ELECTRIC PROPULSION SYSTEM FOR A MANEUVERABLE ORBITAL VEHICLE

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Abstract

This paper presents a proposed maneuverable orbital vehicle based on the International Space Station (ISS) equipped with electric thrusters. The vehicle makes use of an external site of the ISS (e.g., the Express Pallet) to host a detachable platform which is able to perform a variety of missions, including formation flying with the ISS and missions to very low Earth orbit, down to 130 km altitude. After having accomplished a mission, the vehicle flies back to the ISS and rendez-vous in a semi-autonomuous mode to be refurbished and prepared for the next flight. The possible applications of such system include interferometric astronomy, the study of the extreme layers of the atmosphere, and high-resolution Earth imaging. The electric propulsion system features a cluster of high power Hall-effect thrusters, sized such as to give sufficient thrust authority to drive the vehicle without the need of chemical propulsion systems, yet able to be powered by standard deployable solar panels of acceptable extension. The vehicle is feasible with currently available electric propulsion and power generation systems.

Introduction

As it was initially conceived, the International Space Station (ISS) was intended as an orbital laboratory for a variety of scientific experiments, as well as a possible outpost to be used as a starting base towards interplanetary space. In spite of the many difficulties of the ISS programme, the first goal has been achieved, albeit partially. The second objective is perceived as too much far-fetched for today’s space business, and was essentially dropped quite early.

Another possible way of exploiting the ISS which can be considered and is indeed feasible with present technology and with reasonable effort: using the Station as a base for a reusable unmanned vehicle for very low Earth orbit mission and for formation flying with the ISS itself. The basic idea behind this concept is that capabilities for handling external payloads and for docking of vehicles are part of the baseline design of the ISS and are already in place (e.g., the robotic arm), at least partially. A vehicle that departs from the ISS and returns to it can carry out missions in LEO to trajectories significantly different from that of the station with an acceptable total mass.

The enabling technology for this vehicle is high power electric propulsion. Departure from the ISS, acquisition of the target trajectory, orbital maintenance and return can all be performed with low thrust maneuvers. Higher thrust devices are obnly needed for ISS proximity operations (docking and undocking); in our study, resistojet sharing the same propellant feeding subsystem as the primary thrusters have been selected.

In this paper, we present the main results of a study aimed at demonstrating the feasibility of a multi-role facility, based on a maneuverable orbital vehicle (MOV) and docked to an external site on the ISS. The MOV is capable of departing from the ISS to perform several autonomous missions on a wide set of different orbits, at the end of which it would be capable to rendezvous with the ISS and dock back. In this way, the vehicle could be inspected, refurbished and, eventually, modified at the end of every single mission. Several advantages can be provided by this approach: one single spacecraft can accomplish several different scientific missions, mission targets can be modified and readdressed several times, spacecraft subsystems could be repaired or upgraded and, last but not least, the recurring costs could be greatly reduced by the fact that the whole spacecraft platform does not require to be re-designed, built and launched for every mission. The study shows that the facility is feasible using technologies that are either existing or in their final development phase.

Vehicle Configuration and Mission Scenarios

The MOV is hosted on an external site of the ISS. The station provides several suitable docking sites, such as the Express Pallet, the Japanese Exposed Module and some sites on the European and Russian modules of the station. For the purpose of this study it was assumed to use one of the six Express Pallet platforms, which do in fact represent a worst case among the possible accommodations. The four starboard platforms mounted on the ISS main truss are shown in Fig. 1 (left). The vehicle is brought to the ISS already mounted on the Express Pallet and can be returned to Earth in the same fashion. The docking and undocking phases are performed with the aid of the Station's robotic arm, the Space Station Remote Manipulation System (SSRMS), or Canadarm. The same arm, with the eventual addition of the Special Purpose Dexterous Manipulator (SPDM, Fig. 1), is used also for the most of the docked operations, e.g. servicing, refurbishment, payload substitution, and so on.

