Space Sector: Spacekeeping & Servicing
Economic Analysis

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PURPOSE

The purpose of this paper is to provide an economic analysis of the space industry sector "Spacekeeping & Servicing." This sector encompasses the following types of activities of which some are still only speculative: space debris monitoring, space debris/ spacecraft removal from orbit, on-orbit spacecraft refurbishment, and space material recycling. This paper will address each of this sector's activity types and evaluate each in terms of the economic factors supply, demand, framework, market trends, inter-sector dependencies, and overall feasibility.

BACKGROUND

On April 12, 1961, Yuri Gagarin began mankind's exploration and exploitation of space. In the subsequent 37 years we have seen quantum leaps in technology and the accumulation of debris in space. The space industry goals over this time period were focused on technological advances not the preservation of the space environment of future use. The result is 35,117,000 objects in near-Earth space with an estimated mass of approximately 2,000,000kg [NSTCC 1995] and growing. There are approximately 35 operational spacecraft [Bates 1997] out of the total objects occupying near-Earth space the rest are debris or garbage. The types of debris that exist fall into the following categories: [AIAA 1992, 1-16]

(1) Discarded rocket bodies/stages - Launch vehicle upper stages (17%);

(2) Inactive payloads/spacecraft - Spacecraft that have had a catastrophic system failure or have past their functional lifetime due to propellant depletion or programmatic decision (23%);

(3) Operational Debris - Spacecraft or launch vehicle parts released as part of operations, deployment, or anomaly (e.g. lens covers, payload shrouds, bolts, pyrotechnic material, surface degradation material, solid rocket ejecta and biological remains) (12%);

(4) Collision and Explosion Fragments - Debris resultant from debris and space vehicle (spacecraft or launch vehicle) collision or any combination of the two

and that debris which is the result of an intentional or unintentional explosion of a space vehicle or space vehicle part (42%).

All types of debris are potentially very dangerous to space operations. The magnitude of the risk to space operations depends on the velocity, size/mass, and proximity of space debris to operational assets. Debris size and effect on spacecraft can be grouped into the following categories: [NSTCC 1995]

(1) Debris less than 0.01cm - Causes surface pitting and erosion which may have significant effect on the spacecraft after long exposures.

(2) Debris 0.01cm to 1cm - Causes significant impact damage which can be serious depending on spacecraft system design.

(3) Debris larger than 1cm - Causes significant damage and may cause the catastrophic loss of the spacecraft.

The likelihood of debris colliding with a spacecraft and causing the loss or significant damage to a spacecraft is no longer a theoretical issue. The Russian Kosmos-1275 is believed to have been destroyed by space debris [Wilson 1996]. The French Cerise spacecraft lost its stabilizing boom due to a debris impact [AP 1997]. The U.S. Space Shuttle has spent $5Million on replacing windows damaged by debris [Wilson 1996]. Therefore there must be something done to eliminate space debris and/or control the creation of space debris or eventually our highly profitable near-Earth space environment will be unusable and/or untraversable for outer space exploration.

Today, NASA Policy NSS 1740.14, NASA Policy Directive 8710.XX, DOD Space Policy 1987, and the following national and international positions require that debris generation mitigation is to be performed [NSTCC 1995, Part 2].

> "...All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness..." The November 1989 Presidential Directive [AIAA 1992, 9]

> "...Recognizing that space debris constitutes an unacceptable (man-made) risk to man and materials in space and on ground, the objective for the future must be to minimize the consequences of the existence of space debris and

minimize the creation of additional space debris...” 1989 ESA Position [AIAA 1992, 10]

However, both the development of spacekeeping activities by the ‘Spacekeeping and Servicing’ sector and intersector cooperation / mandate compliance (Note: historical operations did not consider debris generation as part of design and operations planning) are needed to ensure the safe and reliable availability of space for all space sectors in the future.

INTERSECTOR COOPERATION

Launch operations and in-orbit operations can produce ‘operational debris’ and the potential for ‘collision and explosion fragments’ while launch operations can also produce ‘discarded rocket bodies/stages’. Therefore launch vehicle and spacecraft operators and manufacturers can and should take the following actions to mitigate this possibility and remain compliant with the aforementioned policies: [AIAA 1992, 19-21]

(1) Launch vehicle manufacturers can modify launch vehicle upper stages to accelerate orbital decay and guarantee their re-entry. This can be done by the adding of a drag augmentation device or active de-orbiting (planned for Ariane-5 [Eichler 1992, 196-202]). Drag augmentation, such as a drag balloon, requires the addition of additional hardware and control procedures for it to work and is limited to low altitudes [Petro 1989, 169-182]. Active de-orbit requires that the resultant individual stage be capable of attitude control and command processing to perform the de-orbit maneuver [AIAA 1992, 19-21] or incorporation of a passive deceleration system as used by the Russians.

