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ECOSYSTEM FOR NEAR-EARTH SPACE CONTROL: METHODS AND SYSTEMS FOR PERMANENT DEBRIS REMOVAL PLUS ENHANCED NATIONAL SECURITY CAPABILITIES

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ABSTRACT

The discovery of a cost-effective and viable approach to the removal of dangerous low-Earth-orbiting (LEO) debris leads to several new and related concepts for significantly and permanently improving and protecting the near-Earth space environment, enhancing space situational awareness capabilities, protecting commercial and government constellations and increasing the resiliency of space-based national security assets. This is a fundamental introduction to what may become a new and future space program paradigm. The proposed methods and systems are novel and are based on a fresh look at the challenge of wholesale removal of the most threatening near-Earth orbiting debris objects. Most previously suggested solutions require the use of extremely expensive and complex space systems in order to accomplish the removal of single debris objects. In fact, the implied complexity and expense of such approaches have prohibited actual debris removal missions. Early estimates indicate that the wholesale-removal approach proposed here will cost only a small fraction of other possible options for cleaning up low-Earth orbit and will sustain the near-Earth space environment and enhance space-based national security operations.

ACRONYMS

DCU = Debris Collection Unit
DIP = Debris Impact Pad
LDEF = Long Duration Exposure Facility
LEO = Low Earth Orbit
LTC = Launchspace Technologies Corporation
OSRF = Orbital Servicing and Remanufacturing Facility
SSA = Space Situational Awareness
SUT = Servicing Unit/Tender

INTRODUCTION

Launchspace Technologies Corporation (LTC) is pursuing the development and operation of a completely integrated solution to excessive orbital debris in low-Earth orbits (LEOs) as a first step toward creating a comprehensive ecosystem for near-Earth space-environmental control.(1) Debris congestion in these orbits is approaching a critical level with increasing threats to operational satellites and constellations. A reduction in the debris population will become mandatory in order to maintain access to these orbits.(2) Any acceptable solution will have to include permanent control of debris levels for long-term on-orbit safety and continued access to space.

To be clear, the safety of operating satellites has been decreasing over the past few decades and it has now reached a serious level for satellite and constellation operators. Additionally, an increase in LEO usage will occur with the addition of large numbers of cubesats and thousands of broadband satellites.(3) The potential result is that, if nothing is done to remove debris, operating satellites will, at some point, experience catastrophic encounters with debris objects. This could mean the possible total loss of satellite services provided by LEO constellations and individual satellites. In fact, it is possible that all civil, commercial and national security space applications will be lost for at least several decades.(4) Such a situation is clearly unacceptable. An innovative solution offered by LTC may permanently resolve this issue. The evolution of a commercial debris removal system will offer near-term operations and platforms in support of desired government applications.

BACKGROUND

Objects that are in orbit around the earth as the result of space initiatives that no longer serve any function are called orbital debris. Examples of such debris include expired spacecraft, upper stages of launch vehicles, debris released during spacecraft separation from its launch vehicle or during mission operations, debris created as a result of spacecraft and upper stage explosions or collisions, solid rocket motor effluents and paint flecks. Most of the orbital debris is concentrated in low-Earth orbits. The United States Space Surveillance Network operated by the Air Force estimates that there are more than 500,000 pieces of debris larger than 1 cm orbiting Earth today, including well over 20,000 pieces larger than 10 centimeters that are actively tracked. This ignores the majority of the estimated one-hundred-trillion (10^{14}) untracked smaller bits that are in the LEO region.

Exhibit 1 offers a visual summary of the LEO debris situation as of 1997. Debris objects range in size from microscopic particles to several meters, with the largest pieces (5 cm and larger) being tracked. The total number of tracked objects has been estimated at roughly 30,000. Debris of sizes between 1 mm and 5 cm have been identified as being the most damaging to operational satellites, because they are much more numerous than large trackable objects but are too large to shield satellites against serious damage. The smallest objects (less than 1 mm in size) can be mitigated with spacecraft shielding, but this debris has the potential to eventually clog the LEO zone. Damaging debris objects in the 1 mm to 5 cm size range have an estimated population of roughly one-hundred-million (10^8).