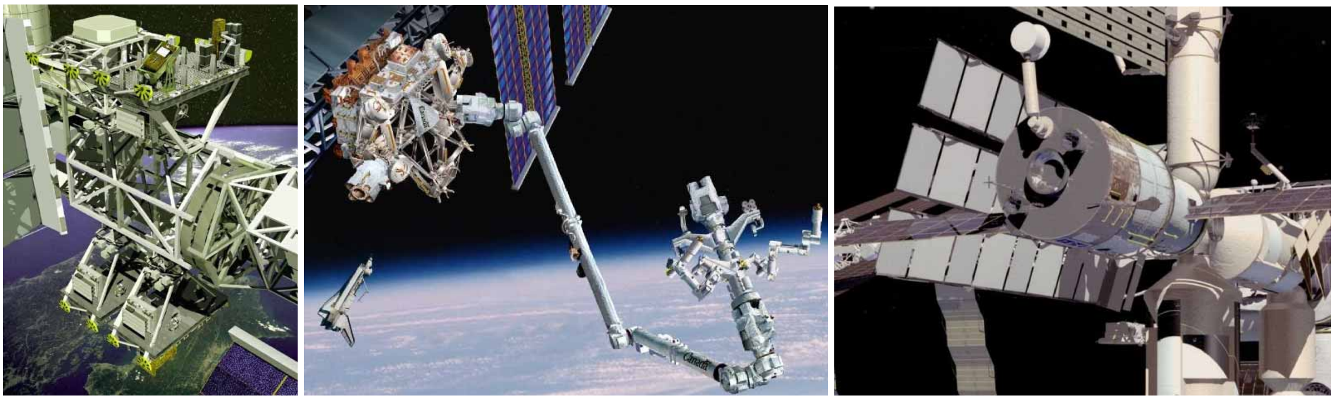


Fig. 1: Express Pallet platforms on the Main Truss, left; Remote Manipulation System "Canadarm" and Special Purpose Dexterous Manipulator, middle; Russian module "Zvedza", right.

The vehicle is equipped with its own power generation and storage, propulsion, attitude control, thermal conditioning, telecommunication and telecommand subsystems. Data collected by the vehicle's payload(s) can be stored on board, relayed to the ISS or directly sent to a ground station. During the docked phase, the MOV is in a dormant status.

The main mission classes considered are as follows:

- "downward" missions, i.e. missions in circular or elliptic orbits at a lower altitude than that of the ISS. The most promising missions belonging to this category are the VLEO (Very Low Earth Orbit) missions, whose target is to reach the minimum possible orbital altitude;
- missions "around" the ISS, or missions performed flying in formation with the ISS.

"Upward" missions, i.e. missions in circular or elliptic orbits at a higher altitude than that of the ISS, may be conceived but have not been considered in this study.

VLEO Missions

Several applications are envisaged for the Very Low Earth Orbit missions:

- Remote sensing: ecology & environment, navigation
- Aeronomy: study of atmospheric density variations depending on altitude, solar activity, season, etc.
- High atmosphere study: components chemistry, plasma dynamics, cosmic rays, etc.
- Geodesy: Earth gravitational field higher harmonics
- Characterization of the Earth magnetic field
- Technological applications: study of drag coefficients in hypersonic regime (re-entry vehicles), effects of hypersonic flux on materials, validation of novel guidance systems.

For missions downwards, the lower limit to the achievable altitude is determined by atmospheric drag: when the orbital energy drain produced on the spacecraft by drag cannot be overcome by the propulsion system, the vehicle is not able to gain altitude anymore and cannot come back to the docking port. For a given available orbital energy, the minimum altitude can be obtained by flying elliptical orbits, where the maximum drag is limited to a small orbit arc close to the perigee. In this case, the propulsion subsystem task is to change or maintain both the orbital semi-major axis (i.e., the orbital period) and eccentricity. In some cases also control of the argument of perigee, inclination and right ascension of ascending node may be required. With the assumptions of this study, orbits with perigee as low as 137 km can be flown.

<u>ISS Formation Flying</u>

In formation flying, the motion of the vehicle with respect to the ISS is finely controlled. Several types of formation flight are possible, depending on the mission applicability: maintenance of a fixed position in front or behind the station, non-Keplerian orbits with the vehicle “hovering” over or below the station, “orbiting” around the station by means of suitable orbits with a slightly different inclination or eccentricity. For these applications, the propulsion subsystem has to control the orbital elements, as well as compensate for the different effects on the two bodies (ISS and free-flyer) of the various perturbations. The operational limits of this missions are mainly determined by the achievable precision of the guidance system.

