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# Aerodynamic Technologies for Earth Observation Missions in Very Low Earth Orbit

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**ABSTRACT**

Flying at VLEO has several advantages such as the increase of the resolution of images recorded by optical instruments, the increase of geospatial position accuracy, the improvement of the signal to noise ratio and the reduction of energy consumption by active payloads. However, the drag produced by the interaction of the atmospheric gas particles with the surfaces of the spacecraft requires an extended knowledge of orbital aerodynamics. The aim of this work is to carry out a study from the principles of orbital aerodynamics to the definition of requirements for a set of satellite platforms covering Earth Observation applications taking advantage of operating in Very Low Earth Orbit (VLEO) and making use of aerodynamic technologies. Four platform concepts were defined: optical coverage platforms, optical Very High Resolution (VHR) for high performance platforms, low cost optical VHR platforms and Synthetic Aperture Radar (SAR) platforms. In addition, the main orbit and attitude control operations to be done with these concepts were analyzed. A relation between the different mission concepts and the performances to be obtained with enhanced aerodynamics was established to identify which of the four platform concepts could perform as a commercial platform to guarantee the use for different applications.

**KEYWORDS: Aerodynamic Technologies, Earth Observation, VLEO, Aerodynamic Geometries, Satellite Operations, Attitude Control, Orbit Control, Aerostability, Aeroassisted Maneuvers.**

## 1 INTRODUCTION

Very Low Earth Orbits (VLEO) were defined as the orbits with a mean altitude below 450 km [1]. The operation of a satellite in these orbits can provide several benefits in the Earth Observation (EO) field:

- Increase in the resolution of optical payloads: resolution is directly proportional to altitude, then flying at lower altitudes with the same optical payload increases the resolution.
- Increase in the radiometric performance: radiometric techniques in optics characterize the distribution of the radiation's power in space. The power density of a signal is proportional to the inverse square distance from its source, i.e. the orbit altitude; therefore the power density increases in VLEO, improving the signal to noise ratio (SNR).
- Increase of geospatial position accuracy: the spacecraft is closer to the target; thus, for a given angular uncertainty on the pointing direction, the error in the location of a ground target is also reduced.
- Lower risk of collision with space debris: orbiting at VLEO could reduce the probability of collision with space debris.

- Low radiation levels: lower orbits are protected from solar radiation by the inner Van Allen belt and the Earth magnetic field. Flying at lower altitude also provides protection to the spacecraft from solar activity effects: for example, solar flares and coronal mass ejection.
- Non disposal maneuver is required: flying in VLEO, drag forces facilitate the re-entry of a satellite.
- Interaction forces and torques generated by a denser atmosphere can be used for orbital and attitude control. Besides, traditional attitude and orbit control systems can be supported or substituted (in some cases) by aerodynamic technologies.

Nevertheless, flying in VLEO with a satellite also presents the following challenges:

- The density of the atmosphere is low and it does not behave as a continuous fluid. The atmosphere at these altitudes is in free molecular flow (FMF). For instance, lift forces are much lower than drag forces.
- The time window for communications with the satellite decreases.
- The mean revisit time can also be reduced in optical satellites because the reduction in altitude implies a reduction of the field of view, given the same imager.

Therefore, designing a spacecraft flying at VLEO requires a multidisciplinary knowledge.

In this work, the analysis of the state of the art was first conducted both for aerodynamic technologies and operations in EO missions. The study started with the establishment of the principles of orbital aerodynamics, directed by the behavior of a body in free molecular flow, and the analysis of viable aerodynamic technologies and control strategies. Then, their applicability was studied in the Earth Observation field by considering four common types of platforms linked to well determined mission concepts: i) Optical coverage platform, ii) Optical Very High Resolution (VHR) for high performance platform, iii) Low cost optical VHR platform, iv) Synthetic Aperture Radar (SAR) platform.

The main orbit and attitude control operations to be done with these common platforms were analyzed. A relation between the different mission concepts and the performances to be obtained with enhanced aerodynamics was established to identify which of the four platform concepts could perform as a commercial platform in VLEO to guarantee the use for different applications.

