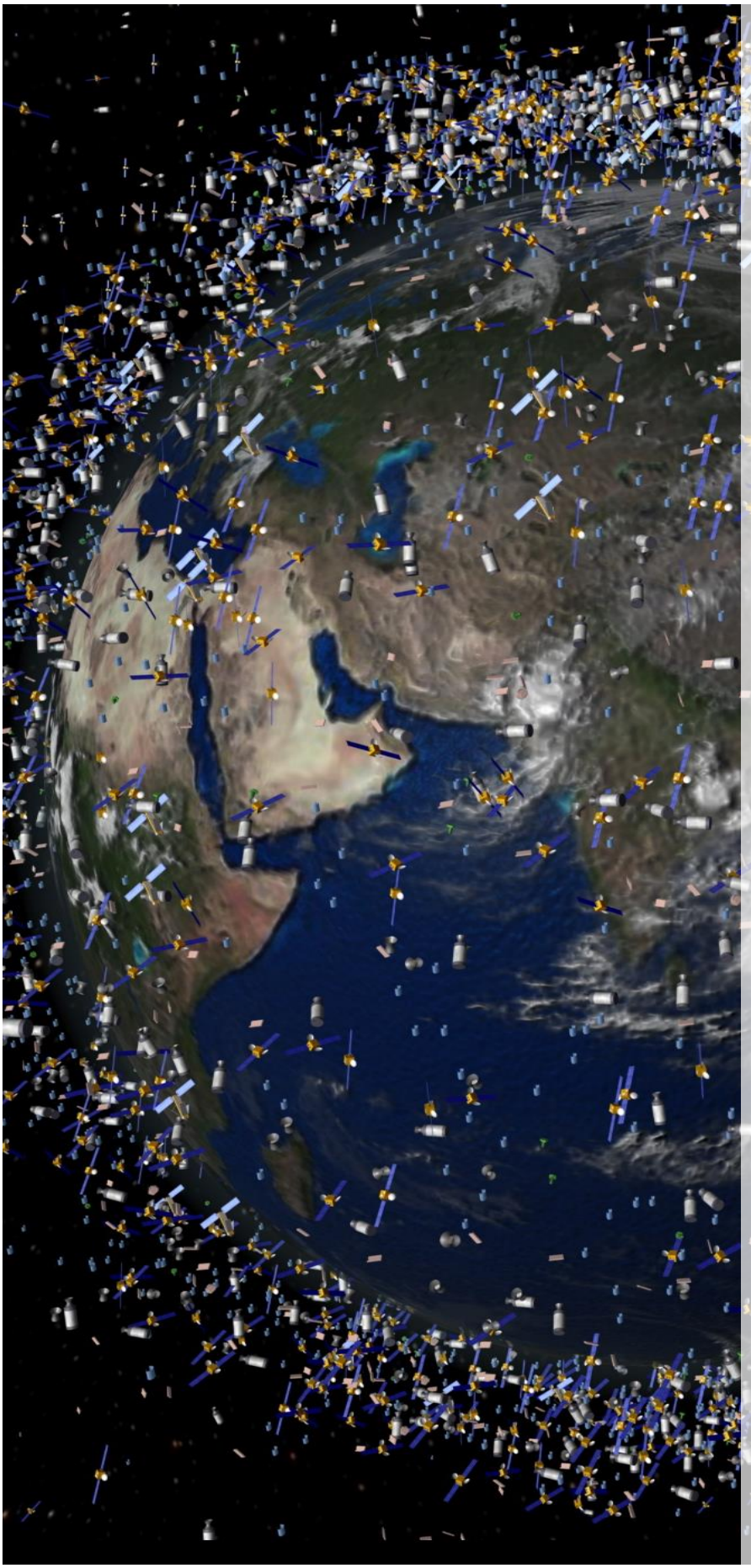


Routes to Market Report

23 – On Orbit Servicing and Space Debris Mitigation

Innovate UK

in-space missions limited

CATAPULT Satellite Applications

Contents

1. Introduction and Scope

The market study scope addresses both the nascent On-Orbit Servicing and the Space Debris Mitigation markets. This report makes use of the author's expert knowledge of the domain and various on-line, print and personal sources.