Most interesting formation flying applications concern:

- Stereoscopic remote sensing: land and oceans 3-D mapping;
- Interferometric astronomy;
- Atmosphere stereoscopic analysis;
- Geodesy: Earth gravitational field higher harmonics;
- ISS monitoring.

<u>System and Subsystem Design</u>

Among the possible operational scenarios, the more stringent system requirements are provided by the VLEO missions. The need to compensate for high drag at the lowest possible altitudes translates in the following two design drivers:

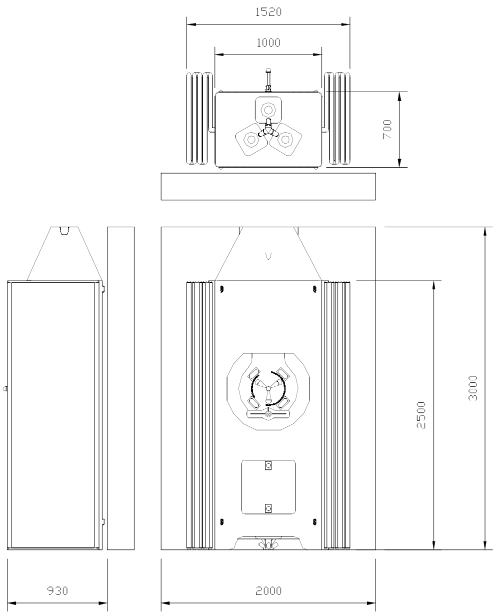
- maximisation of the electric energy produced with every orbit;
- minimisation of aerodynamic drag.

The first point is approached in two ways: using state-of-the-art components for all the power generation, conditioning, storage and distribution subsystems, and providing the vehicle with a large enough solar array surface. Since any selected ISS docking site will have more or less stringent dimensional specifications, it is required that the solar arrays be deployable and re-foldable immediately before docking.

As for the second point, a slender configuration is adopted in order to minimise the cross-sectional front area. The bus dimension along the ram direction is larger than the other two. This also implies that the solar panels will be deployed on a surface that is parallel to the ram direction (i.e. to the velocity vector). Finally, some reduction in the drag coefficient can be gained by suitable design of the front surfaces.

Mass and dimensional constraints

The mass and dimensional constraints are determined by the particular docking site on the ISS, where not exceeding the transportation constraints (e.g. the Space Shuttle cargo bay dimensions and maximum load). In the considered case, the Express Pallet upper tray allows for a maximum mass of 1350 kg, with dimensions not exceeding 3 m length, 2 m width and 1 m height. The preliminary design of the MOV meets these constraints through the configuration presented in Figure 2 (left), showing the vehicle dimensions in the docked configuration, with folded solar array. The bus dimensions are 3000x1000x700 mm, while the docked configuration boundary box, including the folded panels, is 3000x1520x700 mm. The total ram area, including solar array profile, is 0.94 m^2. Figure 2 (right) shows the dimensions of the (partly) unfolded solar array. The total array area is 20 m^2, with a total vehicle width of 9 m (with completely unfolded array).



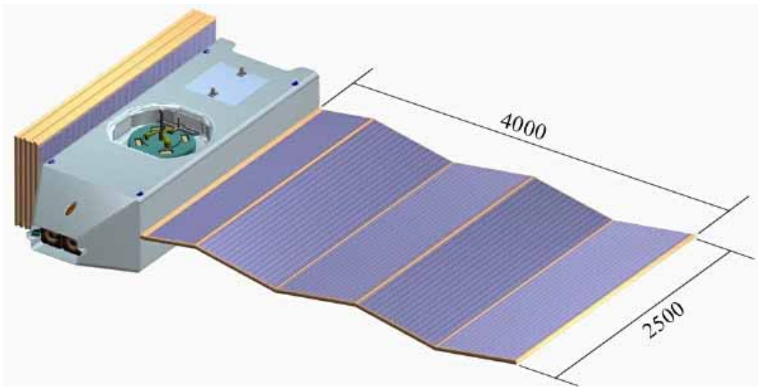


Fig. 2 - MOV dimensions (in mm) mounted on the Express Pallet platform, left;
MOV solar array dimensions (in mm) with port array deployed, starboard array folded (right)

The MOV total mass is 1350 kg. The mass breakdown among the major subsystems is shown in Figure 3 for the maximum loaded propellant case. A sketch of the allocation of internal volume to the subsystems is also shown.