(2) Launch vehicle and spacecraft manufacturers/operators can modify deployment systems to avoid the deposit of debris in orbit. Lanyards and debris trapping devices can be added to both spacecraft and launch vehicles to minimize the creation of operational debris such as instrument covers and pyrotechnic material.

(3) Launch vehicle and spacecraft manufacturers/operators can modify deployment operations to avoid the deposit of debris in orbit. This action would require that the release times for operational debris, such as payload shrouds, be changed so that the releases occur at low enough altitudes to ensure quick re-entry and elimination.

(4) Collision and explosion fragment debris comes from those un-controlled objects that remain in space and can not be removed. Launch vehicle and spacecraft manufacturers/ operators can modify end-of-life (EOL) capabilities and procedures to minimize this hazard. Specifically, both groups can perform passivation procedures to avoid explosion and/or the relocate of their space

objects to avoid collision. Passivation requires spacecraft or launch vehicle manufacturers to provide for stored energy (i.e., batteries and propulsion) dissipation. One passivation technique is the passivation of batteries which can be done by managing them to an EOL full discharge and then subsequently short-circuiting them. Another passivation technique is the passivation of propulsion systems which requires spacecraft or launch vehicle manufacturers to provide for propellant/pressurant venting and/or fuel depletion burns. Relocation requires that spacecraft and launch vehicle manufacturers provide an EOL maneuvering capability that can take their space object (i.e., a launch vehicle upper stage or an entire satellite) to another orbit. In the case of debris this relocation can be to disposal orbit higher the GEO orbits to avoid collision.

Intersector cooperation as described above is essential in guaranteeing the future availability of near-Earth space.   A lack of intersector cooperation will result in the continuation of the current rate of debris production which will by far overpower the proposed clean-up efforts of the 'Spacekeeping and Servicing' sector in a very short time. The onus is on the space industry regulatory commissions and customers to demand that the policies referenced above be enforced beyond the limited voluntary compliance that exists today to avoid the loss of such a valuable resource. The 'Spacekeeping and Servicing' sector's activities will then be able to be effective in mitigating the dangers posed by the remaining objects which will still double in 50 years [NRC 1995, 167-172] even with intersector cooperation.

SPEACEKEEPING AN SERVICING SECTOR ACTIVITIES

<u>Activity 1: Space Debris Monitoring</u>

<u>Product/Service</u>: Space debris monitoring is the service of collecting observatory data (currently optical and radar data) and producing accurate and up-to-date space debris location/path catalogs to prevent collisions, supplying predictions of where and when a space object will reenter, and preventing inadvertent triggering of global missile attack warning sensors [SPACECOM 1997]. Observatory data is limited by the currently developed optical and radar technology that limits debris reliable detection to those objects 1cm or greater. Therefore due to these limits supplemental technologies and simulations have been used and are being developed to increase the accuracy of this service.

<u>Suppliers</u>: Specifically, the routine provider of this service is a world-wide network of observatories as coordinated in the majority of cases by the U.S. Space Surveillance Network (SSN) as described in Table 1. In addition, observation data quantifying the debris environment beyond what can be observed by Earth-based facilities has been gathered by the Orbital Meteoroid Debris Counting (OMDC) Experiment added to the Clementine Interstage Adapter

Spacecraft [Poole 1997], the 1983 Infrared Astronomical Satellite (IRAS) [DeJonge 1992, 245-247], and the Brilliant Eyes Satellite System [FAS 1996].

Supply: Although the monitoring of space debris is a costly undertaking it is necessary to ensure safe launch, flight and deployment of space systems therefore the supply of this service is inelastic.

Demand: Governments will demand this service regardless of cost as long as they are interested in conducting space activities. A government's purchase of the service ensures that their space operations are safe and secure thereby mitigates their liability potential for loss or damage to spacecraft of their nation or spacecraft of another nation. Therefore the government demand for this service is inelastic. The commercial space industry suppliers are required to review the publicly supplied space object/debris catalogs to ensure safety before launches are approved by their associated governments. Framework: This demand exists because according to ‘The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies’ the states/governments are responsible for the activities of their nationals and themselves and are not allowed to cause “potentially harmful interference with the activities of other parties” [NSTCC 1995] which a collision with a spacecraft or debris would be. The commercial space industry is thereby a secondary inelastic demander

Future of Service: This service activity is fully funded by direct or in-direct government funding therefore does not operate under the competitive environment of the ‘free market.' However, as stated earlier the success of all other space sectors’ activities depends on the knowledge provided by this service. At this time the commercialization of this service does not appear to be economically feasible due to its global observatory infrastructure needs and high facility operating costs.