Historical data indicate that even though there are roughly 30,000 LEO objects of size greater than 5 cm that can be tracked, they represent a minimal threat to active satellites and constellations because their numbers are relatively small when compared to the large volume in LEO space. Thus, an acceptable solution to the collision threat to operating satellites seems to be the reduction of a fraction of the 1-mm to 5-cm objects. It should be noted that there may be a requirement for an occasional removal of a particularly threatening large object. However, in the first half-century of space flight, there has been only one known collision between two satellites and only a handful of other large debris events. Therefore, the method presented here focuses on removal of the most dangerous debris population, debris objects that cannot be tracked, i.e., objects less than 5 cm in size, of which there are an estimated 10^{14} items.

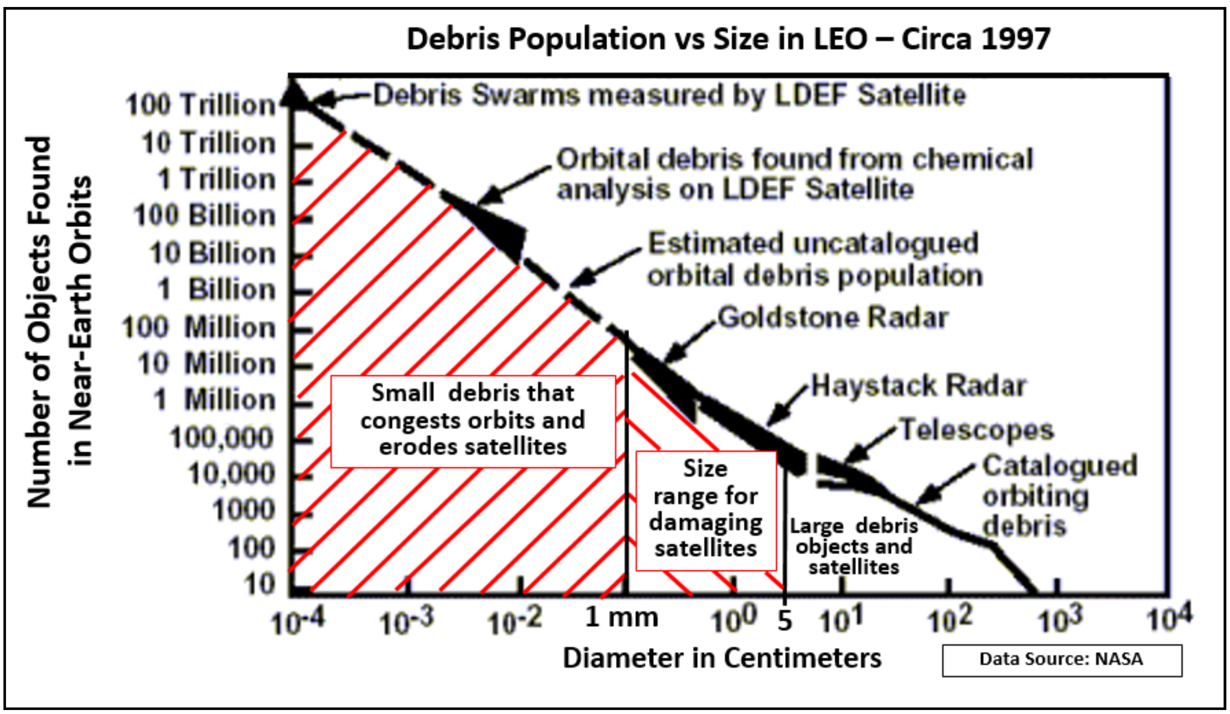

Exhibit 1. A Visual Summary of the LEO Debris Situation as of 1997

Since it is the presence of the smaller debris pieces, especially in the 1-mm to 5-cm size range, that results in most of the serious debris damage to satellites, by simply continuously removing a portion of the small debris population, flight safety and free access to space can be permanently maintained. Thus, on-orbit operations are intended to maintain the removal of sufficient numbers of these smaller objects to achieve permanent stability and safety.