## 2 VERY LOW EARTH ORBIT AERODYNAMICS

The effects of external disturbance torques from aerodynamic forces in orbit were not experienced until the launch of “paddlewheel” satellites in the late 1960s, such as the Explorer VI [2]. These satellites had solar cell paddles which experienced aerodynamic torques, causing spin-up of the vehicle. This caused these satellites to decay faster than expected. Similarly, aerodynamic lift in orbit was first experienced during the analysis of inclination in the S3-1 satellite [3], in 1977.

The design of a spacecraft for operating in VLEO requires knowledge of the aerodynamic forces and torques due to the interaction of the atmospheric gas particles with the surfaces of the vehicle. The main aerodynamic force experienced by a satellite in VLEO is drag, causing orbital decay and eventually re-entry. For instance, the use of aerodynamic torques and forces has been proposed for a number of different applications in spacecraft orbit and attitude control. In this section aerodynamics principles and applicability are identified.

### *2.1 Principles of orbital aerodynamics*

Spacecraft flying in low earth orbit have to perform under very demanding environmental conditions. In addition, flying at VLEO has additional atmosphere interaction, since its density is higher but not dense enough to be considered as a continuous fluid. For this reason, the flow regime at VLEO is typically considered as a free molecular flow rather than as a continuum flow regime.

Forces and torques occurring on a free body under FMF conditions are principally produced by the energy exchange taking place between the incident gas particles and the external surfaces. These Gas-Surface-Interactions (GSIs) are affected by the gas properties, the surface properties, the cleanliness of the surface, and the angle of interaction between the incident particles and the surface (Figure 1). In GSI mechanics, an energy accommodation coefficient describes how the kinetic energy of an incident gas particle is adjusted towards the thermal equilibrium with the surface. The surface adsorption and energy accommodation were observed to change in function of the orbital altitude and density, and they generally increase at lower altitudes. Typical accommodation coefficients for VLEO are in the range 0.85 to 1.00, see [4] and [5].

By considering the Sentman’s model, it is remarkable that aerodynamic lift in orbit is much smaller than drag [6]. Therefore, a satellite orbiting in VLEO might have the largest surface areas parallel oriented to the direction of the flow in order to minimize the drag force. This would decrease the decay rate of a satellite operating in such orbits.

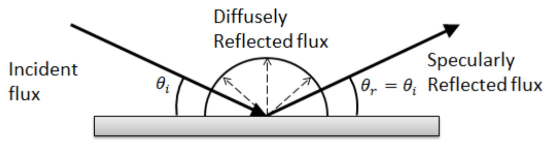


**Figure 1: Specular and diffuse reemitted particle fluxes ($\theta_i$ is the incident angle and $\theta_r$ the reflected angle).**

***2.2 Aerostability***

The aerodynamic forces and torques produced by the interaction with the residual atmosphere in VLEO can be used to provide stability in orbit, this is known as aerostability.

Stability is required for a spacecraft to maintain a pointing direction in a certain time period for different purposes such as taking images or communicating with a ground station. Below approximately 400 km these aerodynamic effects are generally the most significant disturbances to the satellite's orbit [2]. In order to achieve static aerostability, the center-of-pressure of the vehicle shall be located behind the center-of-mass, generating an aerodynamic bias. Thus, if the vehicle is disturbed from its equilibrium position with respect to the incoming flow, a restoring torque is generated. In practice, this can be achieved by moving the center-of-mass of the body forward or by placing additional aerodynamic surfaces towards the aft. However, whilst such a configuration can produce static stability, aerodynamic damping is not sufficient to ensure dynamic stability in the FMF environment of orbits above approximately 160 km and the spacecraft will therefore oscillate about the equilibrium point [7]. An angular damping rate is therefore necessary to support true aerostability and it can be provided by either passive methods (e.g. magnetic hysteresis rods or viscous dampers) [8] and [9] or active methods (e.g. magnetorquers or reaction/momentum wheels) [9].