Table 1: WORLD-WIDE OBSERVATORY NETWORK

Observation System	Location	Mission/ Capability	Funding Source	Operating Costs Estimates
Space Surveillance Network (SSN) Headquartered at Cheyenne Mt. (CMOC)	Global: Diego Garcia, Indian Ocean, Eglin AFB, Florida, Maui, Hawaii, Naval Space Surv. System, Socorro, New Mexico Antigua, British West Indies Ascension Island, S. Atlantic Ocean Beale AFB, California, Cape Cod AFS, Massachusetts, Cavalier AFS, North Dakota, Clear Air Station, Alaska Fylingdales, England, Oahu, Hawaii Thule, Greenland, Kwajalein, Marshall Islands, Tyngsboro, Massachusetts Perimeter Acquisition Characterization Radar System (PARCS), North Dakota	Debris >= 10cm	US Space Command	CMOC - $175 Million per year and $24Million per year for Clear Air & PARCS and an Overall SSN for Debris - >$300Million (TBR) per year
NASA Orbital Debris Observatory	Lincoln National Forest, New Mexico	LEO Debris >= 5cm	NASA	$160K per year
Haystack Observatory and its associated Millstone Radar & Firepond Telescope	Massachusetts	Debris 1-30cm & limited <1cm	MIT Lincoln Laboratory	$7.5Million per year & $2.5Million per year
FGAN Tracking and Imaging Radar	Germany	Debris 1-50cm in LEO, GEO & GTO	NASA	Unavailable but presumed to be comparable to those sited
JSC's 50Mhz Ionization Radar	JSC/Portable	Atmospheric/ Re-entry Debris <= 100microns	NASA	Unavailable but presumed to be comparable to those sited
Communication Research Lab	Japan	GEO Debris >= 20cm	Japanese Government	Unavailable but presumed to be comparable to those sited
National Astronomical Observatory (NAO)	Mitaka, Japan	Unpublished	Japanese Government	Unavailable but presumed to be comparable to those sited
Middle and Upper Atmosphere (MU) Radar System	Japan	LEO Debris >= 1m	Japanese Government	Unavailable but presumed to be comparable to those sited
Royal Greenwich Observatory	United Kingdom/England	Unpublished	United Kingdom's Government	Unavailable but presumed to be comparable to those sited

Table Data From:
http://www.sunspot.noao.edu/NODO/nodo.html, http://www.spacecom.af.mil/usspace/space.htm, http://sn-callisto.jsc.nasa.gov/index.html, http://www.spacecom.af.mil/usspacecom/cmotrivia.htm, http://www.un.or.at/OOSA_Kiosk/spdeb/spdeb94/spdeb94.html, http://www.nao.ac.jp, http://www.crl.go.jp, http://www.un.or.at/OOSA_Kiosk/spdeb/spdeb95/spger.html, & emails from Mark Ulrooney 1/28/98 & Alan Blackburn 2/12/98.

Activity 2: Space Debris/Spacecraft Removal from Orbit

Product/Service: Space debris/spacecraft removal is the service of collecting and removing debris or spacecraft that has no means of removing itself from usable orbits or in the best case from space. The concepts of how to perform such a service vary according to the debris to be removed and are listed below divided into the categories of large and small debris removal with the applicable debris types, as defined earlier, identified.

- Concepts for discarded rocket bodies/stages debris & inactive payloads/ spacecraft debris (large debris) removal:

    1. The University of Braunschweig concept of using a remover space vehicle that would decrease the orbital energy of debris by transferring that energy to its self and therefore causing the debris to re-enter and burn-up [Eichler 1992, 196-202]: Specifically, the retrieval process combines the two space objects therefore changes their orbital dynamics. The remover climbs and the debris falls. Until separation of the two objects, the debris is stabilized by local gravity gradients forces along the vertical without changing its orbital velocity.   Separation of the two objects will therefore cause the released debris, which is now at a new lower altitude with the same velocity it needed to sustain the higher altitude, to fall and eventually re-enter.   Conversely at separation the remover will be sent into an elliptical orbit because its speed at separation is not appropriate for its mass and orbit height. The remover can then use this new elliptical orbit as a transfer orbit for its next mission. An alternative implementation of the same concept is the use of NASA's Orbital Maneuvering Vehicle (OMV) to directly de-orbit debris. Cost estimates for the OMV-type implementation are $15-20Million per remover [Petro 1989, 185-186]. Due to the great similarities of these two implementation strategies for the same concept the OMV estimate can be presumed to also be valid for a 'Braunschweig remover.' However, the range of these types of devices is limited by their propulsion or energy transfer capabilities which would therefore require the use of multiple removers to make a significant impact on debris population.

