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Geosynchronous Large Debris Reorbiter: Challenges and Prospects

Hanspeter Schaub[1] and Daniel F. Moorer, Jr.[2]

Abstract

An elegant solution is proposed to an old problem of how to remove expired or malfunctioning satellites from the geosynchronous belt. Previous "space-tug" concepts describe a scenario where one craft (the tug) docks with another (debris) and then boosts that object to a super-synchronous orbit. The most challenging aspect of these concepts is the very complex proximity operations to an aging, possibly rotating and, probably, non-cooperative satellite. Instead, the proposed method uses an elegant blend of electrostatic charge control and low-thrust propulsion to avoid any contact requirement. The Geosynchronous Large Debris Reorbiter (GLiDeR) uses active charge emission to raise its own absolute potential to 10's of kilovolts and, in addition, directs a stream of charged particles at the debris to increase its absolute potential. In a puller configuration the opposite polarity of the debris creates an attractive force between the GLiDeR and the debris. Pusher configurations are feasible as well. Next, fuel-efficient micro-thrusters are employed to gently move the reorbiter relative to the debris, and then accelerate the debris out of its geosynchronous slot and deposit it in a disposal orbit. Preliminary analysis shows that a 1000 kg debris object can be re-orbited over two-four months. During the reorbit phase the separation distance is held nominally fixed without physical contact, even if the debris is tumbling, by actively controlling the charge transfer between the reorbiter and the debris. Numerical simulations are presented illustrating the expected performance, taking into account also the solar radiation pressure.

Introduction

The Geosynchronous Earth Orbit (GEO) or, generally, the geosynchronous belt, is becoming very crowded with communication and science satellites. If a satellite becomes inoperable or reaches its end-of-life without exiting the geostationary belt, then this satellite continues to occupy a valuable geostationary "slot." Even worse, without further orbit control, these satellites may drift because of lunar and solar radiation disturbances, allowing them to wander the geostationary belt and,

[1]Associate Professor, H. Joseph Smead Fellow, Aerospace Engineering Sciences Department, University of Colorado, AAS Member.
[2]President and CEO, Wacari Group LLC, Boulder 80302.

possibly, threaten other satellites in geostationary orbit. As of 2006, of the over 1100 geostationary objects being tracked, less than 400 were still actively having their position controlled [1].

Initially, satellite operators did not deem space debris to be a significant issue [2]. However, after the recent Iridium/Cosmos collision [3] in early 2009, space debris has become a matter of national concern. As discussed by Kessler in reference [4], once a critical debris density has been reached, the debris population will continue to increase because of collisions even without the injection of additional debris. Although this scenario does not yet exist for geostationary orbit regime, it is critical to begin to remove debris objects from this valuable space real estate.

Current practice requires a satellite to retain sufficient end-of-life fuel to exit the geostationary belt to a super-synchronous orbit [5]. In these orbits, the periapses of the disposed satellite cannot enter the geostationary orbit altitude, even with solar radiation pressure and lunar gravitational perturbations. However, given that this practice is a relatively recent requirement, there continues to be a need to remove older satellites, malfunctioning satellites, and space debris from geostationary orbit. Previous concepts for removing expired satellites are particularly challenging considering that:

1. Close proximity operation (including contact) with the defunct non-cooperative satellite is difficult because of the defunct vehicle's uncontrolled attitude (possibly rotating).
2. Grappling the defunct vehicle poses significant danger to the space-tug because of the uncertain structural integrity of the debris object, and its rotations may cause a damaging collision.
3. When physically pulling the debris out of its orbit, the vehicle is only pulled at the contact point of the craft raising the possibility of the defunct vehicle breaking apart.
4. Significant amounts of fuel can be consumed to perform the initial approach, docking, and orbit raising maneuvers, limiting the space-tug life span and usefulness.

Reference [6] provides a good overview of early space-tug concepts. Here a spacecraft is held in a parking orbit until it is required to interface with a malfunctioning or defunct satellite and re-orbit it to a new desired trajectory. The 1980s and 1990s saw several space-tug concepts being proposed such as a lunar payload return space-tug using aero-braking in Earth's atmosphere[3]. Reference [7] discusses space-tug concepts to carry spacecraft to higher orbits than what is feasible with the Space Shuttle performance envelope. Reference [8] studies reusable Low Earth Orbit (LEO) space-tug concepts. With all of these, the relatively large changes in velocity required here to reposition a satellite, in particular if orbit plane changes are required, lead to concepts based on advanced propulsion concepts such as nuclear propulsion or arcjet engines.