***2.3 Aerodynamic attitude control***

No active aerodynamic attitude control has been demonstrated in orbit so far. However, some studies have investigated the possibility of performing pointing control and Geostationary Transfer Orbit perigee raising [10], [11] and [12].

The concept for pointing control by using aerodynamic forces and torques utilize aerodynamic control surfaces. Two principal configurations have been considered: shuttlecock [13] and feathered panel [14] designs. These configurations are analyzed in depth in Section 3.

***2.4 Orbit control***

Due to the predominance of drag in LEO, aerodynamic orbit control methods using this force have principally been studied and demonstrated. These maneuvers have included orbit maintenance, collision avoidance, and re-entry location targeting. Furthermore, for multiple satellite systems differential drag methods have been proposed and demonstrated for formation-keeping, rendezvous, and constellation maintenance purposes.

The first work on orbital maintenance using differential drag maneuvers was presented by Leonard et al. [15] with the aim of reducing the mass/fuel requirements and limiting propulsion system use. Later, du Toit et al. [16] proposed that the orientation of the satellite body itself could be used to modulate the drag force experienced and therefore perform constellation maintenance maneuvers. Numerous studies [17], [18], [19], [20], [21], [22] and [23] have further explored these concepts, considering adaptive and optimal control strategies and the role of uncertainties and perturbations including J2 and variations in the atmospheric density. Differential drag orbit control maneuvers in orbit were first demonstrated by the satellites of the ORBCOMM constellation for orbit maintenance [24]. Subsequent demonstration of differential drag maneuvers for formation-control of nanosatellite-class payloads has also been performed by the AeroCube-4 mission [25] of two 1U satellites with retractable wings for drag modulation, and the Planet Labs constellation of "Dove" satellites [26] and [27].

Horsley et al. [28] extended the work of differential drag for rendezvous and formation control by also considering differential lift, enabling modest control over the relative out-of-plane motion. A further reported benefit of the use of differential lift is the alleviation in the orbital decay which is associated with drag-based maneuvers.

The use of both in-plane and out-of-plane lift forces were proposed to do orbit control in [29] and [30].

***2.5 Aeroassisted maneuvers***

Aeroassisted maneuvers using a hybrid combination of propulsive maneuvering and aerodynamic maneuvers in the low atmosphere have also been considered in the literature. London in [31] presented the first work in this area on plane-change maneuvers. Aeroassisted maneuvers were proposed for in-plane and out-of-plane orbit-change maneuvers. The foundational work on these aeroassisted maneuver concepts was well reviewed by Walberg [32] and by Miele [33]. Aeroassisted maneuvers have typically been proposed for orbital transfers between LEO and HEO, often for Orbit Transfer Vehicle (OTV) operations. Applications of aeroassisted maneuvers for operations in LEO are comparatively sparse, and primarily address out-of-plane transfers.

## 3 AERODYNAMIC TECHNOLOGIES AND APPLICABILITY

The generation of aerodynamic forces in orbit depends on the characteristics of the materials used in the spacecraft surfaces and in its geometry. Next, both concepts and their applicability are analyzed.

### *3.1 Aerodynamic geometries*

Induced drag by the increased atmospheric density at VLEO causes an acceleration of the decay rate of the satellite's orbit, leading to a reduction in lifetime. At these orbits, spacecraft geometries might be optimized in order to mitigate this negative effect. Platforms might be as compact as possible and slender shaped in the axis coincident with the velocity direction. This would reduce the effect of drag, increasing satellite lifetime or enabling savings in propellant of a drag compensation propulsion system. A number of different spacecraft geometries and control surface concepts were proposed with the aim of improving drag characteristics and enabling aerodynamic control and maneuvering of spacecraft:

- Aft-located aerodynamic skirt [34]
- Off-centre weighted design [10]
- Aerodynamic fins [7]
- Shuttlecock design [13]
- Deployable wings [35]
- Movable panels [10]
- Wedge-shaped geometry [36]

A study of low-drag geometry spacecraft for VLEO was presented by Park et al. in [37], providing a comparison between geometries with different shaped front surfaces. In order to perform differential drag maneuvering deployable surfaces or variable geometries are required.