In summary, large debris objects of at least 5 cm in size are not generally hazardous to operating satellites and are not a primary target of this approach because the volume of the LEO space is very large and the average space between large objects is expansive. However, if no action is taken and the number of small debris objects continues to increase, the LEO population of these objects will eventually clog near-earth space while those items that are at least 5 cm in size will continue to be of no statistical consequence. Thus, at some time in the future the congestion will overwhelm all operating spacecraft in and transiting LEO. At that point a state of "gridlock" will exist, i.e., the Kessler Syndrome* will have been realized.

Even though the space debris threat represents a growing international crisis, space agencies have taken almost no action to remove debris and have only limited capabilities in debris sensing and tracking for LEO objects larger than 5 cm. Trajectory projections based on collected tracking data are often supplied to satellite owners and operators. Those few operators that have maneuverable satellites may try to carry out collision-avoidance maneuvers based on projections derived from the debris tracking data. However, such maneuvers are rarely tried because the time to react is usually short and, often, the accuracy of collision predictions is insufficient to warrant an expensive and complicated change in a satellite's orbit.

Since no debris-removal flight programs have been funded, satellite operators with assets in high-density debris zones have no assurance of safety from collisions. However, over the past several years there have been numerous reports of small debris encounters but only one reported collision between an operational satellite and an expired satellite, i.e., the 2009 Iridium-Kosmos incident.(5) Nevertheless, based on post-flight examination of satellites and computer modeling, the frequency of collisions is trending upward, especially in the 600 km to 1,200 km altitude region of near-Earth space.

While the addition of debris shielding on operating satellites may be partially effective, it is simply a matter of time before the collision frequency and level of damage are intolerable. The prevention of future debris creation has been suggested, but the debris density has already passed the point where its increase due to ongoing collisions has resulted in an unstable situation and the debris population will continue to increase regardless of the number of future launches.(6) Thus, some amount of ongoing debris removal will be necessary in order to maintain at least a minimum acceptable level of safety in orbit. A solution to this growing threat of catastrophic destruction of all satellite assets in the high-density debris zone is becoming an international priority. Clearly, a permanent solution will be necessary in order to maintain access to space and safe operations.

Although many proposed solutions recognize the significant adverse effects of debris colliding with active spacecraft, they do not offer an effective and affordable solution for reducing the population of threatening debris objects. Furthermore, most previously suggested devices require complex maneuvering and excessive use of propellant. LTC's new technology does not.

FUNDAMENTAL OBSERVATIONS

There are several physical realities concerning orbital dynamics that constrain debris removal options. Here are a few of the most important observations:(7)

- LEO debris objects are moving in circular, or near-circular orbits at speeds in excess of 7.25 km/sec. These objects are all moving independently in different directions. Thus, the maximum relative speed at which collisions can take place is approximately 14.5 km/sec. An estimated average closing speed between objects is about 10 km/sec.
- All orbits about the Earth are planar, i.e., in planes that contain the center of the Earth. Thus, all objects that travel in highly inclined orbits tend to intensify the density of objects as they fly over the polar regions of the Earth. For this reason it is suspected that a higher frequency of collisions between debris and spacecraft and among debris objects themselves, occurs near the north- and south-polar regions. A corollary to this fact is: The region of least debris object density is the equatorial zone.
- LEO debris of most concern to satellite operators resides in the altitude range from 600 km to 1,200 km and in orbits that are inclined at least 30 degrees to the equator. More specifically, there are several narrow altitude bands where the debris density is higher than in other bands.
- While the density of the debris field is lowest near the equator, the laws of orbital mechanics require that every object in orbit must cross the equator twice per circuit around the Earth. In other words, every object in orbit between 600 km and 1,200 km crosses the equator every hour. Another way to state this is: All one-hundred-trillion objects (10^{14}) in LEO cross the equator at least once per hour.

