An Electric Propulsion “Shepherd” for Active Debris Removal that Utilizes Ambient Gas as Propellant

Mark Matney

There is a growing consensus among the space debris technical community that limiting the long-term growth of debris in Low-Earth Orbit (LEO) requires that space users limit the accumulation of mass in orbit. This is partially accomplished by mitigation measures for current and future LEO systems, but there is now interest in removing mass that has already accumulated in LEO from more than 50 years of space activity (termed “Active Debris Removal”, or ADR).

Many ADR proposals face complex technical issues of how to grapple with uncooperative targets. Some researchers have suggested the use of conventional ion thrusters to gently “blow” on objects to gradually change their orbits, without ever having to come into physical contact with the target. The chief drawback with these methods is the cost per object removed. Typically, a space “tug” or an ion-drive “shepherd” can only remove a few objects per mission due to limited propellant. Unless a cost-effective way that removes tens of objects per mission can be found, it is not clear that any of the ideas so far proposed will be economically viable.

In this paper, a modified version of the ion-drive “shepherd” is proposed that uses ambient atmospheric gases in LEO as propellant for the ion drives. This method has the potential to greatly extend the operational lifetime of an ADR mission, as the only mission limit is the lifetime of the components of the satellite itself, not on its fuel supply.

An ambient-gas ion-drive “shepherd” would enhance the local atmospheric drag on an object by ionizing and accelerating the ambient gas the target would have encountered anyway, thereby hastening its decay. Also, the “shepherd” satellite itself has a great deal of flexibility to maneuver back to high altitude and rendezvous with its next target using the ion drive not limited by fuel supply. However, the amount of available ambient gas is closely tied to the altitude of the spacecraft. It may be possible to use a “hybrid” approach that supplements high-altitude ion-drive operations with stored gas, and transitions to ambient gas at lower altitudes.

This paper will include realistic numbers on the estimated times needed to deorbit objects from different orbit regimes using drives that either partially or completely take advantage of ambient gas. It will conclude with recommendations on whether this is a viable candidate for future ADR efforts.

INTRODUCTION

Liou and Johnson [1] demonstrated that the multinational efforts over the last several decades to limit the generation of debris are, at best, only a temporary solution. In the past, the primary contributor to debris hazardous to active spacecraft has been from spacecraft and rocket body explosions. In the coming decades, however, random collisions between large intact objects will become a major source of debris in the low-Earth orbit (LEO) regions. Because a sufficient population of “legacy objects” already exists in LEO to begin and maintain this collisional process, the best way to mitigate long-term future collisions is to remove objects already in LEO.

This process, known as Active Debris Removal (ADR), is now a fertile field of creative ideas. Researchers have proposed using high-powered lasers [2], electrodynamic tethers [3], and a variety of other devices to remove old spacecraft and rocket bodies from long-lived orbits.

There are a number of important factors needed for such an ADR device to be effective. It must be able to remove uncooperative debris. Most of the high-interest targets researchers have identified were not designed to be grappled and de-spun. So a significant amount of research has been conducted in how to grapple uncooperative targets.

Another aspect is the economic cost to remove objects from orbit. Launches and spacecraft are expensive, so an economically viable ADR mission would at the very least need to remove >10 objects per mission to even hope to be cost-effective.

Ion Shepherd

Some researchers have put forward the idea of using "ion beam shepherds" to deorbit large uncooperative targets in LEO from long-lived orbits [4]. The idea is to "park" a spacecraft with a conventional ion drive unit in front of the target object, and "blow" on the target using a low-divergence ion beam to accelerate the target's decay. The ions from the shepherd spacecraft ion beam would embed in the surface layers of the target, resulting in a nearly 100% momentum transfer. This method is very appealing because the shepherd spacecraft need never make physical contact with its target, so all the challenges of grappling and de-spinning an uncooperative target are avoided.