In order to stabilize the satellite without power consumption, stabilizer fins at its aft combined with passive dampers can be used. Some examples of approaches for stabilizing spacecraft by using aerodynamics are the following:

- Offset center of mass [38], [39] and [40].
- Space arrow [41].
- Aerostable fins [42].
- Space arrow and shuttlecocks [43] and [13].

Furthermore, to achieve set pointing angles, the aerostability can be used to assist the detumbling procedure of a spacecraft after launch and release [44].

Some technologies related to aerodynamic attitude control have been proposed: Gargasz in [10] first considered the shuttlecock configuration for a cubic satellite featuring split moving panels hinged from the top and bottom spacecraft surfaces, see Figure 2. This concept enables three-axis control of satellite using only aerodynamic torques. The ΔDSat concept introduced by Virgili Llop and Roberts in [11] utilized fins (Figure 3) to enable attitude control. The implementation of four steerable fins at the tail of the spacecraft would enable control in all the three rotation angles: roll, pitch and yaw. In addition, active dumping would enable up to 1º attitude control with respect to the oncoming flow. Mostaza-Prieto and Roberts in [12] presented the design of an optimal attitude maneuver with the consideration of the aerodynamic and gravity-gradient torques for the low-altitude perigee passage of geostationary satellites during electric orbit raising maneuvers. The solar arrays were optimally rotated during the perigee pass, taking advantage of the natural environmental torques. This action seemed to reduce requirements on active attitude control actuators avoiding saturation and momentum dumping.

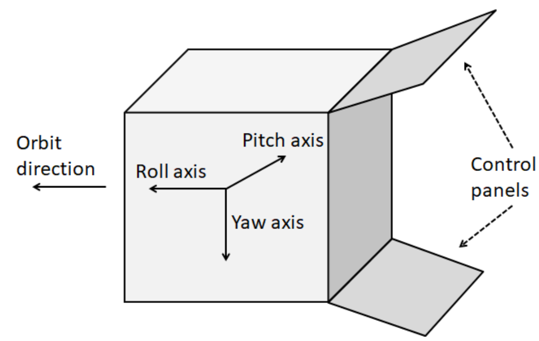


**Figure 2: CubeSat concept for 3-axis aerodynamic control.**

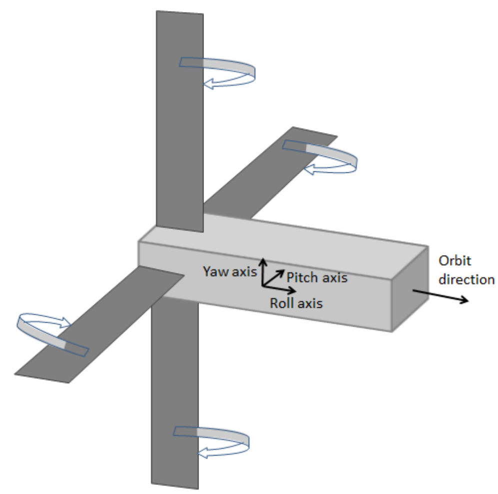


**Figure 3: External configuration of the ΔDsat CubeSat.**

### *3.2 Materials*

Due to the nature of GSIs in orbit, new materials are being researched. Materials with lower surface accommodation coefficients can encourage specular and quasi-specular particle reemission, and are resistant to contamination and erosion are therefore of key interest [6].

In addition, atomic oxygen, generated by the photo-dissociation of diatomic oxygen by ultraviolet radiation, is highly reactive and it is the most abundant atmospheric constituent between approximately 150 km to 650 km [45] and [6]. Materials which are adsorption and erosion resistant by atomic oxygen have therefore formed the bulk of research in this area so far.