Power subsystem

Electric power production relies on two foldable solar arrays, 10 m^2 of total surface each. The considered technology is based on Ga-As or triple junction solar cells, for an overall efficiency of at least 19% at BOL, and a resulting array specific power production of about 40 W/kg at 1 AU. Peak power is higher than 5 kW, while orbit-average power is dependent upon required mission orbit and attitude.

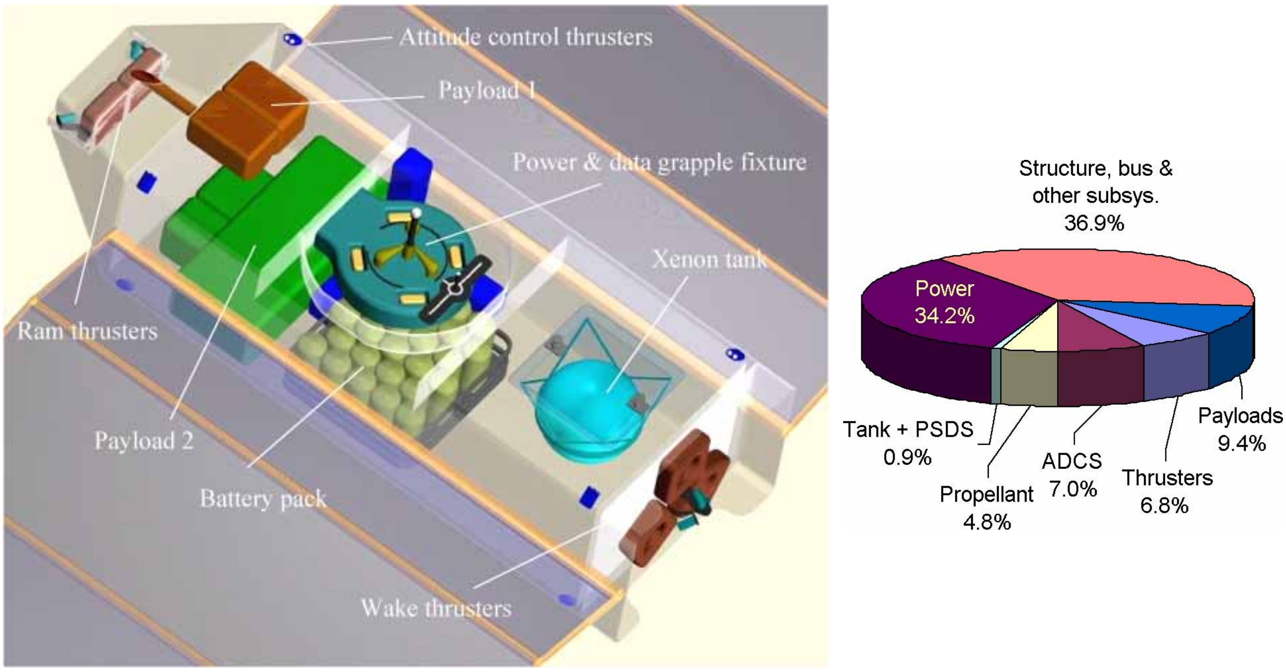


Fig. 3 - Subsystem configuration and mass breakdown

When not directly used by propulsion or other subsystems, electric energy is stored in a suitable battery pack which makes power available during peak absorption phases (e.g., during maximum thrust phases) and during eclipses. In first instance, the considered technology was that of the current space qualified Ni-H, single pressure vessel batteries, allowing a specific energy of about 47 Wh/kg. Future design options, however, envisage the use of Li-ion batteries, currently under development, promising as much as 200 Wh/kg. Batteries were dimensioned in order to keep the average depth-of-discharge below 40%, in order to guarantee up to 10 years of overall orbit lifetime.