Current space-tug concepts capable of re-orbiting debris and defunct satellites include a range of technologies [9] such as the use of gossamer spacecraft [10], electrodynamic tether spacecraft [11], as well as satellites equipped with robotic manipulators. For the geostationary regime the electrodynamic tether solutions are not feasible because of the low densities of electrons in the local space plasma. In

[3]http://www.astronautix.com/craft/spacetug.htm.

addition, all these space-tug concepts require a mechanical interface with the payload to re-orbit it. For example, reference [10] envisions netting devices. The benefit of a net is that no precise docking is required. However, predicting the low-tension dynamics of a net is a challenging task. Further, given that most defunct geostationary satellites may be rotating, multi-ton objects, care must be taken such that the fragile spacecraft components such as solar panels or communication antennas are not torn off, creating addition debris in the process. Large angular momentum makes capturing such objects with lightweight nets very challenging.

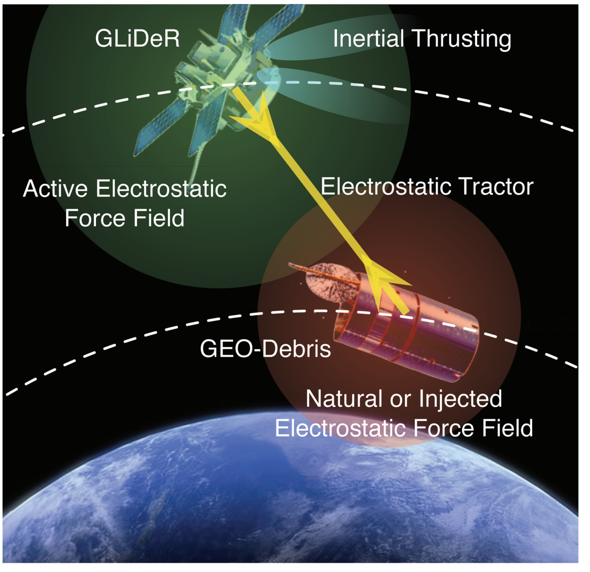
Several current research projects are investigating the use of robotic manipulators to grabble and reorbit debris. Such systems include the European Robotic Geostationary Orbit Restorer (ROGER) [12], the DARPA/NRL Front-end Robotics Enabling Near-term Demonstration (FREND) project [13], as well as the technologies developed for the NASA Hubble telescope robotic servicing mission [14]. As stated above, assuming a non-cooperative spinning debris object, the grappling process can be challenging because of the large angular momentum of the debris. This can lead to increased fuel usage to circumnavigate carefully into position, as well as increased danger of collision and further debris generation.

This paper presents a novel, patent-pending method called the Geosynchronous Large Debris Reorbiter (GLiDeR). Here debris objects can be re-orbited without requiring physical contact between the tug and the debris object. This has significant benefits in reducing the dangers and fuel- expenditure challenges of performing relative navigation to a non-cooperative, large, and spinning debris object right up to the point of contact. Instead, the GLiDeR employs electrostatic forces to accelerate the debris, while the tug uses inertial thrusters to gently raise the debris orbit to a super-synchronous geostationary disposal orbit. This paper presents the basic GLiDeR concept for re-orbiting debris object from high Earth orbits. The inertial thrust levels required to raise the debris orbit are limited by the strength of the electrostatic actuation. Numerical performance studies are performed to investigate the effectiveness of using small milli-Newton force levels to dispose large geostationary debris. Of interest are the amount of time required to raise the orbit by 300 kilometers, as well as the ability of the GLiDeR to avoid other geostationary residents. Further, the impact of the Solar Radiation Pressure Force (SRPF) on the GLiDeR performance is investigated through numerical simulations.

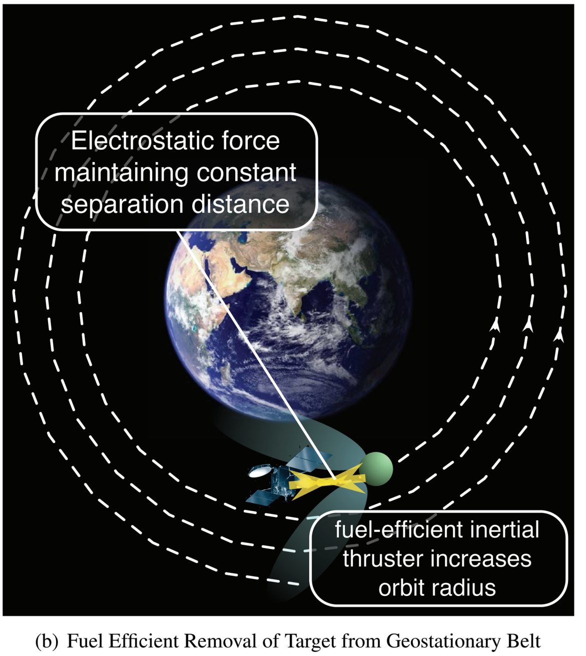
Large Geo Debris Reorbiter Concept Description