* The Kessler Syndrome, proposed by the NASA scientist Donald J. Kessler in 1978, is a scenario in which the density of objects in low Earth orbit (LEO) is high enough that collisions between objects could cause a cascade, each collision generating space debris that increases the likelihood of further collisions.

NEW APPROACH TO STABILIZING THE LEO DEBRIS FIELD

To reiterate, there are roughly one-hundred-million (10^8) debris objects larger than 1 mm in size that can seriously damage a spacecraft in LEO and roughly 10^{14} objects that can do at least minor damage. Every one of these crosses the equator every 45 to 55 minutes. If a spacecraft designed to intercept debris were stationed in an equatorial orbit of altitude between 600 km and 1,200 km, such a spacecraft would have 10^{14} opportunities to capture or deflect debris objects every hour. Therefore, a constellation of such spacecraft, all stationed in equatorial orbits, could eliminate thousands of debris items every day without targeting any specific object.[†]

A notional debris-collection space system might be made up of two major systems: a Debris Collection Unit (DCU) and the Servicing Unit/Tender (SUT). A DCU could contain a replaceable Debris Impact Pad (DIP) designed to safely absorb the impact of small debris of sizes up to 5 cm. Objects that encounter the pad will experience one of three scenarios:

1. Impact causes limited energy loss and some change in orbital direction. The loss of energy will result in exposure to increased atmospheric drag and to eventual reentry.
2. Impact causes significant energy loss resulting in orbital decay and reentry.
3. Impact results in objects being absorbed by the DIP.

In order to succeed, each DIP must be placed on a path that will result in debris encounters as debris pieces cross the equator.

It is important to note that a primary function of the guidance systems on SUTs and DCUs is to avoid contact with all tracked LEO objects, including operating satellites. Thus, DCUs would logically be placed in equatorial orbits synchronized to passively encounter small debris items only. Since the most dangerous debris is that which cannot be tracked, this approach would allow the creation of an equilibrium environment in which enough debris could be continuously removed in order to maintain an acceptable and safe level for satellite operators in LEO.

According to international treaties, no one country is allowed to dock with a spacecraft owned by another country without permission. However, none of the captured debris objects would be identifiable and the ownership of each item would remain unknown. This situation should avoid substantive complaints from other spacefaring nations.

Subsequent to a series of impact events, each DCU could be reattached to its SUT and maneuvered to intercept another series of objects or towed to an Orbital Servicing and Remanufacturing Facility (OSRF). Repositioning maneuvers could be repeated until the DCU requires replacement of its DIP, which could be accomplished by either de-orbiting it into a near-equatorial ocean or refurbishing it at the OSRF. Although reentry of a DIP would be possible, it should be more desirable to remanufacture or repurpose these devices for other equatorial applications. When a DIP would be ready for refurbishment a SUT could maneuver the DCU to the OSRF where the DIP would be removed and replaced with a fresh pad. The OSRF might eventually include a complete in-orbit manufacturing capability where old DIPs can be reprocessed and remanufactured either for use in a new DIP or for some other useful product.

One important advantage of employing equatorial orbits is that SUTs could easily maneuver between DCUs for the purpose of reshaping orbits, servicing, making repairs and refueling propellant tanks. A single SUT could service several DCUs, thanks to the ease with which SUTs could maneuver in a single orbital plane.

During debris encounter activities, impact events may result in attitude disturbances that could cause slight reorientation and limited attitude motion of the DCU. However, on board propulsion and attitude control systems will maintain stability and orientation of the unit.

The debris elimination process can be accelerated through the use of multiple DCUs. In fact, multiple units in equatorial orbits can increase the rate of removal dramatically. All DCU missions could be designed and optimized such that the frequency of debris removal events would be maximized. An important and novel aspect of this approach is that resident DCUs within the equatorial plane need be maneuvered in only two dimensions (in plane) such as to be purposely placed in conflict with undesirable orbiting objects. Thus, maneuvers would require minimal use of onboard propellants.

