THE FP7 LEOSWEEP PROJECT: IMPROVING LOW EARTH ORBIT SECURITY WITH ENHANCED ELECTRIC PROPULSION

Mercedes Ruiz (mercedes.ruiz@sener.es), Igone Urdampilleta
SENER Ingeniería y Sistemas, Tres Cantos, Madrid, Spain

Claudio Bombardelli
Space Dynamics Group, UPM, Madrid, Spain

Eduardo Ahedo, Mario Merino, Filippo Cichocki
Equipo de Propulsión Espacial y Plasmas (EP2), UC3M, Leganés, Madrid, Spain

1. ABSTRACT

Since the first Space launch, the total number of objects and mass of Space Debris orbiting the Earth has increased to a dangerous extent. The risks that this condition poses on current and future missions have led the Space community to look for solutions to stabilise and improve the existing situation. This paper presents the LEOSWEEP project (improving **L**ow **E**arth **O**rbit **S**ecurity **W**ith **E**nhanced **E**lectric **P**ropulsion), aimed to achieve major advances in the analysis, implementation and applicability of the recently proposed Ion Beam Shepherd (IBS) concept for Active Space Debris Removal (ADR). LEOSWEEP has been awarded a grant by European Commission within the 7th Frame Programme 2013 call, and it will be developed by an international consortium of 11 partners distributed in 6 countries.

The IBS is essentially a “contactless” actuator, which allows modifying the orbit and/or the attitude of a generic object (the “target”) using the momentum transferred from one or more ion beams produced by Electric Propulsion (EP) thrusters onboard a nearby spacecraft (the “shepherd”), and properly pointed towards the target by means of the shepherd’s attitude control that includes Chemical Propulsion (CP) thrusters. In order to demonstrate the feasibility of the concept and prepare for its future implementation, LEOSWEEP will address several key technological and legal issues. It will also include a feasibility study of the IBS use for a first ADR mission of a Ukrainian rocket upper stage.

This report will summarise the technical challenges of such IBS technique that will be investigated in LEOSWEEP, especially focusing on the ones involving the use of different kind of in-Space Propulsion devices and their control to effectively actuate on the target debris. These challenges will imply the study and detailed understanding of (1) the physics underlying the IBS concept, including (2) the plume impingement and backsputtering from the target, (3) the constraints in terms of plume divergence for (4) efficient actuation and control, (5) the development of a low divergence ion thruster, (6) the physics of the ion beams used for actuation on the target and (7) the execution of ground-based laboratory experiments.

The indentified development needs and roadmap for the IBS concept will be also presented as an introduction to the project development and dissemination activities to be carried out in the coming years.

2. THE SPACE DEBRIS REMOVAL PROBLEM

About 2,500 tons of debris material, divided into retired spacecraft, rocket bodies, break-up fragments and non-fragmentation sources (e.g. solid rocket motor effluents), surrounds the Low Earth Orbit (LEO) region [1]. Collisions of debris objects with active spacecraft as well as with other debris have occurred and are expected to increase, posing a serious threat for space activities in the near future.

The size distribution of the LEO debris objects follows roughly a power law where the number of fragments rises steeply with decreasing size. Ultimately, as it is widely recognised, the root of the space debris problem is due to potential large objects collisions. Any proposal to tackle this problem will face the challenge of removing hundreds of tons of debris material from the most congested LEO orbital regions.

By looking at the "taxonomy" of resident debris objects, one immediately realises that the quasitotality of the LEO debris mass is concentrated in objects with mass larger than 200 kg and that objects greater than 1 ton make up more than about 75% of the total LEO mass.

That means that whatever removal concept is adopted, it must demonstrate the capability to deal with a typical one-ton object or larger. These objects concentrate at LEO altitude peaks of 950-1000 km and 800-850 km and around specific inclinations (82, 98, 75 deg) [1].

By looking more closely at the totality of LEO objects heavier than 1-ton it is found that about 63% of their total mass is concentrated into launchers upper stages. Upper stages are therefore ideal candidates for the implementation of large-scale debris removal (or alternatively, relocation) operations for at least three main reasons:

1. A successful technology demonstration mission aimed at a few targets could open the way towards the removal of hundreds of tons of debris material in the future.
2. Upper stage families are clustered at specific inclinations, which makes it possible to implement multiple removal operations (if the removal technology allows multiple uses).
3. Upper stages are less affected by confidentiality issues complicating removal operations at international level.