A novel and elegant solution to the old problem of removing defunct satellites and debris from the geosynchronous belt is proposed through the GLiDeR concept. Here, electrostatic forces are employed to perform the initial approach where both craft will settle at a fixed separation distance as illustrated in Fig. 1(a). The Coulomb force can nominally be generated using Watt-levels of power, and consumes essentially no propellant [15]. Next, the Coulomb force is used as an *electrostatic virtual tether* to maintain a fixed separation distance while the reorbiter uses fuel efficient electric (ion) propulsion to gently raise the orbit radius as shown in Fig. 1(b). This new concept addresses the large geostationary debris re-orbiting challenges in the following manner:

1. The need for a space-tug to approach the debris up to the point of contact is avoided altogether. Instead, the GLiDeR only needs to maneuver to within a few dozen meters with respect to the debris and engage the charge control. The



(a) Initial Approach to Geostationary Target



(b) Fuel Efficient Removal of Target from Geostationary Belt

FIG. 1. Geosynchronous Large Debris Reorbiter Illustration.

Coulomb force is modulated to stabilize the relative motion and have the craft settle at a desired separation distance. One candidate approach uses an innovative charge control solution which aligns the spacecraft center of masses automatically along the orbit nadir axis [16]. Now the separation distance can be safely decreased to the final value by controlling the electrostatic force [17]. This approach only requires simple separation distance measurements, and consumes single-digit Watt-levels of electrical power while being essentially propellantless.

2. The electrostatic force solution avoids any potential collision of the reorbiter with components of the uncontrolled defunct vehicle by never having to actually make contact with it. Instead, electrostatics generate an Coulomb force from a safe distance.

3. In contrast to tugging the defunct satellite to a higher orbit by pulling at a single contact point of uncertain structural integrity, the electrostatic force will gently accelerate the entire debris object simultaneously. This avoids issues of where to grab the satellite and whether that component is structurally sound.

4. Because electrostatic forces can be generated using essentially no fuel (I_{sp} fuel efficiencies millions of times higher than even electric engines), the GLiDeR concept can perform repeated approaches and orbit raising maneuvers over several years. While the ion engine operation is similar to a charge emission device required for Coulomb thrusting, [18] the resulting force on the spacecraft is generated using the charge transport principle, and not from the momentum exchange of the expelled particles. Over a few tens of meters separation distance, this mechanism requires far fewer charged particles (propellant) to be expelled to generate an electrostatic force that is equivalent to the ion engine thrust. This efficiency will allow a single GLiDeR to remove multiple high Earth orbit debris objects over its lifetime.

The time required to remove debris is less critical than the ability to remove the debris. Because of the fuel-efficient method to lock in a safe separation distance, and then gently raise the orbit radius, a single reorbiter could move 2–4 debris objects per year depending on the debris orbits. A multi-year GLiDeR lifetime is envisioned, making this an economically interesting proposition to clean up valuable GEO slots for new use.

Generating the Electrostatic Tractor Force

Geostationary spacecraft can naturally develop kilo-Volt potentials because of the natural environment. For example, the 1970s spacecraft SCATHA did extensive monitoring of its surface potentials and recorded potentials reaching 10 kilo-Volt [19]. These micro-Newton levels of forces can be large enough to cause 100's of meters of relative orbit errors if the craft are initially flying dozens of meters apart [15, 20]. Geostationary spacecraft are usually designed such that this absolute charge can occur without causing significant differential charging and arcing by ensuring all components are mutually grounded, or covered with a thin conducting layer.

Because a spacecraft has no physical ground connection to the surrounding space plasma environment, it is free to assume an electrostatic potential that is different from that in the plasma. Such a potential difference occurs naturally from the balance of free charge (currents) to and from the vehicle as illustrated in Fig. 2. To maintain a reorbiter *non-equilibrium absolute charge level,* continuous charge emission is required to compensate for the charge influx from the space environment [15]. As stated previously, a non-equilibrium charge level can be maintained using only Watts of electrical power while using essentially no propellant [20, 21]. Missions showing the feasibility of active charge control include INTERBALL-2 [22], Equator-S [23], Geotail [24], and Cluster-II [18, 25]. All of these missions relied on a similar active-charge-control device that utilized a low-power beam of indium ions to neutralize vehicle charge. Total mass of the active charge control system was less than 2 kg and total power consumption was

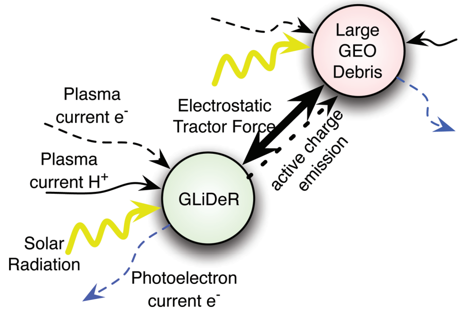


FIG. 2. Balance of space environmental currents interacting with a spacecraft. The spacecraft equilibrium potential is obtained when the net current is zero.