All planned impact events could be coordinated through an optimization process that assures high frequency debris object removal. Stabilization of LEO can be achieved by removing a fraction of the objects smaller than 5 cm. Although that fraction is not yet known, we do understand that rolling back the debris population to that of a time

[†] Patent approved by USPTO.

when debris was not sufficiently dense to cause concern would be the target level in order to ensure safety for constellations.

Once established, a DCU constellation in the equatorial plane should open the possibility of making these spacecraft multi-functional, multi-mission satellites that can detect, track and process information related to orbiting objects. Such measurements may be used to increase the accuracy of object trajectory models that currently suffer from inaccuracies. Upon achievement of improved accuracy, DCUs may become even more efficient in the debris removal process. Since all Earth-orbiting objects must cross through the equatorial plane twice per orbit circuit, the placement of detectors and tracking devices on DCUs may offer significant advantages to the accuracy of tracking techniques, increased orbital surveillance operations, assistance with space traffic management and other yet-to-be identified innovations.

PRELIMINARY REQUIREMENTS

In order to make an early estimate of system requirements and costs several assumptions are necessary. It is initially assumed that all removal operations will be in an equatorial band between 600 km and 1,200 km altitude. In reality, it is likely that the focus of collection activities will be in several very narrow bands that correspond to the densest population layers of debris. Even though the two-dimensional area of the 600 km to 1,200 km equatorial band represents an area of 27.4×10^6 km^2, the actual area of interest for debris interception may be much smaller. In fact, an accurate value of area will require the development of a sophisticated stochastic model of the small debris field based on various sources of existing data on in-orbit measurements of debris events. For example, Exhibit 1 offers a 1997 overall population model based on measurements and interpolation where there were data gaps.

Exhibit 2 offers insight into the optimization process for debris cleanup.[3] This depicts the altitudes and inclinations of active LEO satellites. Clearly, there are altitude bands that contain large numbers of satellites. Since maintaining safety for these spacecraft is of primary interest it is likely that debris in these bands would be of most concern and would be candidates for removal.

Exhibit 3 illustrates the altitude distribution of LEO debris objects that mirrors the active satellite population.[3] Clearly, DCUs should be deployed near these altitudes at and above 600 km in order to capture the small debris associated with the clustering shown in Exhibit 2. Note that even though there is a populous debris field below 600 km, these objects will decay naturally within 25 years. Exhibit 2 suggests that a primary cleanup focus zone should be in the 600 km to 800 km altitude range. Note that DCU orbits may be elliptical with perigees between 600 km and 800 km, but with apogees ranging up to and beyond 1,200 km. Specific orbit shapes will be determined by a combination of the location of both high-density debris fields and large objects, including satellites.

If only the roughly 30,000 largest debris objects were removed, most of the 10^{14} objects would remain and would continue to grow in numbers, i.e., there would be almost no improvement in safety. This argument is supported by the fact that only one known satellite-satellite collision has occurred since the beginning of the Space Age. Experts predict that another such event is likely to happen within the next few years. However, a specific event of this type cannot be predicted. Thus, such events cannot be avoided unless many large objects are removed at a very high cost. Since the cost of removing several large objects would far exceed the value of a damaged satellite, it seems logical that removing only large objects would be a waste of money when compared to the cost of in-orbit insurance.

One must conclude that while orbital cleanup is necessary to maintain access to space, the cleanup should be focused on the worst threat source, i.e., small debris. Thus, one can argue that the cleanup target should include only objects in the size range starting at 1 mm and going up to a size that represents the largest debris above which an economical argument cannot be made. Based on the above discussion, the largest roughly 30,000 objects can be ignored. This leaves the upper limit on debris removal size at about 5 cm.