Any mission aiming to remove such kind of objects will need to provide the required significant impulse to deorbit or relocate the target debris. Different removal methods have been proposed lately, most of them using capture mechanisms to grab the target and then employing the impulse provided by the main platform propulsion system (either chemical or electrical) to perform the manoeuvre. The IBS concept is a contactless method that uses the shepherd's propulsion system in a different approach, as explained in the next section.

3. THE ION BEAM SHEPHERD CONCEPT

Overview

The basic working principle of electric propulsion systems commonly used for in-Space applications, consists of accelerating a stream of plasma ions (typically Xenon) by an electric or electromagnetic field to produce a reaction force on a satellite in the opposite direction with respect to flux of the accelerated ions.

Using a "reversed perspective" one could think of exploiting the momentum of the accelerated ions to produce a force on a nearby target body by pointing the thruster plume towards it. The ions reaching the target surface penetrate in the material substrate until they stop as a result of collisions, transfer their momentum, and generate an action force. This mechanism does not require mechanical contact with target. This paradigm shift in the use of propulsion technology is the base of the Ion Beam Shepherd concept recently proposed by the Technical University of Madrid (UPM) [2].

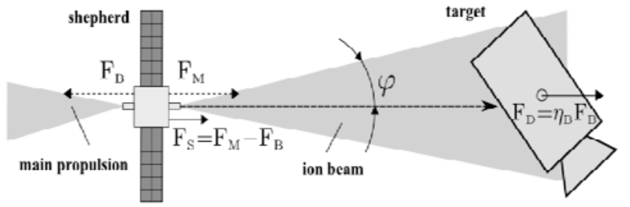

Figure 1. Schematic of the IBS concept.

In order to produce a continuous contactless actuation on the target, the shepherd satellite main propulsion system must employ at least two similar thrusters: an Impulse Transfer Thruster (ITT) pointed at the target and an Impulse Compensation Thruster (ICT) generating a counteractive force on the shepherd in order to avoid the latter from accelerating away (Figure 1). A small beam divergence allows the shepherd to operate efficiently (i.e. with almost full beam overlap and momentum transmission) at a safe distance from a target body, in the 10-20 meters range depending on beam divergence and Guidance, Navigation and Control (GNC) capabilities.

Contactless Momentum Transfer

The physical mechanism governing the momentum transfer of a beam of ions following the impact with a macroscopic object is solid and well understood. After reaching the object surface, the accelerated ions (at typical keV energies levels) pass through the material substrate and ionise the atoms or molecules they encounter. Following both nuclear (elastic) and electronic (inelastic) collisions, the ions gradually lose energy in many small steps until they stop. At macroscopic scale, conservation of linear momentum implies a transmitted force.

A key aspect to be underlined when computing the beam momentum transmission is the fact that the momentum contribution of particles emitted from the surface following the impingement of the ions is typically negligible [4].

From the above considerations one can infer that the force transmitted to the target cannot exceed the reaction force of the thruster itself and such condition is reached when ideally all plasma ions intercept the target surface. It is therefore convenient to introduce the beam momentum transfer efficiency defined as the ratio between the axial component (i.e. along the beam axis, here denoted with x) of the force transmitted to the object divided by the total Impulse Transfer Thruster thrust:

$$\eta_B = \frac{F_x}{F_{ITT}} \quad \textbf{(1)}$$

In order to obtain a momentum transfer efficiency as large as possible, the distance between the shepherd and the target must be kept as short as practicable. This would be limited by safety interbody (shepherd and target) distance constraints and GNC capabilities, whose analysis is out of the scope of current paper.

For the particular case of spherical target with its geometrical centre on the beam axis and assuming the beam is Gaussian and conical with 95%-current half-cone beam divergence β we have:

$$\eta_B = 1 - exp\left[-\frac{3}{tan^2\beta(\delta^2-1)}\right] \qquad \textbf{(2)}$$

where δ represents the distance of the target from the beam source measured in target radii.

The above formula can be easily inverted to derive the required target distance for a given efficiency:

$$\delta = \sqrt{1 - \frac{3}{tan^2\beta ln(1-\eta_B)}} \qquad \textbf{(3)}$$

The importance of reducing the ion beam divergence as much as possible can be immediately appreciated by plotting Eq.(**3**) for different angles beta (Figure 2).

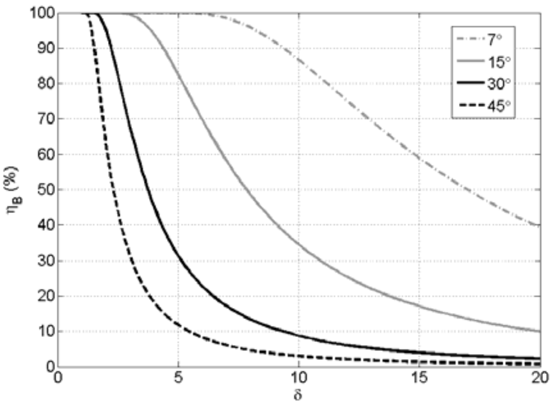

Figure 2. Momentum transfer efficiency for a spherical target centred on a Gaussian conical beam as a function of the separation distance (in target radii) and for different beam divergence angles.