2.4 W. However, active spacecraft charge control has not been used yet to control the relative motion.

The electrostatic potential V about a point charge in a plasma environment is

$$V = k_c \frac{q}{L} e^{-L/\lambda_d} \tag{1}$$

where q_i is the vehicle charge level, L is the separation distance and λ_d is the plasma Debye length [26]. Debye charge shielding causes the electrostatic interaction between two craft to be partially shielded because of the interaction with the local space plasma. However, at GEO the Debye lengths average about 180 meters, and range between 80 and 1000 meters [21, 27], making the electrostatic tether concept feasible at these orbit altitudes. The electrostatic (Coulomb) force magnitude produced between two neighboring spacecraft in a space plasma environment is approximated by

$$|F_C| = |\nabla V \cdot q_2| = k_c \frac{q_1 q_2}{L^2} e^{-\frac{L}{\lambda_d}} \left(1 + \frac{L}{\lambda_d}\right) \tag{2}$$

This approximation to the full electrostatic field solution in equation (1) assumes that the vehicle potential is small compared to the local plasma temperature. For higher potentials this forms a more conservative upper bound on the amount of charge shielding.

To increase the electrostatic force magnitude F_C the reorbiter charge q_1 will be as large as feasible. This can be achieved by designing the tug to have a larger capacity through a larger outer surface, or be able to achieve large potentials. To maximize the re-orbiting performance capability, the GLiDeR design seeks to maximize the charge to mass ratio of the vehicle. Compared to methods which seek to grapple with the debris and need to have strong (thus massive) manipulator arms, the GLiDeR concept ideally would be a light weight vehicle to minimize the launch costs to geostationary altitudes. However, to increase the vehicle capacitance a large outer surface (such as a large conducting sphere like object) helps decrease the required potential for a given charge level.

Concerning the debris absolute charge level, while a natural charge q_2 will accumulate on the debris object, its average value may not be sufficient for effective re-orbiting maneuvers. As shown in equation (2), if q_2 is small, then q_1 must be increased to obtain a desired electrostatic tractor force level. To increase

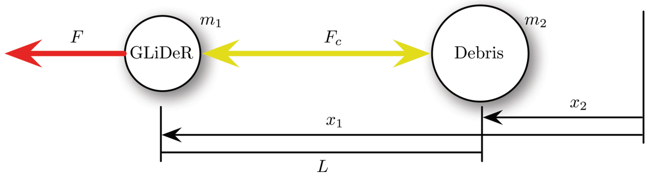


FIG. 3. GLiDeR/Debris Force Diagram Illustration.

the debris charge level and thus the electrostatic attraction, it is possible to direct the charge emission of the reorbiter at the geosynchronous debris object. This causes the debris to charge to an opposite polarity of the reorbiter charge, and thus increase the electrostatic interaction. Because of the relatively low density of plasma at GEO, such a charge transfer beam is expected to remain stable over dozens of meters. Laboratory experiments have illustrated wireless charge transfer to a particle in a plasma environment using an electron beam [28, 29]. The actual amount of charge q_2 imparted on the debris will depend on the debris size and material properties, as well as the local space weather. Thus, even if a debris object is a large and massive object, the increase in size will assist in storing more charge on the debris, and as a result helps produce a stronger electrostatic attraction with the GLiDeR vehicle. Note that with additional tug charge emission it is also possible to create repulsive electrostatic forces. The analysis in this paper does not depend on the tug pulling or pushing, but rather illustrates how certain absolute electrostatic charge levels can result in significant geostationary reorbiting capabilities. The pulling configuration is the simpler method to implement, and is used as a default in examples.

Glider Performance Estimate

Debris Acceleration

To estimate how well the electrostatic tractor can accelerate a space debris object to a new orbit, let us consider the simple one-dimensional force diagram illustrated in Fig. 3. Let F be the total inertial thrust being generated by the GLiDeR vehicle, while F_c is the electrostatic attraction between the two bodies. This setup assumes the tug is operating on the orbit along-track axis relative to the debris. Using a free-body force diagram of each object leads to

$$F - F_c = m_1 a_\theta \tag{3a}$$

$$F_c = m_2 a_\theta \tag{3b}$$

where a_θ is the along-track acceleration. Because of the separation distance being nominally fixed with $\dot{L} = 0$, this is the same acceleration experienced by both bodies. Equation (3b) shows that the orbit along-track acceleration is determined through

$$a_\theta = \frac{F_c}{m_2} \tag{4}$$

Thus, the tangential debris acceleration is proportional to the electrostatic force magnitude, and scales inversely with the debris mass m_2. Note that this acceleration a_θ is independent of the tug mass m_1. Using equations (3a) and (4), the inertial thrust required to keep the tug ahead of the debris by a fixed separation distance L is

$$F = m_1 a_\theta + F_c = \frac{m_1 + m_2}{m_2} F_c > F_c \tag{5}$$

Thus, while the tug mass m_1 influences how strong the inertial force F needs to be to accelerate both the debris and the tug at a fixed separation distance, the tug mass itself does not influence the GLiDeR performance. Only the electrostatic force magnitude F_c and debris mass m_2 determine the resulting GLiDeR/debris along-track acceleration a_θ as shown in equation (4). The inertial thrust F of the GLiDeR would be produced using a fuel-efficient propulsion system such as, for example, electric propulsion systems. The magnitude of F is lower bounded by the desired electrostatic force F_c. For example, for the special case where $m_1 = m_2$ and $F_c = 1$ milli-Newton, then F would need to be two milli-Newtons.