2. Market Overview and Opportunities

The existing and future markets for On-Orbit Servicing and space Debris Mitigation are identified in the table below. These markets are subdivided in terms of the technologies required from both the servicer and serviced satellite. For example, a non-contact servicing mission might observe and provide clever augmentation to a customer satellite but it would not make physical contact and therefore cannot physically modify the customer satellite. A full contact servicing mission will most likely attach itself to the customer satellite and make significant functional and physical changes to this satellite.

<table>
<tr><th></th><th>Level of Co-operation</th><th>Non-Modification</th><th>Functional Modification</th><th>Physical Modification</th></tr>
<tr><td rowspan="2">Non-Contact</td><td>Cooperative</td><td>Inspection in support of anomaly resolution, performance monitoring
Inspection in support of insurance claims</td><td>Power and Communications augmentation</td><td></td></tr>
<tr><td>Non-Cooperative</td><td>Inspection and monitoring of target assets</td><td>Interference with power and communication – e.g. target shadowing</td><td>Destructive behaviour – EMP or fragmentation device</td></tr>
<tr><td rowspan="2">Contact</td><td>Cooperative</td><td>Inspection in support of anomaly resolution, performance monitoring</td><td>Orbital Transfer including Life Extension, Orbital Tug and De-orbiting</td><td>Refuel, Repair, Upgrade and Assemble</td></tr>
<tr><td>Non-Cooperative</td><td>Inspection and monitoring of target assets</td><td>Orbital Transfer - particularly De-orbiting of dead assets
Orbital Transfer – e.g. de-orbiting or repositioning of target assets</td><td>Destructive behaviour – damage to key subsystems</td></tr>
</table>

The areas indicated in red are outside of the discussions in this report. This is due to the sensitive, national security and defence nature of these markets which makes assessing a market value and providing attributable evidence a challenge.

An additional, relevant, area that is not considered in this report is the Asteroid Mining market. This market will exploit many of the same technologies being developed for (non-)

cooperative satellite modification. The value of the raw metals resident in the asteroid belt between Mars and Jupiter is estimated to be $700 quintillion (Business Insider, n.d.). However, the costs to access these resources are on the order of trillions of dollars and will require significant investment and technology development. Companies such as Planetary Resources and Deep Space Industries have initiated development in these technologies.

The areas indicated in yellow are considered low value, low growth as the technologies being developed elsewhere will overtake the implementation of these areas.

The areas indicated in green are considered the high growth markets and are expected to mature significantly over the next 15 years.

This is supported in part by a quote from Steve Oldham, the Senior Vice President of Strategic Business Development from Space Systems Loral where he stated (Satellite Today - Steve Oldham SSL Interview, 2017) in Feb 2017:

'If you're an operator you want to be able to do several things. If a satellite is meeting your market needs and is performing correctly, why do you have to replace it? You want to be able to extend the life of a satellite that is working perfectly fine but is running out of station-keeping. You want to be able to inspect your satellites to see what state they're in, or repair them if they fail. You want to be able to grab them from an incorrect orbit and put them in a better place. You want to augment your satellites, adding new payloads over time or replacing old ones. And finally you want to be able to assemble satellites in space because by doing so you have more freedom from the constraints of launch.'

The identified markets under discussion are:

- Orbital transfer:
    - Life extension
    - De-orbiting of co-operative assets
    - Orbital Tug
    - De-orbiting of dead assets
- Refuel, Repair, Upgrade and Assemble

2.1 Orbital Transfer market

Here the offering is for a servicing satellite to physically attach itself to a customer satellite and to provide additional manoeuvring capability to this satellite over a period of time. This is typically done by the servicing satellite attaching itself to the customer satellite whereby it performs the function of the customer's satellite's propulsion (and in some cases attitude control) system.