The mass of the whole power production and management subsystem, including solar arrays with deployment mechanisms, battery, converters, regulation electronics and harness, is about 35% of the total S/C mass, i.e. about 470 kg.

<u>Attitude control</u>

Maximum operational flexibility is obtained via a full three-axes active attitude control system, based on reaction wheels and attitude control (AC) thrusters. The focus here will be on the AC thrusters, required to provide for wheel desaturation and active momentum control when peak momentum authority is required. Moreover, the AC thrusters may also provide for thrust in the cross-velocity directions, where fine orbit control is required, e.g. in the last part of the rendezvous and docking phases.

For the sake of simplicity, resistojets have been selected as AC thrusters. In spite of the quite limited specific impulse, resisojets have a number of advantages with respect to other systems (e.g., arcjets or non-electric systems) when high thrust and a limited total impulse is required. In principle, resistojets can use any kind of gaseous propellant, with hydrogen, helium, nitrogen, argon, ammonia, water and hydrazine being only a few examples. In our case, resistojets will be fed with xenon propellant like the main orbit control thrusters, therefore allowing for the use of a single common tank. In addition to simplification at system-level, commonality of the tank allows to re-fuel the whole vehicle with a single operation (e.g., by replacing an empty tank). Moreover, the electric power supply and control subsystem of the resistojets is very simple and doesn't require much dedicated onboard electronics. In case of failure of the critical part of the resistojet, i.e. the heater, the thruster can still be used in a cold-gas mode, albeit with degraded performance, thus providing additional margin of safety during ISS proximity operations.

Resistojets can be designed to a large variety of thrust levels, being thrust mainly influenced by nozzle throat dimensions and bulk pressure and temperature conditions. The relatively low I_{sp} of xenon resistojets, in the order of 70-80 s, is compensated by the small amount of total impulse required to the attitude control thrusters, and by the overall mass and volume savings due to the use of a common tank. The configuration of the attitude control thrusters is shown in Figure 4. Eight pairs of thrusters (1 active and 1 cold redundant) are distributed at the vehicle corners in order to provide pure torques about the three body axes.

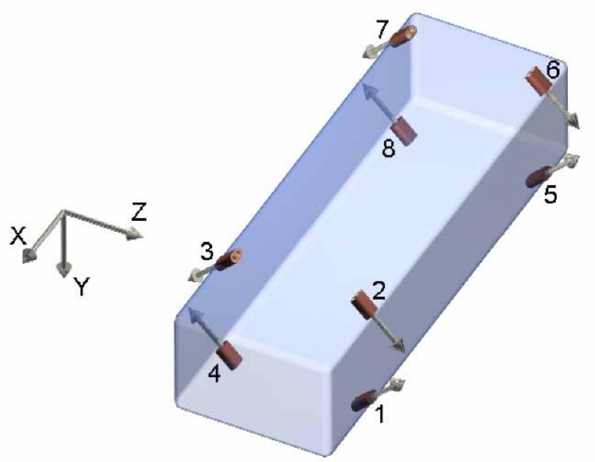


Fig. 4 - Attitude control thruster locations and thrust vector orientations.

<u>Orbit Control Subsystem</u>

Orbit control and maneuvers are performed with a system of five Hall effect thrusters (HET), two of which are placed on the front (ram) face of the spacecraft, while three are located in the back (wake) face, as shown in Figure 5. The main advantage of the HET technology with respect to other electric thrusters (gridded ion engines, arcjets) is the simplicity, robustness and compactness of the ion source, which results in remarkable reliability. Specific impulse, much higher than in chemical thrusters, is low enough to allow production of the thrust level required for this application with a reasonably small electric power consumption. Present state of the art thrusters have demonstrated reliable operation for much longer periods than needed by the longest MOV mission examined.