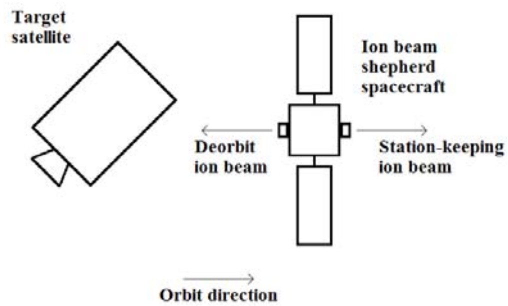

Figure 1 – A conventional ion beam shepherd takes up a position in front of the target object and directs an ion beam on the target satellite. The ions from the beam will imbed in the target and provide an enhanced drag force to deorbit it. The shepherd spacecraft needs a second beam with a force nearly equal in magnitude but opposite in direction to maintain position in front of the target. All of the propellant gas for both ion beams must be carried in tanks aboard the shepherd spacecraft.

The chief drawback to the ion shepherd is that it must carry its own ion propellant. Because the spacecraft needs to maintain position in front of the target, only half the total propellant load can be used to "push" the target. The other half of the propellant must be used to counter the thrust of the shepherding beam so that the shepherd can maintain position. It can take hundreds of kilograms of propellant to deorbit one target object. The total fuel load therefore limits the total number of objects that can be deorbited.

Use of Ambient Neutral Atmosphere

One intriguing idea is to avoid the use of on-board propellant by making use of the thin ambient neutral atmosphere in LEO as a possible source of gas for the ion drive. This neutral atmosphere constantly impinges on the target object and is responsible for the long-term decay of the target due to drag. The idea is to have the shepherd spacecraft position itself in front the target spacecraft, just as in the standard ion shepherd case. From that position, the shepherd would intercept the neutral gas that normally impinges on the target object, ionize it, and accelerate the ions so that they would hit the target with much higher velocity and momentum than the neutral atmosphere alone. This would effectively increase the drag rate on the target.

The idea of using the ambient neutral gas as fuel for an ion drive system is not new. Conley [5] proposed using such a system to dynamically counter drag for very low altitude spacecraft (< 200 km) and allow them to remain in orbit indefinitely. Conley's design consisted of a very large thruster some 5 meters in length and 15 meters in radius. The front section consisted of an ionization chamber that used magnetic fields to trap a cloud of electrons from a central cathode. This cloud was intended to ionize the neutral gas using electron-atom collisions. Depending on the design parameters, it might be possible to build an ionizer with nearly 100% ionization efficiency. I note that the magnetic field design he proposed was very simple, consisting of a cylindrical solenoid. Using modern rare-earth

magnets and more creative magnetic field designs, it might be possible to build a more efficient magnetic bottle trap or even a Penning-type trap for the electron cloud.