However, while m_1 does not influence a_θ, this mass should still be kept small if possible to reduce the orbit insertion costs to launch GLiDeR into a near geostationary orbit.

Orbit Periapses Raising Capability

To reorbit the debris to a disposal orbit, assume the semimajor axis a (SMA) needs to be increased by a particular amount $\Delta\tilde{a}$. Gauss' variational equation for a is [30, 31]

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{2a^2}{h}\frac{p}{r} a_\theta \tag{6}$$

where h is the orbit angular momentum, p is the semi-latus rectum and r is the current orbit radius. While the debris reorbit is accomplished through an outward spiraling trajectory, we can locally approximate this motion as a circle to develop approximate analytical performance measures. For a nearly-circular orbit with a vanishingly small eccentricity, the momentum is approximated through

$$h = \sqrt{\mu p} = r^2 \dot{f} \approx a^2 n \tag{7}$$

where f is the true anomaly angle, μ is the gravitational constant, and n is the mean orbit rate. Making the small eccentricity assumption $p \approx r$, the SMA differential equation reduces to

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{2a_\theta}{n} \tag{8}$$

Let $P = 2\pi/n$ be the orbit period, then the SMA change per orbit because of a constant along-track acceleration a_θ is approximated through

$$\Delta a \approx \frac{\mathrm{d}a}{\mathrm{d}t} \cdot P = \frac{4\pi}{n^2} a_\theta \tag{9}$$

For a spherical body of radius R, the voltage V and charge q are related through

$$V = k_c \frac{q}{R} \tag{10}$$

where $k_c = 8.99 \times 10^9\ \mathrm{Nm^2C^{-2}}$ is the Coulomb constant. Equation (10) assumes that the Debye charge shielding is negligible for the nominal separation distance considered (nominal λ_d is on the order of 200 meters at geostationary orbits). Assuming GLiDeR has the states R_1 and V_1, while the debris has the states R_2 and V_2, the electrostatic force magnitude is

$$F_c = k_c \frac{q_1 q_2}{L^2} = \frac{1}{k_c} \frac{R_1 R_2 V_1 V_2}{L^2} \tag{11}$$

The along-track acceleration a_θ produced through the interaction with the space-tug is then

$$a_\theta = \frac{F_c}{m_2} = \frac{1}{m_2\, k_c} \frac{R_1\, R_2 V_1 V_2}{L^2} \tag{12}$$

Substituting equation (12) into equation (9) yields an estimate of the SMA change that can be produced over one orbit revolution

$$\Delta a \approx \frac{4\pi}{n^2} \frac{R_1 R_2 V_1 V_2}{k_c\, m_2\, L^2} \tag{13}$$

Note the linear relationship between spherical vehicle radii R_i and voltages V_i and the resulting increase in the orbit altitude. Both quantities relate to the charge q_i stored on a charged object. For reorbiting maneuvers, the effective debris radius R_2 cannot be changed. However, the effective GLiDeR radius R_1 can be designed large enough to provide sufficient electrostatic actuation. However, doubling R_1 will result in double the SMA changing performance.

Further, the SMA change is inversely proportional to the debris mass m_2. This makes intuitive sense in that it is easier to reorbit lighter objects. Lastly, the SMA changes depend on the inverse square of the nominal separation distance. Thus, to optimize the GLiDeR debris removal per year performance, the vehicle capacity should be maximized by increasing the tug outer surface area through a large R_2, the voltages V_i should be increased, as well as the separation distance L be reduced while avoiding collision issues. The later demand on L is balanced through the need to maintain a safe separation distance of a potentially spinning debris object. However, note that reducing L by a factor of two will lead to a four-fold increase in performance. This makes the electrostatic SMA changing performance sensitive to this distance. Reducing L by a factor of two will quadruple the performance.

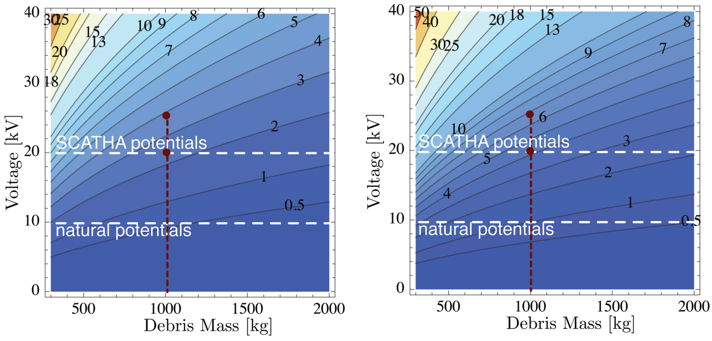
The reorbit time ΔT can be approximated through the fractions of orbits it takes to change the SMA by the desired amount of $\Delta\tilde{a}$.