Beam-Target material interaction

The plasma beam interaction with the object surface material and its consequences is another crucial aspect of the IBS concept. While impinging plasma ions are generally trapped into the target material substrate, their energetic interaction with the material itself releases material atoms and/or clusters of atoms following a phenomenon known as sputtering.

It is important to underline that in the energy regimes considered for IBS applications, only a few percent of the sputtered atoms are ionised, which means that most of the sputtered material will be insensitive to the electric field of the plume.

Backsputtering is a critical aspect of the IBS technology for two main reasons:

1. Backsputtering can damage the target through erosion. Although the extent of the backsputtered material is expected to be a very small fraction of the target mass one has to ensure, for particular applications such as space debris removal, that the target structural integrity is not compromised.
2. The flux of backsputtered atoms released from the target can reach sensitive surfaces on the shepherd spacecraft (e.g. optical sensors, solar panels, thermal coatings,...) and degrade their performance. One has to make sure that the extent of backsputtering contamination is tolerable for the mission.

Preliminary studies [3] have been carried out to correlate the backsputtering flow to the thruster plume divergence, concluding that decreasing the beam divergence from 15 to 6 degrees can lead to a decrease in backsputtering flux of about one order of magnitude for a spherical target. This brings the task of reducing the ion beam divergence as one of the top priorities in the technology development of the IBS.

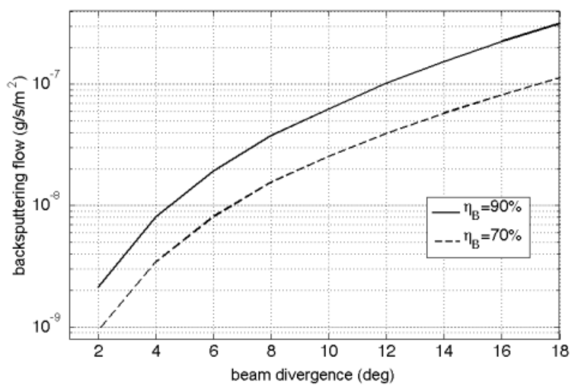

Figure 3. Backsputtering flow reaching the IBS spacecraft from an aluminium spherical target with constant momentum transfer efficiency and varying beam divergence.

Depending on the achievable ion beam divergence, the thrust level, the target material properties and the maximum mission duration, backsputtering contamination limits may eventually constrain the minimum achievable separation distance. This may eventually make it difficult to reach very high momentum transfer efficiencies throughout the entire mission for specific mission scenarios.

4. IBS KEYS AND CHALLENGES AT PROPULSION SYSTEMS LEVEL

Efficient Actuation and Control

The propulsion system is the core technological element of the IBS as it supplies the necessary thrust for target shepherding and relative position control.

The IBS propulsion elements can be subdivided in 3 categories:

1. Impulse Transfer Thruster(s): It is the most critical propulsion element of any IBS mission as it must provide the contactless deorbiting/reorbiting impulse to the target. It is switched on during the whole shepherding phase. The performance requirements for this thruster will depend on the target orbit, size and mass, therefore, they may vary for different mission profiles. Its performance in terms of divergence, efficiency, specific impulse (and lifetime for a long mission) is crucial for the mission. Due to these requirements, only Electric Propulsion thrusters will be considered for this application, since they present important advantages in these respects when compared to chemical propulsion systems.
2. Impulse Compensation Thruster(s): It is the second-most critical propulsion element of any IBS mission as it must compensate for the impulse transfer thrust and keep the separation distance nominally constant. This thruster will also serve for orbit transfer and phasing manoeuvres. Although beam divergence is not critical for this thruster, efficiency, specific impulses (and lifetime for a long mission) are. While the use of exactly the same thruster system for ITT and ICT is recommended, this will be traded off at a more advanced mission design phase. Power limitations, for instance, may impose the use of a lower specific impulse (hence larger beam divergence) ICT. Another issue in this respect to take into account is the required actuation coordination control between the ITT and the ICT, especially if a common power processing, control and distribution unit is to be shared by both thrusters.
3. Reaction Control System (RCS): A set of additional thrusters must be employed in any IBS mission to provide a three-axes relative position and attitude control of the shepherd. These thrusters are also meant to control the relative position of the shepherd-target system in the case of requiring a collision avoidance manoeuvre. Moreover, the RCS is also in charge of the desaturation of the onboard reaction wheels and performing initial commissioning and additional safety manoeuvres. From a propellant economy point of view, and foreseen an intensive use of these thrusters, electric propulsion thrusters could be considered if sufficient power could be installed in the platform. On the other hand, impulsive operation of the RCS would better fit the manoeuvrability requirements for this system. Therefore, chemical thrusters are at this time preferred for this application.