This market exists largely because propellant is a consumable on board satellites and has a direct impact on mission life. The orbital transfer market breaks down into four further submarkets:

<u>Life extension</u>

The market is for satellites that have run out of propellant and can no longer maintain the orbit required to deliver their service. However, the payload and main bus functions are likely

still operating, hence the servicing satellite's job is to maintain the orbital location of the customer satellite while it continues to deliver a high-performance service. The challenge is to ensure that the servicing satellite can perform its manoeuvring task without compromising the pointing, power generation and thermal dissipation capabilities of the customer satellite.

De-orbiting of co-operative assets

This market is mainly for satellites that have used up most of their propellant, have not yet de-orbited or entered a graveyard orbit but are still under control from the ground. This submarket is considered small.

Orbital Tug

This market is for satellites that need to be repositioned into new orbits. Several possible scenarios and customers exist here:

- Satellites that have been delivered into the wrong orbit due to a launch vehicle failure – whereby the asset is written off by the insurance company.
- Low performance launch vehicles which are unable to deliver to some useful, higher orbits – here the launch vehicle provider may make use of a resident orbital tug to deliver the satellites to the correct orbit.
- Satellites that are no longer required by an operator but that can be sold to a new operator and repositioned to a new orbital location.

De-orbiting of dead assets

This market is present primarily due to concerns regarding the growing space debris population making certain key orbits unusable. A number of national activities exist – most notably at ESA and DLR to mitigate against this risk by actively de-orbiting a number of larger dead assets – e.g. Envisat. Several companies internationally have attempted to develop business cases around de-orbiting debris but due to current lack of funding this market is considered risky without institutional investment to tackle the issue.

However, this is now changing due to the advent of the mega-constellations where 'cleanliness' of the constellation orbital neighbourhood will be critical to guarantee service and ensure survivability of the constellation at large. These new non-Geosynchronous Orbit (NGSO) constellations will likely require dedicated space Debris Mitigation services such as those offered by companies like Astroscale:

"Instead of focusing on existing debris, we've decided to focus on future debris, which comes from the dying satellites," said Astroscale CEO Nobu Okada. "For constellation players with satellite networks, they have to keep their orbit clean. Once their orbit is contaminated, they cannot do business." (Space may soon have its first undertaker — for satellites, CNBC, 2017)

2.2 Refuel, Repair, Upgrade and Assemble Market

These capabilities are grouped together as they rely on much more complex technologies and prediction of the market size is much more challenging to predict. In brief:

Refuel

A servicing satellite 'tanker' will attach to a customer's satellite and refuel the propellant tanks. This is preferably done with a customer satellite which is designed to be refueled, however new technologies are under development to cut through the caps and wires on a satellite fuel valve and transfer propellant into existent, orbiting spacecraft that were not designed to be serviced. This technology has already been demonstrated by NASA's Robotic Refueling Mission on the International Space Station in 2013.

The advantage of refueling as opposed to simple Life Extension (see section 2.1) is that a single servicing vehicle can visit multiple customer satellites and provide extended life to these missions in parallel whereas the simpler Life Extension vehicle only extends the life of a mission while it is physically attached. The terrestrial analogy is a car running out fuel which might have the option to either be towed to its destination or to visit a petrol station and then have enough fuel to drive itself to its destination

Repair and Upgrade

A servicing satellite will make physical modifications to a customer satellite. This could include such activities as: applying new thermal tapes; unsticking a mechanism; replacing a failed actuator or even completely upgrading a payload. These operations could be extremely complicated and will require an expert team of human operators in the loop in a ground station and potentially a sophisticated artificial intelligence on-board the servicing satellite.