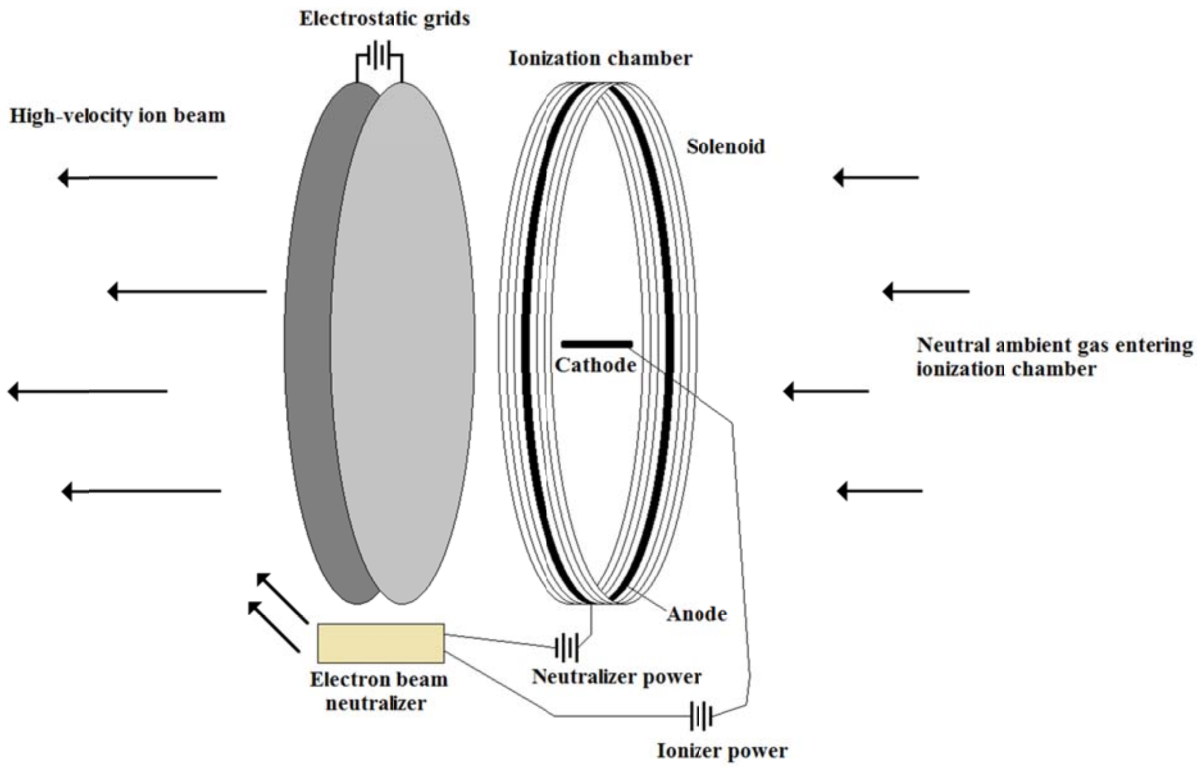

Figure 2 – The proposed design uses the neutral ambient gas as a propellant source. The cathode produces an electron cloud that is held in the ionization chamber by the magnetic field created by the solenoid. Excess electrons collected by the anode are injected into the high-velocity ion beam to neutralize it. Neutral atoms entering the ionization chamber are ionized by collisions with the electrons. These new ions continue to move through the electrostatic grids, and are accelerated by the electric field to form the high-velocity ion beam.

The electron-collision ionization process would not appreciably change the momentum of the newly ionized gas, and the ions would now pass through two electrified grids located behind the ionization chamber and out the rear of the device. The electrified grids would maintain an electrostatic potential in order to accelerate the ions. Conley's design used a potential of 4000 Volts, so for these studies I use that value for the acceleration voltage. However, higher voltages – and consequently higher exit ion velocities – might be achievable.

There are a number of details that must be addressed in such a design. The ion beam that exits the shepherd must be neutralized, else static charge will build up and render the drive system inoperable. Historically, this is handled by using a neutralizer that consists of an electron beam that is injected into the exiting ion stream.

Because the system uses a tremendous amount of power (Conley's design uses several kilowatts), it most probably could only be operated when the spacecraft is in direct sunlight to power the solar panels. This means that the thrust can only be applied to the target approximately half the time.

The most challenging problem is that the shepherd itself experiences thrust from the ion acceleration. This thrust will typically be greater than that received by the target, and it will push the shepherd "ahead" of the target even as the target is pushed "back". Because the neutral gas only enters from the front of the shepherd, the accelerator will

probably require the capability to reverse the polarity periodically to maintain position relative to the target. This means that it can maintain thrust on the target no more than half the time it is operating.

Of course, details of fine pointing and station keeping would be quite an engineering challenge for such a design, but for the purposes of this study, we will assume that could be accomplished using the primary thrust capability.

Theory

The magnitude of the force on a satellite due to atmospheric drag is

$$F = \frac{1}{2} C_D A \rho {v_n}^2$$

where C_D is the coefficient of drag (for orbiting satellites in free molecular flow, it has a typical value near "2"), A is the area of the satellite, ρ is the mass density of the neutral atmosphere, and v_n is the speed of the gas in the frame of the spacecraft (this corresponds to the orbital velocity). At first glance, increasing the velocity of the neutral gas by ionizing and accelerating it would seem to have a very strong effect because of the square of the velocity term. However, this equation must be modified using the continuity equation. If the density and velocity of the neutral gas entering the shepherd is ρ_1 and v_1, and the density and velocity of the accelerated ionized gas exiting the shepherd is ρ_1 and v_2, the conservation of mass requires that

$$\rho_1 v_1 A = \rho_2 v_2 A$$

So, the force from the accelerated ionized gas will be

$$F = \frac{1}{2} C_D A \rho_2 {v_2}^2 = \frac{1}{2} C_D (A \rho_1 v_1) v_2$$

Therefore, the increase in "drag" on the target is only linearly proportional to the increase in the velocity of the accelerated ions.