These propulsion systems can be considered as the key actuators of the Attitude and Orbit Control Subsystem (AOCS) of the shepherd platform. The efficient use of the associated thrusters will be the responsibility of the onboard Guidance, Navigation and Control, that will also implement other actuators (reaction wheels) and a complete and complex sensing suite for accurate interbody distance estimation and efficient relative distance and attitude control. LEOSWEEP will take specific care of these issues through the activities devoted to GNC design and simulation, but carefully taking into account the resulting ITT design performances.

Impulse Transfer Thruster

Because ion-beam divergence has never been a primary objective of electric propulsion system design, especially when compared with key performance indicators like specific impulse and propulsion efficiency, attempts to minimise it have been modest and mostly related to the recent interest of Japan for the IBS concept. Gridded ion thrusters, unlike Hall-effect thrusters, enjoy a relatively small divergence (typically 15 to 20 deg), which is considered acceptable for conventional applications. A recently proposed 4-grid ion thruster design (called DS4G) has shown a considerably lower divergence (less than 6 deg) after a testing campaign conducted at ESA [5]. Although the presence of two additional grids played a role in reducing the beam divergence, the improvement is partly due to the very high electric potential employed (up to 30 kV) which led to a specific impulse of more than 20,000 s (that was the primary objective of the thruster design). The DS4G thruster has not been tested in space yet and may be too extreme a solution for the IBS concept in general, and definitely not suitable for a concept demonstration mission.

The LEOSWEEP project aims at achieving a considerable improvement (a factor of two or more is envisioned) in the divergence of a space-qualified thruster. From the commercially-available plasma thruster types, gridded ion engines are specially indicated as the ITT and ICT thrusters for their high I_{sp} and low plume divergence. These were identified as the most interesting candidates in previous studies [6]. In particular, the radio-frequency ion thrusters (RIT), due to their lack of inner cathode, present a lower complexity (both in terms of electrical components and number of independent voltages). The main point here is that the divergence reduction will be the ultimate goal of the design, which means that a wide range of design modification possibilities not previously considered will have to be taken into consideration to maximise the chance of success.

An analysis and comparison of different electric propulsion technologies will be performed under

LEOSWEEP project to discuss the suitability of each thruster type as the ITT and as the ICT for an IBS mission depending on its duration and its requirements.

Lastly, other types of thrusters, both chemical and electric propulsion ones, will be considered and traded-off for RCS purposes.

Ion Beam Physics

In order to better understand the momentum transfer efficiency, the beam interaction with the impinged surface and to consider the beam as a "reversed actuator" within the shepherd's AOCS, it will be necessary to understand the ion beam physics as well as to develop and use detailed beam models.

Ion beam modelling for understanding, design and analysis of the IBS concept requires using two types of models and codes: first, fast, simpler codes for detailed parametric investigations of the different plume properties and computations of forces on the target; and second, detailed models for analysing more globally the 3D interaction of the plume with the target and the surrounding space environment. Self-similar fluid models are adequate for the first category of problems while models based on the Particle-in-Cell (PIC) methods will be needed for tackling the second one. The objectives of the LEOSWEEP project will require considerable advances in both models.

Approximate self-similar fluid models, characterising the far field-plume of simple unmagnetised plumes, such as those emitted by an ion thruster, will be improved in the project by deriving a unique framework capable of dealing with different plume shapes and extending its validity beyond the total hypersonic limit. Other than unmagnetised plasma beams, considerable effort will be devoted to the analysis of magnetised plumes as characterising advanced thrusters currently under development in Europe. For these thrusters more complicated non-self-similar fluid models have to be employed and key aspects to be solved are (1) the detachment issue for characterising the far-field region, (2) the influence of the plasma energy source on the plume expansion, and (3) the study of multiple beam plumes.