This service would be tremendously enabling and the offered capability could range from fixing a single broken satellite to a servicing fleet upgrading 1000's of satellites in a NGSO mega-constellation.

Assemble

A servicing satellite would in effect build a satellite from component parts in orbit. It is an extension of the capability offered by a repair and upgrade service. However, the power of this enhanced capability is the possibility of assembling structures in space which are significantly larger and heavier than can be accommodated on a single launch vehicle. In addition, with the combination of advanced manufacturing processes making use of in-situ resources it offers the capability to manufacture large parts of satellites from planetary bodies and asteroids where this service converges with the asteroid mining service.

Many of the Refuel, Repair, Upgrade and Assemble services are enabled by the technologies under development for the successful delivery of Orbital Transfer services. The supporting legal frameworks are lagging and at this time the only significant national activity is the DARPA Consortium for Execution of Rendezvous and Servicing Operations (CONFERS).

Through CONFERS, DARPA aims to establish an industry/government forum composed of experts from throughout the space community. The forum would develop non-binding, consensus-derived technical and safety standards for on-orbit servicing operations, and help

create definitions and expectations of responsible behaviour in outer space. (DARPA Selects SSL as Commercial Partner for Revolutionary Goal of Servicing Satellites in GEO, 2017).

It is expected that CONFERS and other nascent national activities will ultimately lead to the legal framework required to manage the satellite servicing market.

3. Customer and value proposition to the customer and end user

3.1 Customers

Typically, the customer for On-Orbit Servicing is a telecoms operator with potential to deliver significant revenues. However, the growing market for Earth Observation, and Position, Navigation and Timing services and the high value of these satellites indicate a similar but more specialised need for On-Orbit Servicing.

Telecommunications satellites in geostationary orbit present the richest current market as all the satellites have functionally very similar designs and requirements and operate in the same orbital plane at the same altitude. This significantly simplifies the design and propellant requirement for a servicing satellite which would be able to service multiple customers. In addition, the consumer and fixed satellite services delivered from geostationary orbit currently generate ~95% of the total global satellite service revenue (State of the Satellite Industry Report - SIA, 2016) and therefore represent the class of customers with the greatest commercial need and ability to pay for such a service. Example satellite operators looking to engage this service include Intelsat, Hispasat and SES as seen in Annex A.

In addition to the GEO telecoms operator, many operators are developing NGSO mega-constellations that utilise multiple orbit planes and 100's to 1000's of satellites:

- SpaceX NGSO System – 4,425 satellites in 83 orbit planes (SPACEX NON-GEOSTATIONARY SATELLITE SYSTEM ATTACHMENT A TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE SCHEDULE 5, n.d.)
- OneWeb – 3000 satellites split over > 40 orbit planes. (OneWeb breaks ground on Florida factory - Space News, 2017)
- Samsung – 4600 satellites (Mobile Internet from the Heavens, 2015)
- Plus, more including Boeing, Leosat and others

As discussed earlier (section 2.1) the operators of these NGSO constellations, based on low cost satellites, will have a strong requirement to provide a belt and braces approach to keeping their orbital region clear of dead satellites. The OneWeb design includes features to enable an active debris removal system to remove failed satellites in the event that their own deorbit system fails (Space News interview with Brian Holz, 2015). To provide a responsive capability and due to propulsion system limitations (deltaV and thrust levels not being sufficient to quickly move between orbit planes) it is likely that the most efficient service deployment will be for each orbital plane to have its own deorbiting satellite. As an example, for a constellation with an altitude of 1000 km, the deltaV (the size of propulsion system burn) to move between planes separated by only 5 degrees is > 600 m/s, this is four times larger than the deltaV required to de-orbit a satellite from the same constellation and would take many months using an electric propulsion system.