Referring to Exhibit 1, there are roughly fifty-million (50×10^6) debris objects of size ranging from 1 mm to 5 cm that are considered to be a primary source of damage to active satellites. However, there are two debris removal objectives: safety for active satellites and avoidance of the Kessler Syndrome. To achieve both, a fraction of all debris objects of sizes up to 5 cm must be removed on a continual and permanent basis. Thus, the removal system must target a portion of more than one-hundred-trillion objects. Since the debris removal operations will not discriminate the debris items that are less than 5 cm in size, both debris problems will be resolved simultaneously during collection activities.

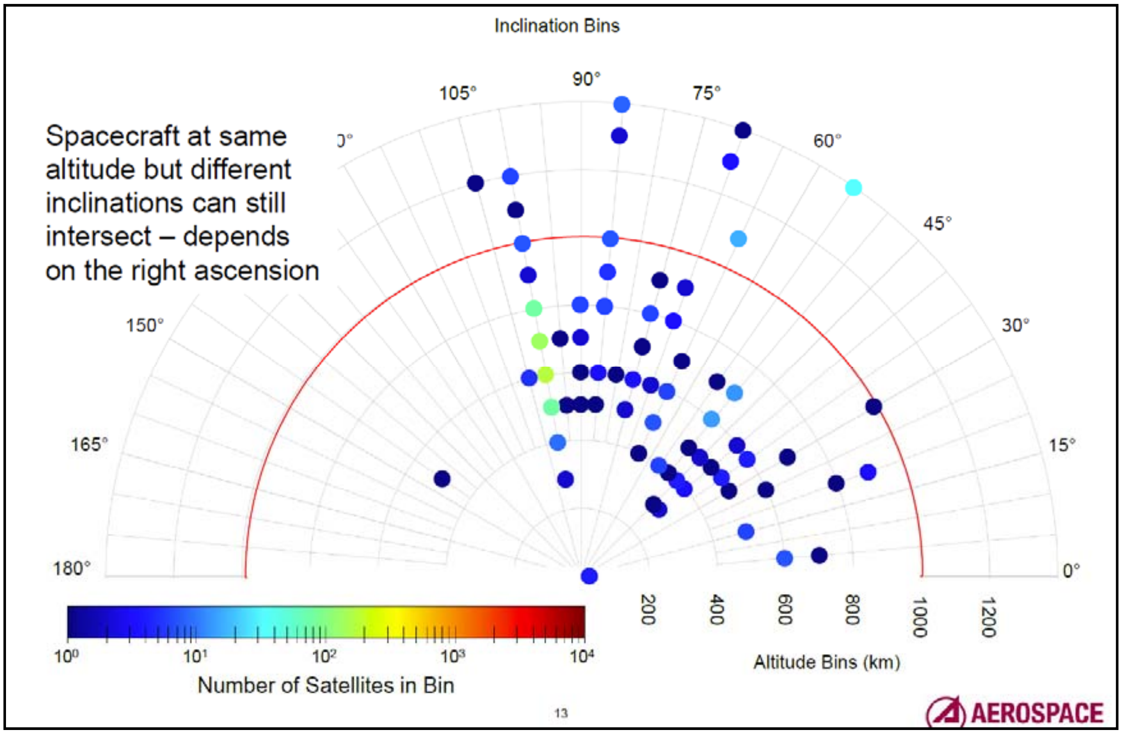

Exhibit 2. Display of Current Active Satellites Separated by Inclination and Altitude