$$\Delta T \approx \frac{\Delta\tilde{a}}{\Delta a} \cdot P = \frac{n}{2a_\theta} \Delta\tilde{a} \tag{14}$$

Using the along-track acceleration approximation in equation (12) leads to the estimated maneuver time expression

$$\Delta T \approx \frac{n m_2 k_c L^2}{2 R_1 R_2 V_1 V_2} \Delta\tilde{a} \tag{15}$$

Although the electrostatic force F_c is small on the order of milli-Newtons, it is sufficient to reorbit the GEO debris to “disposal” orbits. To illustrate this, consider



(a) Nominal separation distance $L = 20$ meters. (b) Nominal separation distance $L = 15$ meters.

FIG. 4. Expected orbit radius changes after a single orbit for various electrostatic potential levels and debris masses. Assumes equal debris and GLiDeR radius (three meters) and potentials.

the numerical results illustrated in Fig. 4. Here a nominal craft radius of $R = R_1 = R_2 = 3$ meters and equal debris and GLiDeR potentials are assumed. The horizontal axes show the mass of debris object, while the vertical axes sweep across various ion thruster force or electrostatic potential levels. The contours show the change in geostationary orbit radius over a GEO orbit period (approximately 24-hours). As a reference dashed lines are included to illustrate the 10 kV potential level (occurs naturally in shaded orbit regions) and the 20 kV levels (active charge experiments have demonstrated such absolute charge control in SCATHA). Figure 4(a) shows the estimated reorbit performance if a nominal separation distance of $L = 20$ meters is used. For example, to move a 1 metric ton (1000 kg) debris object using only 20 kV potential on both GLiDeR and debris results in a 2.5-kilometer SMA increase per orbit. Because of the quadratic SMA change dependency on the potentials used, a small increase to 25 kV results in a significant performance increase to about four-kilometer SMA change per orbit.

As a comparison, Fig. 4(b) shows the same performance study being performed with a nominal separation distance of $L = 15$ meters. Note that this too will cause increase SMA changes per orbit. At the 1 metric ton mark, a 20 kV potential now results in just over a four-kilometer altitude increase per orbit, while 25 kV results in about seven kilometers per orbit SMA increases.

Studying Fig. 4, consider that the SCATHA mission already demonstrated active charge control up to 18 kV in the 1970s. The hybrid electrostatic space-tug concept will not contain any science sensors, and should be carefully built to be able to retain as much absolute charge as possible. Thus, it is encouraging that even 20 kV potential levels can result in good reorbit performance levels. To raise an orbit altitude by 250 kilometers with the conservative $L = 20$ meters and 25 kV on each object results in a maneuver time of about 62.5 days, or just over two months.

Maneuverability

Geostationary satellites are assigned to nominal ± 1-degree-longitude slots within which they must maintain their position. To raise the orbit radius of a defunct satellite, it is important that the satellite be a safe distance above the geostationary orbit when it is moved outside its ± 1-degree- longitude slot.

Of interest is how a small change in the SMA will cause the drift rate of $\dot{\theta}$ to vary. Going from geostationary altitudes (about 42,000 km) to a disposal orbit which is only 200–300 km higher, the change in SMA will remain small compared to the GEO SMA. This allows us to use small variational approximations to predict how the debris will drift relative to the original GEO slot. To determine how fast the constant along-track acceleration a_θ will cause the debris longitude to shift, we define the true longitude angle $\theta = \omega + f$ and the mean longitude angle $\theta_M = \omega + M$ where ω is the argument of periapses and M is the mean anomaly angle. Gauss' variational equations for ω and M are [30, 31]

$$\frac{d\omega}{dt} = \frac{1}{he}(-p\cos f a_r + (p + r)\sin f a_\theta) - \frac{r\sin\theta\cos i}{h\sin i} a_h \tag{16}$$

$$\frac{dM}{dt} = n + \frac{b}{ahe}((p\cos f - 2re)\, a_r - (p + r)\sin f a_\theta) \tag{17}$$

With the GLiDeR concept the nominal orbit radial acceleration a_r and orbit-normal acceleration a_h are zero. Because the geostationary orbit is essentially circular, the semiminor axis b is equal to a.