3.2 The Customer Proposition

In addition to the needs identified earlier, some operators are now facing the challenge of a rapidly changing telecoms market. While it is expected that some operators have well understood and relatively stable broadcast markets, many operators are moving into the satellite broadband market where the technology is rapidly changing and an 18-year design of satellite will become obsolete within 5 years of being launched. As Steve Oldham of Space Systems Loral recently opined in reference to satellite servicing (Satellite Today - Steve Oldham SSL Interview, 2017):

'I would say most importantly it allows satellite operators to be flexible in their decision-making. Today they can't. When you have satellite servicing available, you can start investing your capital expenditure dollars where it makes the most sense. You won't have to replace a satellite because it's broken or when it's run out of fuel. Now you have the ability to do fleet management by servicing some of your assets. Then you can focus your capital expenditure on where it can generate the most profit, which is what every other business in the world does. That's the real benefit for satellite operators: flexibility in capital expenditure planning in a world where budgets are reduced and restricted. There is a lot of change in the market for operators and the flexibility that satellite servicing gives them is a huge positive.'

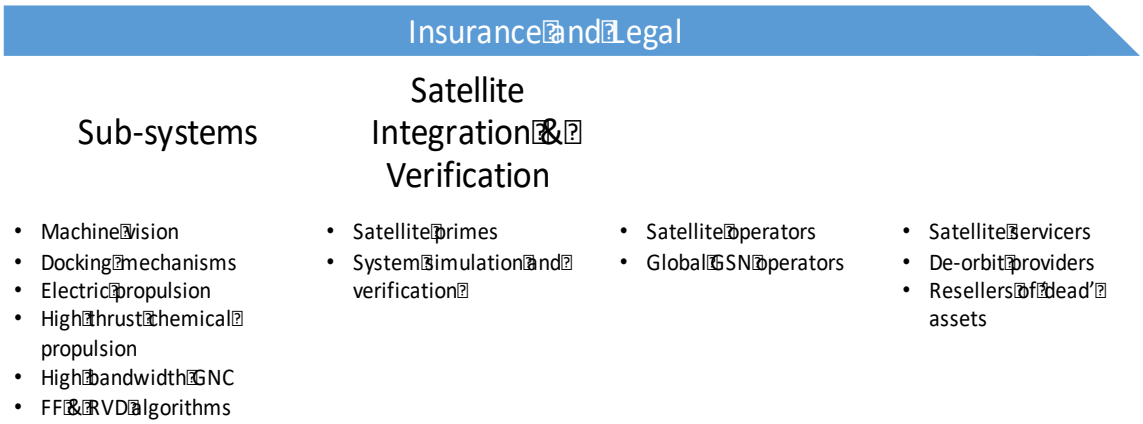
4. Market Competition

Currently the only alternatives for an operator to servicing a failing satellite are to launch a new satellite to replace it or to lease capacity on another satellite. Hence, it is expected that satellite servicing will represent a robust market so long as servicing offers an acceptable risk, lower costs, reduced service downtime and the payload technology is still relevant or will be modified by the servicer.

Regarding Life Extension, the move to satellites embarking electric propulsion systems will impact this market significantly as these satellites have significant propellant reserves and are far less likely to require Life Extension services including refueling. However, even today, many operators are procuring and launching satellites with chemical propulsion and a design life of 18-years and as such this market is expected to last for at least another 20 years by which time the market for 'Repair, Upgrade and Assemble' servicing is expected to have grown significantly.

5. Role of UK companies

A reduced value chain for the combined On-Orbit Servicing and Debris Mitigation market services is shown below along with some indicative examples of where UK companies could exploit existing products and expertise.



Strong existing and nascent capabilities in industry and academia would enable UK based companies to both lead and participate in all parts of the value chain. These capabilities have already attracted the Israeli On-Orbit Servicing company Effective Space Solutions to relocate its headquarters to the UK.