    2. The concept of using NASA's Orbital Maneuvering Vehicle (OMV) to retrieve and attach a controllable propulsive de-orbit package or commandable drag augmentation device [Petro 1989, 169-182]. In this concept the OMV would retrieve the space debris and while grappled to it robotically attach either a propulsive de-orbit package or drag augmentation device (e.g., drag balloon). The OMV would then release the debris at which point the newly attached

devices would be activated. Debris would then de-orbit or begin drag induced orbital decay to re-entry. As stated earlier NASA's Orbital Maneuvering Vehicle (OMV) cost estimate is $15-20Million per vehicle therefore the costs of this type of removal would be that cost plus the cost of each propulsive package, estimated at $7,800,000, or the cost of each drag augmentation device, estimated at $5,000,000-$15,000,000 [Petro 1989, 185-186].

3. The University of Arizona concept of an 'Autonomous Space Processor for Orbital Debris' (ASPOD)[Bates 1997]: This concept is one of an orbital robot with grappling hooks and gathering arms that would collect large debris and process the debris for re-entry or re-cycling. The associated debris processing in this concept is the cutting up of debris with a sun powered torch and packaging it for re-entry burn-up or Earth return and recycling. The cost estimate to build a device like this is $5Million and is expected to have low operating costs.

- Concepts for operational debris & collision and explosion fragment debris (small debris):

1. The concept of using unfolded films 8km in diameter and 20μm thick to slow and destroy (to <0.1cm particles) and/or partially evaporate debris due the characteristics of high velocity (> 15km/s) collisions [Diobyshevski 1995,151-154]. This concept has two problems unless it is enhanced. The first problem is the avoidance of destroying or colliding with operational objects and the second is the disposal of the used film. Both issues can be resolved by enhancing this concept to include a controlling bus to the center of the film capable of both controlled avoidance and de-orbit maneuvering. However, this concept will only handle objects up to 3 cm and will take 20 years to accomplish its task and is therefore felt to be unfeasible.

2. The Marshall Space Flight Center's Jonathan W. Campbell laser illumination concept [Bates 1997]: This concept would use a laser focused on debris targets between 1/2" to 4" to disturb their orbit. Once a debris object's orbit is disturbed it is presumed that it will fall and be destroyed during re-entry. Current laser and tracking technologies limit the size and range this type of service could eliminate to debris 1/2" to 4" at less than 500 miles. Research is on-going on this concept via the Orion Project and is expected to cost $100Million to perform.

3. The concept of using 'sweeper' devices to gather small debris [Petro 1992, 180-184]. This concept would employ one or more spacecraft with large stationary or rotating panels that would collect small debris. The spacecraft(s) would orbit until bus EOL or debris collection panel saturation at which point the craft would be removed as

described above or de-orbit its self. Cost estimates for operation of such a system are expected to be large but have not been quantified beyond that.

4. The Johnson Space Center's Donald Kessler foam balloon concept: This concept would be to place 1 mile wide foam filled balloons in Earth orbit [Petro 1992, 180-184]. Once a balloon was in orbit debris would collide with the balloons and either become embedded or slow down enough that the debris would be bound for re-entry. This concept has two basic problems unless it is enhanced. The first problem is the avoidance of destroying or colliding with operational objects and the second is the disposal of used balloons. Both issues can be resolved by enhancing this concept to include a controlling bus to the balloons capable of both controlled avoidance and de-orbit maneuvering. However, the collision avoidance required for something 1 mile wide is currently thought to be extremely difficult and may require concept refinement prior to any attempt at implementation.

5. The concept of electrically charging debris to cause orbit decay and re-entry[Petro 1992, 185]: This exteremely speculative concept theorizes that once a debris object is charged its interaction with the Earth's magnetic field will cause orbital decay to occur more rapidly. Much more research is needed to refine this concept before even basic feasibility predictions can be made.