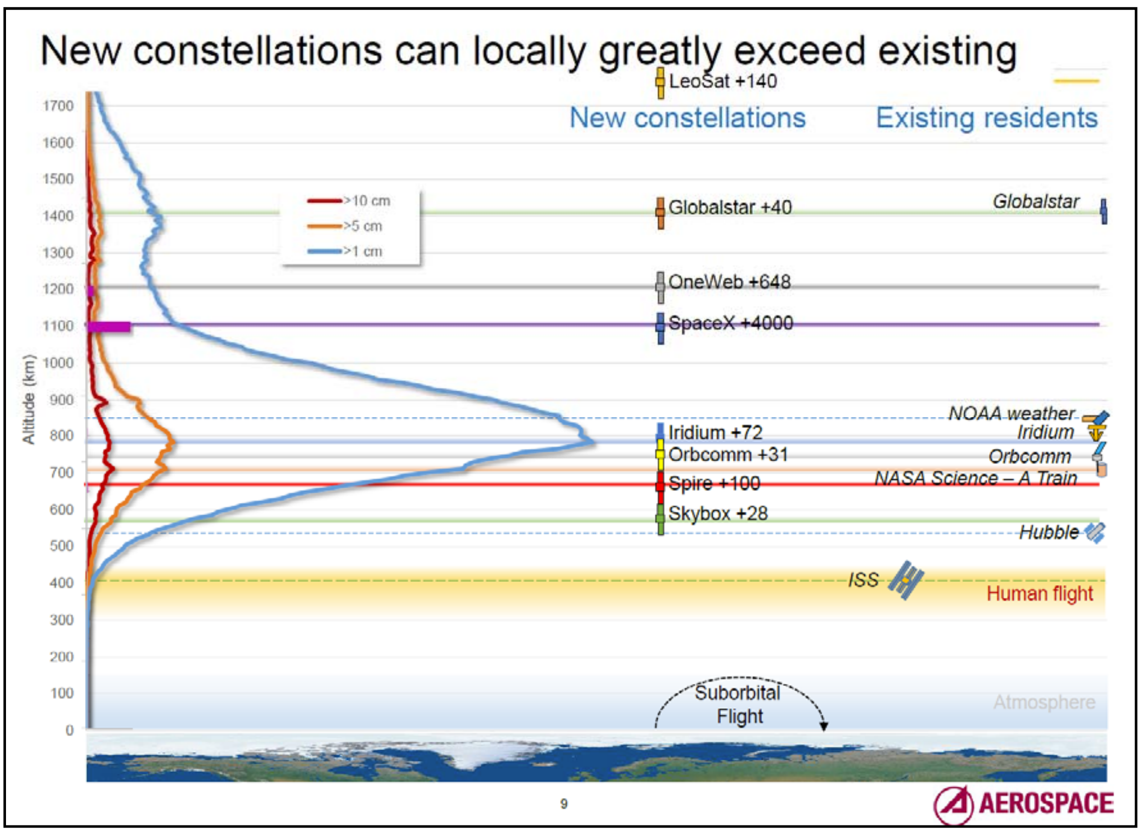

Exhibit 3. Display of Current LEO Debris Distribution as a Function of Altitude

CONCEPT OF OPERATION (CONOPS)

The basic concept of operation is quite simple. A constellation of DCUs is deployed in equatorial orbits that are synchronized and shaped to optimize the rate of small debris cleanup. It is important to note that as long as the units are at altitudes between 600 km and 1,200 km they will encounter and collect debris. There are two conditions under which they will operate. First, the DCUs are not allowed to encounter any object that is large enough to be tracked. Second, DCU orbits are shaped to encounter debris from specific altitudes and planes where the debris objects are most populous or pose serious threats to constellations. Thus, even though the altitude range of 600 km to 1,200 km contains the most debris objects, it is not necessary to deploy the DCUs evenly across this range.

At the point of Initial Operational Capability (IOC), only a few DCUs will be deployed. An OSRF may be added later. Ground facilities will be sufficient to handle all operational requirements at each stage of development. Expendable launch systems may be used until and if reusables become available.

Once a DCU is inserted into orbit, a SUT can be used to maneuver and reshape the orbit such that the DCU, after release, can passively intercept small debris objects while avoiding large objects. Each DCU is maneuvered into a specifically designed and optimized equatorial orbit that will target sensitive debris zones in order to maximize safety for satellites flying in such zones. Periodically, a SUT may retrieve the DCU and slightly change its orbit in order to maintain large object avoidance while optimally collecting small debris pieces. Exhibit 4 depicts the orbital geometry for a DCU as it travels in slightly elliptical equatorial orbits.