As an example, several companies in the UK have experience of developing Formation Flying and Rendezvous and Docking algorithms (FF & RVD) for ESA missions (e.g. IRSI/Darwin) and more recently for experimental demonstrators such as RemoveDEBRIS. Also, companies such as Inmarsat and SSTL have access to a global Ground Station Network (GSN) which could be used to provide 24/7 operations for a satellite servicer.

The UK's lack of historic involvement in manned space has however left a weakness in its ability to deliver space borne robotic systems and it will need to exploit the transfer of knowledge arising at the result of inward investments from companies such as Thales Alenia Space and Macdonald Dettwiller and Associates. In addition, there is some good, relevant expertise in other sectors (e.g. Nuclear, Oil & Gas etc) which could be pulled across.

Note that while electric propulsion systems are required for servicers to enable the large deltaV required through life, high thrust chemical propulsion systems are likely to also be required for the class of satellites where a de-orbiter has to provide a controlled re-entry into the ocean.

6. Revenue Projections

A series of significant opportunities exist inside the markets identified in this report. The following section looks at two example high value opportunities and provides associated financial projections:

1. Life Extension services
    - Customer is geostationary telecommunications satellites
2. Space Debris Mitigation services
    - Customers are NGSO mega-constellation operator and government

6.1 Life Extension Services

Analysing the geostationary Life Extension market, many coarse assumptions can be made:

- 20 new satellites are launched each year into geostationary orbit (this number typically varies between 20 and 30)
- Satellite design life (including consumables – e.g. propellant) is 18 years
- 75% probability of satellite achieving full design life

Because of these assumptions, each year, 15 satellites will reach end of propellant life and still have a fully functioning payload and bus but no means to maintain orbital position or altitude. Typically, at this point a replacement satellite would be launched with an upfront cost (for a large telecoms satellite including launch and insurance) of typically $300-350 million. Assuming a weighted average cost of capital of 7.0 – 9.0% per annum, the value of deferring satellite replacement is $20-32 million per annum (Analysys Mason - Satellite Life Extension, 2016).

The proposition of the Life Extension market is therefore for the service provider to offer a Life Extension service at a price point below $20m/annum. These numbers tie up well with the court papers filed as part of the Orbital ATK legal dispute with U.S. Space over the ViviSat Joint Venture which listed the prices that had been agreed with prospective customers which ranged between $11-14.2 m/annum (Analysys Mason - Satellite Life Extension, 2016). These prices are listed for information in Annex A.

If we assume that of the 15 satellites reaching end of propellant life each year that for 10 of these satellites the operators will make use of a Life Extension service for an average of a further five years or sell the asset on to another operator to exploit and also require Life Extension services. Within 5 years of a Life Extension service being adopted by the industry at large, the accessible market is 48 satellites (assuming 98% probability of failure/year) at any one time requiring Life Extension services. This corresponds to an accessible market size of 48 x $11m/annum → $528m/annum of which the UK can occupy the entire value chain.

Based on existing plans and contracted customers, the first Life Extension missions are expected to be operational by 2019.

6.2 Space Debris Mitigation services

As noted earlier, several constellations are under design and manufacture which utilise multiple orbit planes and 100's to 1000's of satellites:

- SpaceX NGSO System – 4,425 satellites in 83 orbit planes (SPACEX NON-GEOSTATIONARY SATELLITE SYSTEM ATTACHMENT A TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE SCHEDULE 5, n.d.)
- OneWeb – 3000 satellites split over > 40 orbit planes. (OneWeb breaks ground on Florida factory - Space News, 2017)
- Samsung – 4600 satellites (Mobile Internet from the Heavens, 2015)
- Plus, more including Boeing, Leosat and others

As each orbital plane in a constellation is likely to need a de-orbiting satellite and allowing for the case that only two of the proposed constellations are funded and launched then a reasonable estimate would suggest a requirement for over >100 deorbiting satellites to be launched and resident as integral support infrastructure for NGSO constellations. Assuming that this capability would be delivered as an operational service by a third party then the revenues from each deorbiting satellite should be assumed to be of the order of $2m/annum (which would allow an operator to operate in profit) which leads to a potential market of the order of $200m/annum.