Supply/Demand: Today there is no supply or demand for this service. The removal of objects from orbit no matter what concept is implemented is not currently supported by industry due to the costs of developing such a service. Although according to a interagency National Security Council report,

> "...left unchecked, the growth of debris could substantially threaten the safe and reliable operations of manned and unmanned spacecraft in the next century" [Lee 1992, 211]

Framework: In the event that this service is eventually deemed necessary or desirable by the space community, which appears to be inevitable, several political, legal, and economic questions will need to be answered. These questions begin with simply 'Who owns and is responsible for debris?'. Thus far the position of the space community has been that the nation of origin owns and is responsible for the debris forever as defined in the 'The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies' [NSTCC 1995]. However, with this definition of ownership and responsibility nations are vulnerable to tort-type claims for damage caused by their debris and to handle debris removal nationally unless it is permitted for another nation or global organization to remove debris owned by someone else. If the answer to the last question is that it is permitted to remove debris that you do not own then ‘Who pays for the removal service?’. This final question of payment may lead the space community to re-define space object ownership limits and possibly establish an internationally sponsored fund. This fund would get contributions from all space operating entities or debris owners which would pay for the performance of removal services[Eichler 1992, 203].

Activity 3: Spacecraft Refurbishment

Product/Service: Spacecraft refurbishment is the service of collecting and repairing or upgrading spacecraft systems and returning the spacecraft to an operational status. To perform such a service Space debris/spacecraft removal is the service of collecting and removing debris or spacecraft that has no means of removing itself from usable orbits or in the best case from space. To provide such a service the provider (NASA or classical space industry contractors) would have to provide a retrieval/boost device, a platform to do repairs & receive parts, and repair technicians (robot or human).

Suppliers: This may seem theoretical but NASA has already begun servicing spacecraft using the shuttle as the retrieval/boost device and servicing platform with the astronauts as the technicians. One notable example of such servicing accomplishments by the NASA is the servicing work that has been provided for the Hubble Space Telescope (HST). Development of servicing systems with more range and possibly less expensive than the space shuttle are being researched. Specifically, Thiokol is looking at designing a high-impulse electric propulsion system as a possible retrieval/boost device [AIAA 1992, 24] which may have more range and allow the servicing of GEO satellites. In addition, the Canadian Space Agency is currently working on a Mobile Servicing System which would provide robot servicing capability for Space Station Freedom (Cost Estimate $170Million Canadian) [CSA 1997] and the technology developed through this effort may make servicing less expensive due to eliminating the human-factor. Robot servicing technology is also being developed by European Space Agency (ESA) and their project The Experimental Servicing Satellite (ESS) is planning a three-month demonstration flight of their system[Settelmeyer 1997].

Supply/Demand: However, until the cost of servicing operations (estimated @ $150Mil + launch + equipment for one HST service) are significantly reduced by technology advances the demand will be limited to government/ NASA and the supply will be limited to that generated by government (national or international) or NASA contracts. Therefore the supply and demand and demand for this service are inelastic changing very little with a small change in price.

Future of Service: The future of this type of service could be bright if technology can be found to make equipment supply and deployment of a servicing platform which both depend on the launch services of the transportation sector more economical. Advances in robotics will also reduce operating costs of servicing since a human team does not need to be support thereby eliminating this services dependence on the manned flight sector. However until that point of cost reduction (i.e., When commercial satellite industries can repair or upgrade a satellite more cheaply than the can build and deploy a new one.) growth of this service will remain low.

Activity 4: Space Material Recycling

Product/Service: Space material recycling is re-use of materials used in space operations. Specifically, if space equipment and collected debris can be returned to Earth safely the equipment could be re-used or the materials that comprise it could be recycled along with the debris. A service of this kind would be a spin-off of the removal service described above using its retrieval systems and providing containment devices for material that could be safely brought down to Earth by the shuttle or some new transportation system. Currently, only those rocket parts such as the shuttle's boosters that fall to the sea are recovered and recycled. If this service became a reality in the future it could be another possible way of funding the costs of removing debris from space.

Framework: Since this service too would be removing objects from it would have to deal with the same political, legal, and economic questions that the removal service did as discussed earlier. However, the revenue generated by recycling any materials collected in space would need to be that of the recycler not the generator of the debris/material for this service to be plausible.

Supply/Demand Outlook: Since this is still a theoretical service it has not established any demand or supply yet. However, as debris and on-orbit spacecraft obsolescence grows the need for the removal service will become an eventuality and this service would grow as a result of that.

OUTLOOK FOR THE FUTURE OF THE SPEACEKEEPING AN SERVICING SECTOR

The outlook for this sector in the future is good so long as the space community fully adapts to the intent of the policies it has today. Intersector cooperation in conjunction with an active debris elimination plan will serve to provide a viable revenue making space environment for the future. Necessity is the driver for technology and in the case of spacekeeping the necessity point may be upon us all too soon and the concepts presented here for the services of this sector could become a reality and possibly revenue generating (servicing & recycling) opportunities.

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