This increase in velocity is different for each atomic species

$$v_{ion} = \sqrt{{v_n}^2 + \frac{2\varepsilon}{m_i}} = \sqrt{{v_n}^2 + \frac{2q_i V}{m_i}}$$

Here, the energy ε is determined by the voltage V across the grids and the charge q_i and mass m_i of the ion species i. The maximum increase in exit velocity and, consequently, in drag force will be from the lightest elements.

Using the term θ to designate the ionization efficiency of the shepherd ionization chamber, the composite drag rate (ignoring the effects of the electrified grids on the flow) is

$$F = (1-\theta) \frac{1}{2} C_D A \sum_i m_i n_i {v_n}^2 + \theta \frac{1}{2} C_D A \sum_i m_i n_i v_n \sqrt{{v_n}^2 + \frac{2q_i V}{m_i}}$$

Note v_n here is the neutral gas velocity in the spacecraft frame, which is equivalent to the spacecraft velocity.

Case Studies

In order to analyze the effectiveness of this design, I make the following assumptions. The voltage for the ion accelerators is chosen as 4000 Volts, as in the Conley design. The shepherd is assumed to have sufficient area so

that the entire target object is covered by the ion beam. The ion beam only acts on the target ¼ of the time – half for the day/night limitations on using solar-electric power, and half for station keeping by the shepherd.

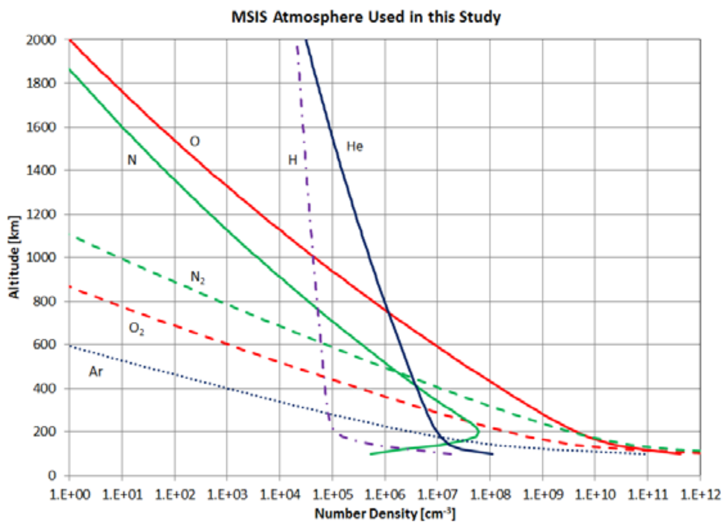

Figure 3 – The MSIS atmosphere tracks the density of different species by altitude. This chart represents an "average" atmosphere used for the calculations in this paper. Note that the light species dominate the atmosphere above about 1000 km altitude.

The MSIS atmosphere is used for these calculations, because the MSIS model breaks out the atmospheric density by atomic and molecular species. Figure 3 shows the atmosphere used for these calculations, based on a "nominal" solar activity of 150 Solar Flux Units and an Ap value of 14.

Three cases are analyzed – 1% ionization efficiency, 10% ionization efficiency, and 100% ionization efficiency. Figure 4 shows the enhancement to the neutral drag force by ionizing and accelerating the ambient gas for a target object in a circular orbit.