Thus, numerous protective mechanisms and surface coatings for atomic oxygen protection were discussed by Reddy [4]. However, the aerodynamic properties of these treatments were not discussed beyond their resistance to atomic oxygen attack. More recent reviews of materials are provided by Banks et al. [5] and Samwel [45].

### *3.3 Application of aerodynamic technologies*

For general operations in VLEO, aerostable designs and low-drag geometries can support increased orbital lifetimes and enable attitude stability with respect to the oncoming flow velocity. Aerodynamic technologies can also counteract perturbation by external forces and perform detumbling operations generating torques up to $10^{-7}$ Nm at 500 km and up to $10^{-5}$ Nm at 300 km. While using aerodynamic control surfaces, coarse pointing capability up to 5º in pitch and yaw is expected to be achievable with existing materials.

The method for descending sun-synchronous orbit (SSO) inclination correction presented by Virgili Llop et al. in [36] is particularly applicable to Earth Observation missions that often occupy these orbits to take advantage of the regularity in local time of ascending node and therefore solar illumination angle.

Differential lift orbit control methods have also been proposed for Earth Observation constellation maintenance. Li and Mason [21] and Foster et al. [27] presented the in-plane constellation maintenance of the Planet Labs Flock constellation for Earth Observation. Similarly, Leppinen in [46] proposed a method to enable a multi-plane constellation to be deployed from a single insertion point, to optimize the constellation revisit time.

## 4. EARTH OBSERVATION APPLICATIONS AND OPERATIONS

### *4.1 Earth Observation applications for VLEO*

Circular SSO orbits at altitudes between 600 km and 1000 km are commonly preferred for EO applications due to the regular lighting conditions and the low aerodynamic drag effects. During recent years, the interest in operating small spacecraft at lower orbit altitudes has raised, due to the growing competitiveness in the commercial space market. Furthermore, recent studies have introduced the potential benefits of orbiting at VLEO [47], where the atmospheric drag is increased and the spacecraft flight dynamics is dominated by the aerodynamics forces.

EO applications take advantage of the higher resolutions achieved in lower orbits with the same optics. In general, flying at lower altitudes can seem convenient for missions in which very high resolution is needed. Besides, flying at VLEO implies higher orbital velocity. This, in principle, may seem that a target can be acquired more frequently. However, for a given payload, if it is acquiring images at a lower altitude, the swath is proportionally reduced to the reduction of altitude, and for instance, it can reduce the frequency at which the target can be acquired, i.e. the time to revisit a spot of land can be increased which may reduce the time at which a target can be.

According to the resolution and revisit time conditions of a mission in VLEO some EO applications which are feasible for VLEO are shown in Table 1. In the following sections a deeper analysis of the aerodynamic technologies and platform concepts is carried out.

### *4.2 Operations in Earth Observation missions*

The type of mission has a strong impact in the configuration of the satellite and imposes important requirements on the attitude and orbit control. In the analysis of operations in EO missions, the four most representative types of platforms were selected:

- Optical coverage: the objective is to record the surface characteristics of large targets such as regions, countries or coast profiles. A wide swath is required. Thus attitude control requirements are not very demanding, while image stabilization is enhanced. Agility is often not required since nadir pointing is the most frequent pointing mode. The following representative examples can be considered: Deimos-1, Sentinel-2, Flock constellation.
- Optical VHR high performance: this group of satellites is part of EO missions with tactical purposes that make use of optical payloads with very high resolution integrated on very agile platforms. Attitude requirements are very demanding for these missions as well as orbit control for precise location when imaging. The following spacecraft can be considered as examples: Pleiades-HR, WorldView-4.
- Optical VHR low cost: this type of platforms is also applied for tactical purposes with very high resolution images. However, they have smaller, lighter, cheaper and simpler platforms: Deimos-2, RapidEye, SkySat constellation.