The mean longitude rate $\dot{\theta}_M$ is found to be

$$\dot{\theta}_M = \frac{d\omega}{dt} + \frac{dM}{dt} = n = \sqrt{\frac{a^3}{\mu}} \tag{18}$$

Note that the non-zero a_θ acceleration has no direct influence on $\dot{\theta}_M$. For near circular orbits with near-zero eccentricities, note that $\theta \approx \theta_M$. Taking the first variation of this nominal rate expression yields

$$\delta\dot{\theta}_M \approx \delta\dot{\theta} = -\frac{3n}{2}\frac{\delta a}{a} \tag{19}$$

The constant SMA rate $\dot{a}$ because of a constant a_θ acceleration is given in equation (8). The SMA difference thus grows linearly with time t as

$$\delta a\,(t) = \dot{a}t = \frac{2a_\theta}{n} t \tag{20}$$

Substituting equation (20) into equation (19) yields the simple ordinary differential equation

$$\delta\dot{\theta} = -3\frac{a_\theta}{a} t \tag{21}$$

Assuming a zero initial longitude variation $\delta\theta\,(0) = 0$, the desired longitude drift rate is approximated as

$$\delta\theta(t) = -\frac{3}{2}\frac{a_\theta}{a} t^2 \tag{22}$$

Let t^* be the time that the debris has drifted by an angular amount of $-\delta\theta^*$ (i.e., $\delta\theta(t^*) = -\delta\theta^*$). Solving equation (22) for the required drift time yields

$$t^* = \sqrt{\frac{2a\delta\theta^*}{3a_\theta}} \tag{23}$$

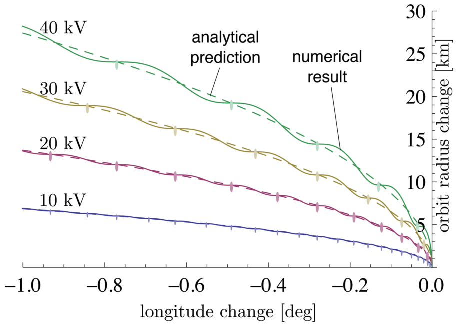


FIG. 5. Orbit radius changes over a one-degree longitude shift to move a 2000 kg debris object. Ticks indicate orbit completions, voltages are per vehicle.

For example, if $\delta\theta^* = 1$ degree, then we can determine how long it will take for the debris to be tugged outside a one-degree slot.

To determine the SMA difference as the debris leaves a slot of size $\delta\theta^*$, substitute equation (23) into (20) to find

$$\delta a\,(\delta\theta^*) = \frac{2}{n}\sqrt{\frac{2aa_\theta\delta\theta^*}{3}} \tag{24}$$

Making the earlier simplifying assumption that debris and tug have the same spherical shape, size, and potential, then we can use the a_θ acceleration in equation (12) to estimate by how much the debris will change its SMA after drifting by $\delta\theta^*$ as

$$\delta a\,(\delta\theta^*) = \frac{2}{nL}\sqrt{\frac{2a\delta\theta^* R_1 R_2 V_1 V_2}{3m_2\,k_c}} \tag{25}$$

To increase the maneuverability of the GLiDeR assuming $V_1 = V_2$, the SMA changes are directly proportional to the potential V, and inversely proportional to the separation distance L.

To get a feel of by how much the SMA changes with respect to the debris longitude change, numerical simulations of the full nonlinear orbital motion are run. Figure 5 illustrates numerical simulation results where the continuous thrust is maintained for several orbits (solid lines), and compares the numerical results to the predicted gross changes in equation (25) (dashed lines). The spacecraft are assumed to maintain a nominal separation distance of $L = 20$ meters, and have a spherical shape with $R = 3$ meters. The debris mass is 2000 kg, representing a worst case situation with a very large geostationary debris object. Even with a small force equivalent to a 10 kV potential, the orbit radius is boosted by almost six kilometers by the time the Debris has been tugged outside its “slot,” a significant safety margin. The tradeoff in using a smaller force is an increased time to change the orbit radius by a desired amount. In this scenario a 20 kV nominal potential would lead to a six-kilometer radius change in only five orbits, versus the 20 orbits required with 10 kV.

Further, the analytical SMA change predictions match the gross motion of the numerical results very well. Thus, if a lighter debris object of 1000 kg is used (two-fold reduction of m_2), then the 10 kV GLiDeR would increase the SMA by about 12 kilometers as it leaves a one degree longitude slot.

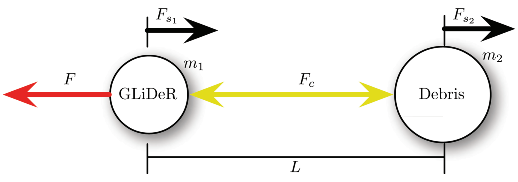


FIG. 6. GLiDeR and Debris Force Illustration with Solar Radiation Pressure.

Solar Radiation Pressure Influence

Solar radiation pressure is a significant perturbation to geostationary objects. Even though it is a small force, on the order of micro-Newtons, it can cause circular orbits to become eccentric over time [32].

Let us investigate how the solar radiation pressure influences the ability of the GLiDeR to reorbit a geostationary debris object. Figure 6 illustrate a simple worst case setup where the solar pressure force is acting against the Coulomb force.