Wake thrusters have a nominal power in the order of 8 to 9 kW, each producing a nominal thrust about 500 mN. The maximum thrust level required by the envisaged mission profiles is 1 N, so that at least one of the three thrusters is redundant. The thrusters can be operated together or alternatively at reduced or nominal thrust levels, respectively, in one of several possible combinations, to deliver the required impulse along each phase of the mission. The estimated mass of a single thruster is 22 kg. Ram thrusters are less powerful (5-6 kW), producing a nominal thrust about 350 mN each. Also in this case, one of the thrusters is kept in cold or hot redundancy. The estimated mass of the ram thrusters is 13.5 kg. This “optimized” system has been chosen for this study, although obviously it is possible to use just 5 or even 6 identical thrusters, to reduce the development costs.

The thruster locations allows thrusting along the S/C body *x*-axis. In this way, tangential and anti-tangential thrusting is permitted during normal and low altitude operation without requiring any attitude slew manoeuvre. Using simple tangential and anti-tangential thrusting, all of the following maneuvers can be performed:

- orbit raising or lowering, semi-major axis and orbit period changing;
- eccentricity modification and control, raising or lowering of perigee or apogee alone;
- argument of perigee control;
- phase control via successive altitude changes and coasting phases;
- corrections of the right ascension of the ascending node via successive altitude changes and coasting phases, taking advantage of the effect of the J_2 harmonic of the Earth's gravitational field;
- atmospheric drag compensation and orbit maintenance.

The only orbital element that cannot be controlled in such manner is orbit inclination. Inclination changes, however, are only occasionally required, and can be performed by rotating the whole spacecraft by a suitable yaw angle.

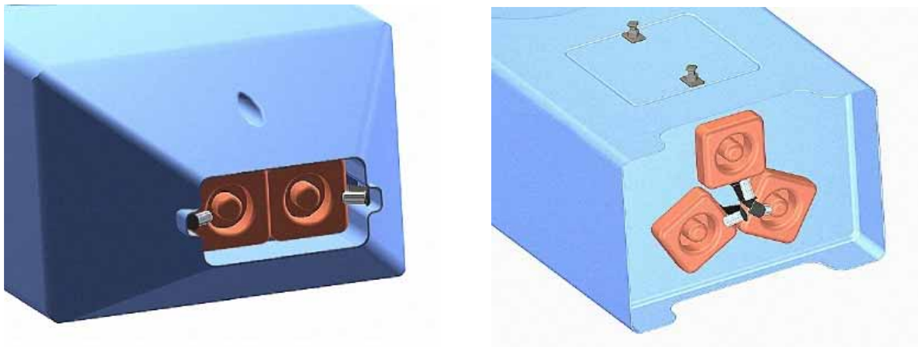


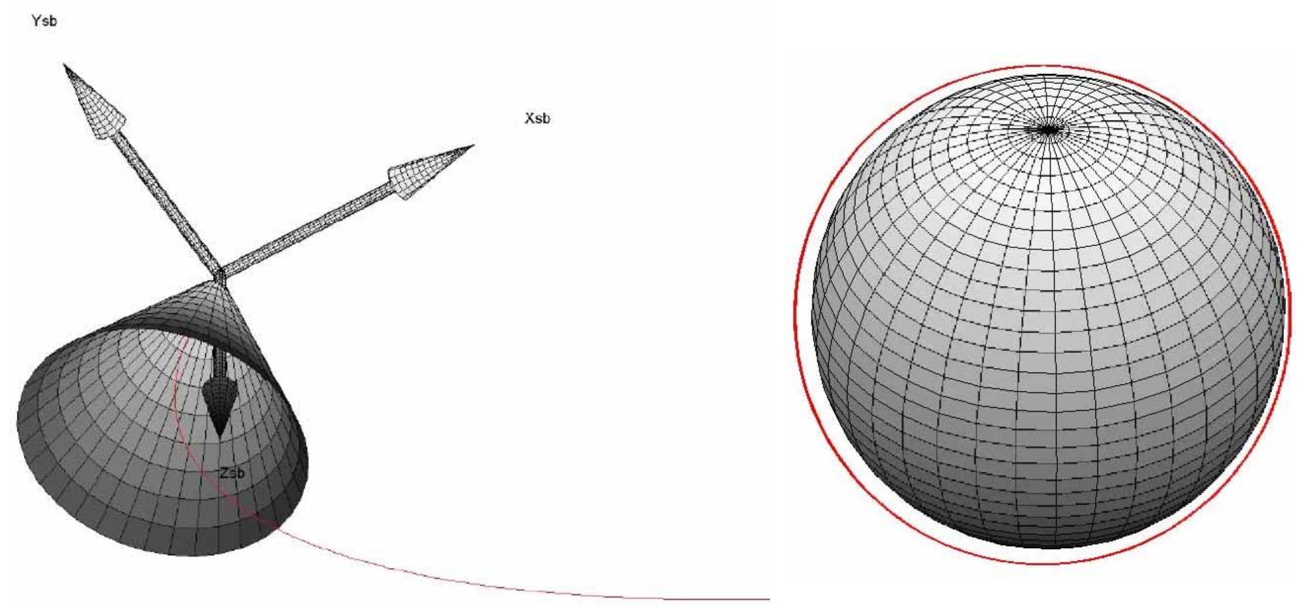
Fig. 5 - Hall thruster locations: ram side, left; wake side, right.