In addition, space based services are now recognised by most countries as critical national infrastructure. As space becomes more congested, the risk to that infrastructure will need to be managed by a combination of space traffic management and controlled deorbiting of existing space debris. It seems likely that at some point in the near future that active debris management will be funded from national budgets, indeed the ESA Cleanspace programme is already investigating the preferred business and technical models to deliver this capability. Private industry is also making proposals to assign a small proportion of national space budgets to address this need – Arie Halsband from Effective Space Solutions recently proposed a figure of 1% of global annual space budgets equivalent to $300m/annum as needed to engage commercial space in delivering such a system (Pioneering Last Mile Logistics in Space - Arie Halsband, 2017). A proposal such as this would take 5-10 years to gain traction but the high likelihood of another high-profile collision – such as the 2009 collision of Iridium-33 and Kosmos-2251 – would accelerate the implementation of a similar proposal.

6.3 Revenue Projection Summary

	2016	2017	2020	2030
Life Extension Services	0	0	$30m	$530m
Space Debris Mitigation Services	0	0	$10m	$500m

The assumption in these projections are 3 active Life Extension missions by 2020 with market achieving full potential by 2030. After around 2040, the Life Extension market is expected to tail off and by replaced by the Repair, Upgrade and Assemble market.
The Space Debris Mitigation market projection assumes an early deployment of 5 De-orbit Satellites by 2020 with full support to 2 NGSO mega-constellations and the allocation of national budgets to fund an active debris removal scheme.

7. SWOT Analysis

The table below provides a SWOT analysis for UK industry's ability to access the On-Orbit Servicing markets combined for both Life Extension and Space Debris Mitigation Services.

Strengths	**Weaknesses**
- Excellent technical and commercial capability across value chain (1)(2) - Responsive regulatory environment (1)(2) - Informed legal and insurance ecosystem (1)(2) - UK seen as moderately neutral entity in most target markets to deliver sensitive services (1)(2)	- Low level of space robotics heritage in UK (1)(2) - No national programme support (1)(2)
Opportunities	**Threats**
- Deployment of mega-NGSO constellations, some of which licensed via UK (2) - Regulatory moves to controlled re-entry (2) - High profile collision driving debris removal multi-lateral agreements (2) - Rapidly changing telecoms market leading to uncertainty in build of space assets (1)	- Move to non-chemical propulsion for station keeping in GEO (1) - Significant US funding via DARPA and NASA for in-orbit demonstration missions (1) - International view of servicing capability as 'dual-use' for military applications may slow down licensing regime and commercial deployment (1)(2)

Key
(1) Pertains to Life Extension Services
(2) Pertains to Space Debris Mitigation Services

8. Opportunity, Blockers, Enablers

Typically, the evolution of the population of satellite assets moves relatively slowly with significant amounts of time allowed to licence, register and coordinate with other space users. The advent of servicing creates a potentially more dynamic and responsive environment for which the current regulatory processes and pace are not fit for purpose. These will require significant review otherwise they will act as a barrier to entry for new servicing operators. Similarly, considerations around insurance and liability will need review to ensure that appropriate legislation and insurance offerings are available. These are currently being looked at by Marsh in the UK amongst other.

Technically, continued UKSA National Space Technology Programme and Innovate UK support to the development in industry and academia of the electric propulsion, docking and machine vision systems required will enable the UK to access significant parts of the subsystem market.

At a higher level, the UK could act as an anchor customer as part of a space sector deal for a satellite servicer either offering to demonstrate de-orbit on a UK asset such as Topsat or via its military satellite communications programme – Skynet 5 – where a number of assets are reaching end of life and would greatly benefit from a Life Extension service.