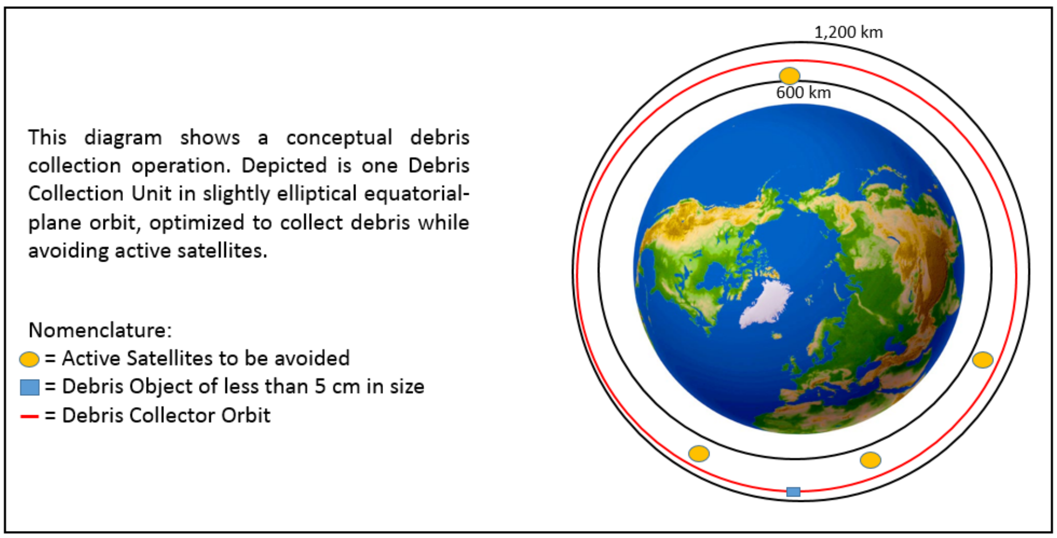

Exhibit 4. Depiction of the Orbital Geometry for Collecting Small Debris

EVOLUTION OF BUSINESS APPLICATIONS

In addition to debris removal, the proposed methods and systems may offer unique advantages for enhancing space-based national security capabilities. For example, satellites placed in low equatorial orbits offer ideal vantage points for detecting and tracking items in connection to Space Situational Awareness (SSA) requirements. In fact, initial proof of concept satellites in the debris removal program will be equipped with sensors for the detection of small debris objects.[8] The data collected are needed for modeling small-debris, high-population zones. These satellites can also provide data on a continuous basis from a location that offers a complete view of all objects in LEO. Debris removal and control services will ultimately be offered to those government agencies that oversee Space Traffic Management activities, e.g., FAA and NASA.

A commercial business income model will be based on providing protection to commercial constellations by selectively removing small debris that present the highest threat to satellites in the constellation. Service contracts with satellite operators may be sought on an annual basis. On the other hand, commercial satellite operators who elect to continue without debris insurance may not be properly protected.

CONCLUSIONS

The growing orbital debris problem is well known to satellite operators and is of concern throughout the space community. However, the solution to debris cleanup is thought to be extremely expensive, highly complex and fraught with legal and political issues. Furthermore, there is, as yet, not a sufficiently significant benefit related to the cost of remediation. At some point in the not-too-distant future, debris issues will have to be addressed or access to space may be greatly diminished.

If this problem is not addressed in a timely fashion, access to space could be denied for many generations. Furthermore, any clean up after near-Earth space is clogged will be much more costly and could set back the industrial world's economies and national security several decades.

While the costly individual removal of large debris objects may delay the worst scenario, this will not resolve the situation.[(6)] Only a permanent wholesale collection approach will assure future safety and access to space.

Once such a system is approved it will offer numerous other applications for civil, commercial and security communities.

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