Beyond fluid models, PIC-based models are necessary for analysing the effect of collisions between multiple species, non-Maxwellian populations, and dealing with complex geometries. The LEOSWEEP project will invest relevant effort to overcome this limitation and extend PIC models capability. For applications of the concept in LEO, a major issue is the possible deviation of the ion beam by the geomagnetic field whose direction varies along the orbit. There is not an established model for this 3D interaction, which is very challenging to tackle with either fluid or particle models. One of the goals of the LEOSWEEP project is to advance in the modelling and analysis of this very complex problem.

5. GROUND-BASED LABORATORY EXPERIMENTS

The ITT development and the testing activities to be carried out in LEOSWEEP will be based on the radiofrequency ion thruster technology, aiming to reduce the plume divergence. For this reason one of the presented objectives of LEOSWEEP work is to design and manufacture an ITT prototype with all required hardware to achieve a plume divergence of approximately 7 degrees. The development and fabrication of such a thruster will require the execution of characterisation tests while developing and integrating the unit. Therefore, the first part of the LEOSWEEP testing campaign will be devoted to the developed ITT characterisation and tuning at manufacturer premises.

Once the thruster is ready, a second testing campaign is planned, where a more detailed thruster characterisation will be performed prior to the execution of transmitted force tests. The net force transmitted to the target along the thruster axial direction will be measured with different targets shapes/sizes in order to test both full and partial beam overlapping. The Project counts on a large vacuum chamber facility for EP testing where different thruster-target distances can be studied.

In addition to these tests, a third campaign will be developed in Ukrainian facilities, where a representative upper stage surface element will be irradiated in order to measure the backsputtering flux and the surface degradation effects after beam exposure.

The final objective of all the tests will be to characterise the key features of the new ITT thruster in relation to the deorbiting of Ukrainian upper stages. Beam divergence, current density and backsputtering measurements will be taken and compared with analytical and numerical results to be validated after ITT thruster characterisation.

6. CONCLUSION

Although the core element of the IBS technology, i.e. the ion flux generation source, can be derived from state of the art space hardware (e.g. gridded ion engines), for the IBS concept to become technically feasible and competitive a number of key technological advances in the areas of propulsion, guidance navigation and control, design and integration will be necessary. As for the propulsion system the crucial element is the ion beam divergence, which should be as small as possible in order to increase the target-shepherd separation without efficiency losses, hence reducing collision risks and backsputtering contamination.

LEOSWEEP has been proposed to consider and study all these technical implications of IBS use for ADR, also including an assessment of policy and legal issues. This paper has focused on the challenges posed by a generic IBS ADR mission to the propulsion elements onboard the shepherd platform.

In addition to the development of a specific reduced divergence ion thruster, a carefully designed laboratory test campaign is also a crucial objective for the LEOSWEEP project as it will allow validating previously obtained analytical and numerical results pertaining to different aspects of the ion-beam physics and beam-target interaction. The tests, to be conducted in environments as close as possible to the ones an IBS will face in a real mission, will employ top-level testing facilities in Europe and Ukraine to ensure the highest possible quality.

7. ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° **607457.**

The authors would also like to acknowledge the collaboration of the full LEOSWEEP team, constituted by SENER, UPM, TransMIT, ITM, DLR, Yuzhnoye SDO, DEIMOS Engenharia, ISLC, University of Southampton, CNRS LPP and UC3M.

8. REFERENCES

[1] Debris data provided by ESA Space debris Office though DISCOS.

[2] Bombardelli, C., Pelaez, J.. Patent B64G1/24-P201030354 “Sistema de modificación de la posición y actitud de cuerpos en órbita por medio de satélites guía”, 2012.

[3] Bombardelli, C., Pelaez, J. “Ion Beam Shepherd for Contactless Space Debris Removal” Journal of Guidance, Control, and Dynamics, Vol. 34, No. 3, May–June 2011, pp 916-920.

[4] Trottenberg, T., Rutscher, J. and Kersten, H.: “Experimental Investigation of Momentum Transfer to Solid Surfaces by the Impact of Energetic Ions and Atoms”. IEPC-2013-329.

[5] D Walker, R., Bramanti, C., Sutherland, O., Boswell, R., Charles, C., Fearn, D., Del Amo, J., Frigot, P., and Orlandi, M., “Initial Experiments on a Dual-Stage 4-Grid Ion Thruster for Very High Specific Impulse and Power,” AIAA Paper 2006-4669, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, CA, 9–12 July 2006.

[6] Bombardelli, C., Merino-Martinez, M., Ahedo, E., Pelaez, J., Urrutxua, H. and Herrera-Montojo, J. “Ariadna Call for Ideas: Active Removal of Space Debris--Ion Beam Shepherd for Contactless Debris Removal, Ariadna 10-6411c”, ARIADNA FINAL REPORT, European Space Agency, Advanced Concepts Team.