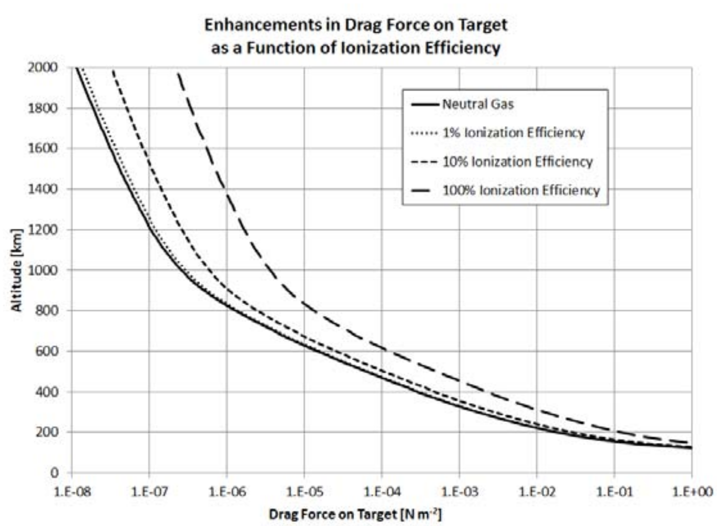

Figure 4 – This charts shows the enhancement in the drag force on the target object by the ionization and acceleration of the ambient neutral gas using the techniques described in the text. Note that at some altitudes, the enhancement can be greater than a factor of 10, but the actual force is still quite small.

Note that the drag enhancement is stronger at higher altitudes where the lighter elements (Hydrogen and Helium) dominate. Under the most optimistic ionization conditions the drag is enhanced by more than a factor of 10, yet the force is still quite low in an absolute sense.

To assess how such a technique would reduce the time necessary to deorbit a target object, a generic target is chosen with an area of 10 m^2 and a mass of 1000 kg (area-to-mass ratio of 0.01 m^2 kg^{-1}). It is assumed to be in a generic circular orbit and that the target and shepherd maintain a circular orbit as the target object is deorbited. Figure 5 shows the estimated time needed to deorbit this generic target using different ionization assumptions. The time to deorbit is enhanced by the shepherd device – in some altitudes by more than a factor of 10 – but the overall decay time is still long, especially when considering that the shepherd would need to continually operate during the entire deorbit.

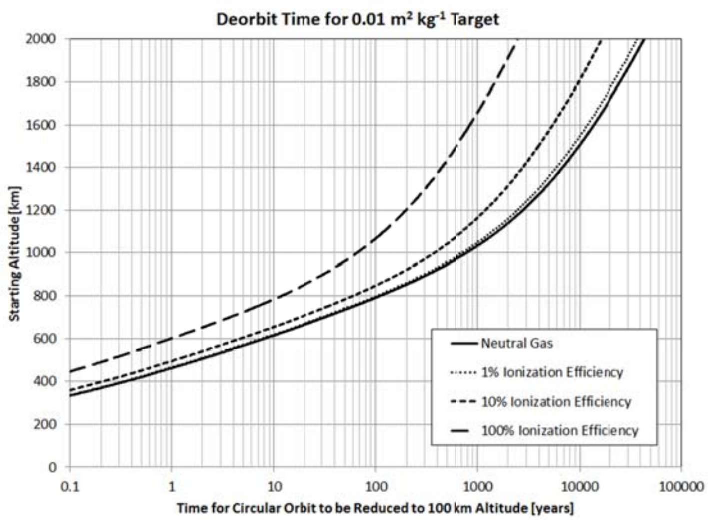

Figure 5 – Using the forces in Figure 4, it is possible to estimate the reduction in deorbit time using the ambient gas ion beam shepherd described in the text. Note that despite the considerable reduction in lifetime, the total deorbit time is still quite long.

Conclusions

This paper has investigated an ion beam shepherd device that uses the ambient neutral atmosphere of the Earth as a propellant source. The basic design is plausible, and demonstrates the capability of increasing the equivalent drag relative to natural decay by a factor of 10 or more, but the resulting forces are still too low and the deorbit times too long to be feasible for large scale ADR operations – especially for high-altitude high-interest targets.

One possibility is to use ambient gas ionization to enhance a more conventional ion beam shepherd in a kind of "hybrid" mode. However, the relatively low density of the ambient gas at the altitudes of interest mean that such a technique probably would never be more than a minor enhancement to extend the "fuel efficiency" of a more effective ion beam shepherd device.

Despite the fact that using the ambient gas as fuel for an ion beam shepherd does not appear to be an effective ADR tool, it is hoped that ideas like this may inspire further designs that will eventually result in a cost-effective operational ADR system.

References

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