Performance Analysis

The propulsion subsystem performance was simulated with reference to the VLEO mission class, since this is the one with the most stringent orbit control requirements. The simulations were carried out on the basis of the theory of low-thrust maneuvers (ref. [2], [3] and [4]) implemented in a dedicated orbital propagator, the 'D-Orbit' code, developed in-house at Alta/Centrospazio. D-Orbit accounts for atmospheric drag (with either CIRA72 or MSISE90, day-averaged, rotating-atmosphere models) and J_2 to J_6 zonal gravitational harmonics, as well as for other perturbations such as lunar and solar gravitation, radiation pressure and effect of eclipses. Most important, the program can account for user-defined thrusting laws. Conservatively, a maximum solar flux MSISE90 atmospheric density model was assumed, together with a drag coefficient C_D = 2.2. The model, however, shows that the atmospheric density is affected only very marginally by the solar flux conditions at the very low altitudes of interest.

We present here the results of the mission simulation for one of the cases studied, used as a reference. The mission profile is as follows:

1. Robotic arm assisted undocking from the dedicated site on the ISS.
2. Departure from the ISS along the standard allowed corridors (Fig. 6, left).
3. Orbit semi-major axis lowering (circular orbit) to perform a shifting of the orbit plane for safety.
4. Eccentricity build-up and semi-major axis reduction to the operative orbit (e.g., 140 x 500 km, Fig. 6 right). Some scientific and sensing operations are possible during this phase.
5. Payload operation with active control for orbit maintenance (drag compensation).
6. Circularisation at higher orbit (e.g. 575 km), to reduce the shift between orbital planes (Fig. 7, left).
7. Orbit lowering with plane and phase control for ISS rendezvous (fig. 7, right).
8. Docking with the robotic arm and final parking at the dedicated site.



Fug. 6 - Departure form the ISS through the departure cone, left; operational orbit (drawing to scale), right.