The solar disturbance force magnitude F_{s_i} is given by

$$F_{s_i} = A_i \frac{\phi}{c} \tag{26}$$

where $A_i = \pi R_i^2$ is the projected surface area in the incoming Sun light direction, and c is the speed of light in a vacuum. The constant $\phi = 1372.5398$ Watts/m^2 is the solar flux constant at 1 AU distance. For example, for an object with a 3 meter radius, the solar radiation force is about 0.168 milli-Newton. While this is about an order of magnitude smaller than the Coulomb force levels considered (milli-Newton levels), F_{s_i} are large enough to be considered as the next significant perturbation.

Considering free-body diagrams of both the tug and debris, we find the following equations of motion

$$F_1 = F - F_{s_1} - F_c = m_1 a_\theta \tag{27}$$

$$F_2 = F_c - F_{s_2} = m_2 a_\theta \tag{28}$$

The along-track acceleration a_θ is solved from equation (28) to be

$$a_\theta = \frac{F_c - F_{s_2}}{m_2} \tag{29}$$

To maintain a fixed separation distance L, this along-track acceleration must be the same for both tug and debris. Equations (27) and (28) are solved for the inertial thrust F that the tug must produce

$$F = \frac{m_1 + m_2}{m_2} F_c - \frac{m_1}{m_2} F_{s_2} + F_{s_1} \tag{30}$$

Note that this inertial thrust F is a worst case scenario where we assume the solar radiation force is acting opposite to the Coulomb force. However, during an orbit the solar radiation force will at times slow down the debris, and then accelerate the debris. Using equation (26), the required nominal inertial thrust F can also be expressed in terms of the vehicle sizes R_i as

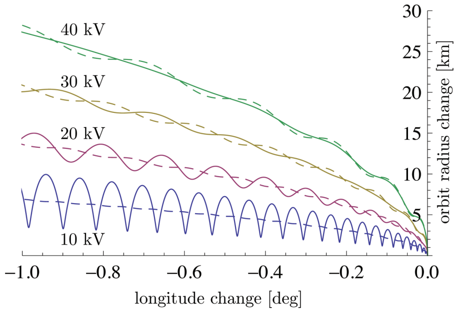


FIG. 7. Orbit radius changes over a one-degree longitude shift to move a 2000 kg debris object with (solid lines) and without (dashed lines) solar radiation pressure. Ticks indicate orbit completions, voltages are per vehicle.

$$F = \frac{m_1 + m_2}{m_2} F_c - \pi \frac{\phi}{c} \left(R_2^2 \frac{m_1}{m_2} - R_1^2 \right) \tag{31}$$

For the special case where the vehicle masses and radii are equal, then the solar radiation pressure has no influence on the nominal inertial thrust computation.

To illustrate the impact of the solar radiation pressure, numerical simulations are run for a range of potentials to examine the SMA change behavior as the debris begins to experience longitude drifts. Figure 7 illustrates the results for 10, 20, 30 and 40 kilo-Volt cases. The unperturbed motion is shown in dashed lines as a reference. While the solar radiation pressure is about an order of magnitude smaller than the Coulomb forces employed, the disturbance can cause additional oscillations by increasing the osculating eccentricity slightly. Note that the pure a_θ also increases the eccentricity some. In these simulations the 40kV case with solar radiation pressure has negligible oscillations in the SMA changes during some longitude periods. Here the eccentricity changes from the solar radiation force and a_θ contributions appear to almost cancel each other.

These simulations illustrate that the solar radiation force impact on the overall GLiDeR performance is small. This is because of the fact that during an orbit the solar influence aids cycles through aiding and impeding the tug in accelerating the debris. While this causes some transient motion within an orbit, the net SMA change is not influence by this perturbation. Further, the GLiDeR position ahead of the debris could be varied from the nominal along-track location to create small orbit radial acceleration components that would compensate for the solar radiation pressure influence. The control bandwidth requirement for such compensation would be very low because these perturbations operate over an orbit period (about 24 h).

Conclusion

A novel method to reorbit large geostationary debris objects is presented. Physical contact is avoided by using electrostatic forces to attract the debris to the tug. Using fuel efficient inertial thrusters the debris is then slowly accelerated over a period of months to a disposal orbit 200–300 kilometers higher than the geosynchronous orbit. The no-contact aspect of this concept is a key benefit, as some geostationary debris can be very large (on the order of metric tons) and rotating at a rate of multiple times per minute. This spin, in particular, makes hard-contact options very challenging logistically in that they increase the risk of collisions and resulting debris, and will consume fuel to negate the debris-satellite's momentum. Performance estimates show that even low 10–20kV levels of absolute charge are sufficient to reorbit a 1000 kg debris object within months. Further, these small force levels are sufficient to raise the semi-major axis by dozens of kilometers as the debris exists one-degree longitude slots. This allows the tug to reorbit debris while being able to avoid other geostationary objects. The most significant perturbation, solar radiation pressure, is shown to have a negligible impact on the net performance because of the cyclic influence of solar radiation on debris motion.

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