9. Market Dynamics and Trends

Several large primes are currently entering this field – Orbital ATK, Space Systems Loral and Airbus. Each have highly capable service offerings and in the case of SSL the support of NASA and DARPA programmes. In addition a number of smaller newspace companies such as ESS (Life Extension) and Astroscale (Debris Mitigation) have raised significant investment funding to develop services. At this time, it is unclear whether the market will support more than one Life Extension service operator – indeed, a senior US industry analyst has recently suggested (under Chatham House rules) that their analysis indicated that the market would bear only one operator.

The longer-term picture is that, while Life Extension services are likely to fall away in the 20-year time frame, the technologies proved will support a new approach to space where satellites are mended, modified and manufactured in space. Once the launcher volume and mass constraints are removed and much bigger satellites can be assembled on orbit, the performance of the GEO telecoms satellites will significantly improve to compete with the NGSO constellations. In addition, the commercial telecoms operators will be unconstrained by the state of the art technology at launch and will be able to rapidly upgrade their systems in response to market needs.

10. References

Analysys Mason - Satellite Life Extension. (2016, July). Retrieved from http://www.analysysmason.com/About-Us/News/Newsletter/Satellite-life-extension-Jul2016/

Business Insider. (n.d.). Retrieved from http://uk.businessinsider.com/the-value-of-asteroid-mining-2016-11?r=US&IR=T

DARPA Selects SSL as Commercial Partner for Revolutionary Goal of Servicing Satellites in GEO. (2017, February). Retrieved from http://www.darpa.mil/news-events/2017-02-09

Mobile Internet from the Heavens. (2015, August). Retrieved from https://arxiv.org/ftp/arxiv/papers/1508/1508.02383.pdf

OneWeb breaks ground on Florida factory - Space News. (2017, March). Retrieved from http://spacenews.com/oneweb-breaks-ground-on-a-florida-factory-that-will-build-thousands-of-satellites/

Pioneering Last Mile Logistics in Space - Arie Halsband. (2017, February). Retrieved from http://www.unoosa.org/documents/pdf/copuos/stsc/2017/tech-51E.pdf

Satellite Today - Steve Oldham SSL Interview. (2017, February). Retrieved from http://www.satellitetoday.com/technology/2017/02/17/steve-oldham-ssl-future-satellite-servicing/?hq_e=el&hq_m=3356994&hq_l=3&hq_v=f8dcbe8911

Space may soon have its first undertaker — for satellites, CNBC. (2017, March). Retrieved from http://www.cnbc.com/2017/03/17/space-may-soon-have-its-first-undertaker-for-satellites.html

Space News interview with Brian Holz. (2015, June). Retrieved from http://spacenews.com/qa-with-brian-holz-director-of-oneweb-space-systems/

SPACEX NON-GEOSTATIONARY SATELLITE SYSTEM ATTACHMENT A TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE SCHEDULE 5. (n.d.). Retrieved from https://cdn3.vox-cdn.com/uploads/chorus_asset/file/8174403/SpaceX_Application_-.0.pdf

State of the Satellite Industry Report - SIA. (2016, September). Retrieved from http://www.sia.org/wp-content/uploads/2017/03/SSIR-2016-update.pdf

11. Annex A

Vivisat JV prices agreed with prospective customers are shown in the table below (Analysys Mason - Satellite Life Extension, 2016). In the case of Vivisat, the service is leased and the customer pays an annual fee while the servicing spacecraft is attached to their satellite and delivering the orbit maintenance service. Typical durations for these service level agreements are 3-5 years as seen in the table.

Operator	*Lease term*	*Annual lease cost(USD million)*	*Revenue over lease term (USD million)*	*Implied average annual price per tug (USD million)*
SES	3 years	10–12	33	11
Hispasat	3 years	8–14	35	11.7
Intelsat	5 years (2 tugs)	24	120	12
Asia Broadcast Satellite	3 years	13	39	13
Measat	5 years	13–15	71	14.2