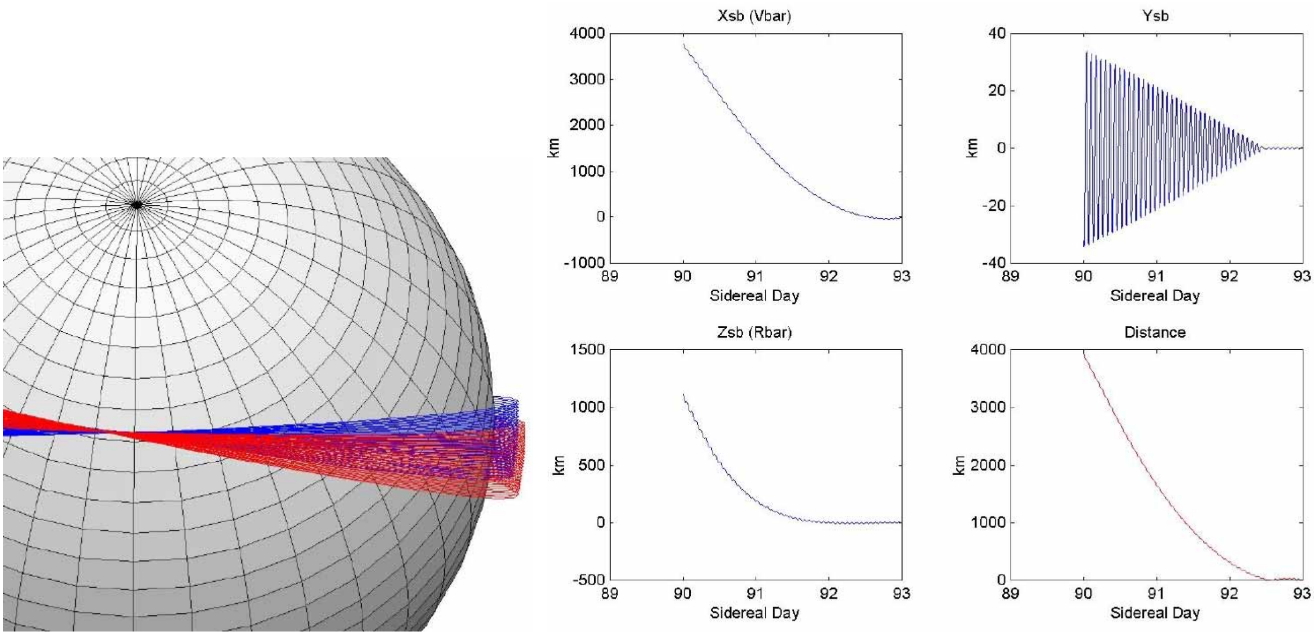


Fig. 7 - Orbit planes shift reduction: ISS orbits in blue, MOV orbits in red (left).
Time history of the relative distance during the rendezvous phase, right.

As a result of the simulations, the following parameters were determined:

- the minimum perigee altitude that can be achieved, still retaining sufficient security margins, and from which it is always possible to raise the vehicle back to the ISS orbit;
- the propellant mass that is required for each phase of the mission;
- the elapsed maneuvering time and the maximum allowed time in worst case operational conditions.

These data are summarized in Table 1.

Minimum achieved perigee altitude	**137 km** (on a 137 x 500 km orbit)
Propellant mass consumption during the orbit lowering phase	6.5 kg
Duration of lowering phase	17 days
Propellant mass consumption during the operational orbit maintenance phase	180 grams/day
Maximum duration of the maintenance phase (with 65 kg total loaded propellant, including contingency)	more than **200 days**
Propellant mass consumption during the raising and rendezvous phases	12 kg
Duration of rising and rendezvous phase (including coasting)	73 days

Table 1 - Simulation results for the reference mission profile.

With a total mass of propellant of 65 kg, the vehicle can spend more than six months in a orbit with a 140 km perigee, with a payload mass of about 120 kg, allowing for investigation of the scarcely know transition zone between the atmosphere and outer space. Such missions would be hardly viable with a disposable satellite launched from ground, while the MOV allows for flexible mission planning and for re-use of the spacecraft.

Conclusions

In spite of the very conservative assumptions made on the allowed mass and dimensions and on the availability of efficient electric power production and storage technologies, the results of this study show that, in principle, a ISS based Maneuverable Orbit Vehicle for exotic missions to very low Earth orbit is feasible. For the given operational requirements (i.e., autonomous navigation in altitude-controlled orbits), the use of electric propulsion is the only option to meet the goals within realistic mass (i.e., cost) limits.

The selected propulsion system, based on high power Hall effect thrusters, is an enabling technology with respect to a brand new class of scientific and Earth Observation missions, allowing to perform the required orbit control strategies with a reasonable propellant mass and electric energy consumption.

Many important aspects of the design of the MOV for very low Earth orbits were not studied in detail, such as the choice of materials to withstand the aerodynamic effects at low altitude and the telecommand/telemetry systems. Performance of the Hall thrusters at relatively high atmospheric density is not well understood, although some laboratory testing evidence indicates that the thruster should perform well enough at background pressures corresponding to the very low Earth orbit environment. Under this respect, ISS-formation flying missions would present no concern.

Acknowledgments

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