**Table 1: Feasibility of EO applications for VLEO**

| Group | Application | GSD (m) | Revisit time |
|---|---|---|---|
| **Forest** | Forest Management | 0.5-10 | 1.5months-1year |
| **Agriculture** | Precision Agriculture | 2.5-100 | 5days-1month |
| | Illicit crops detection | 1-30 | < 1 day |
| | Crop type and health | 2.5-100 | 5days-1month |
| | Vegetation Land Cover & Analysis | 2.5-100 | 5days-1month |
| **Water Management** | Water properties | >5 | 10h-1month |
| **Land** | Minerals, soils and sediments | >10 | 1year-10years |
| | Mapping | 0.5-100 | 1year-10years |
| **Atmosphere** | Meteorology | >100 | 1h-1day |
| **Crisis Response** | Volcanic eruptions, forest fires and large-scale weather-related events | >7.5 | 2h-2days |
| | Flood Risk Analysis | 5-10 | 1day/1year |
| **Urban** | Traffic | 0.5-1.5 | 30min-1day |
| | Urban Development | 0.1-10 | 1year-10years |
| **Marine** | Maritime surveillance | 1-30 | 10min-1month |
| | Oil spill monitoring | 1-30 | < 1 day |
| | Fishing Activity | 1-30 | 10min-1month |
| | Piracy | 1-30 | < 1 day |
| | Port activity | 1–5 | 1 h-1month |

- Synthetic Aperture Radar (SAR): many EO missions are based on radar image acquisition. SAR payloads have advantages such as all-weather capability, day and night operability and are complementary of optical applications as radar is sensitive to dielectric constant, surface roughness, penetration, and slope among other parameters. The following selection includes a list of relevant missions with SAR payloads: TerraSAR-X, Sentinel-1, EnviSat, COSMO-SkyMed Second Generation constellation.

These are the common concepts that are currently covering the demand of commercial EO products provided by singularly operated and constellations of optical satellites and SAR satellites [48]. In the case of VHR concepts, they were divided into two sets: high performance and low cost. The reason is that the type of platform used in terms of mass, volume and instrumentation differ a lot from one concept to the other, VHR low cost being much smaller and with more reduced instrumentation.

For all the four concepts, performances were classified for individual analysis. All the performances were the same for all the mission types, except for orbit maintenance:

- Orbit maintenance: it is particularly important for EO missions and requires keeping the orbit within a narrow range of altitudes, inclination and LTAN/LTDN. In VLEO the most important perturbation is atmospheric drag. Table 2 shows the differences for each mission type.
- Collision avoidance: Manoeuvres to avoid collisions are estimated to be 2 per year.
- Nominal orbit insertion: The design must consider deviations in nominal orbit insertion values and maneuvers to correct them at early mission stages. The values are +/- 50 km SMA, +/- 1 deg inclination.
- Rephasing: Phasing is the relative position between satellites of a constellation in the orbit. Phasing maintenance is called rephrasing. It is estimated to require 2 manoeuvres.
- Deorbiting: Deorbiting to reduce space debris is usually achieved taking advantage of drag. VLEO altitude leads to a drastic reduction in the lifetime, it can be compensated increasing the ballistic coefficient or a propulsion system to compensate the drag and maintain the orbit. A satellite in LEO should be able of re-entering in less than 25 years after the end of operations.

**Table 2: Orbit control performances summary**

| | Optical coverage | Optical VHR high perform | Optical VHR low cost | SAR |
|---|---|---|---|---|
| **Orbit maintenance** | **Lifetime (years)** | | | |
| | 3-7 | 5-7 | 4-7 | 5-10 |
| | **Typical orbit** | | | |
| | SSO LTAN/ LTDN 10:30 | SSO LTAN/ LTDN 10:30 | SSO LTAN/ LTDN 10:30 | SSO Dawn/ Dusk LTAN/ LTDN 06:00 |

**Table 3: Attitude control performances summary**

| | Optical coverage | Optical VHR high performance | Optical VHR low cost | SAR |
|---|---|---|---|---|
| **Agility** | 3-axis<br>> 0.5º/s. | 3-axis<br>Up to 60º with 1.7-2.4º/s. | 3-axis<br>Up to 45º > 1º/s. | 3-axis<br>Up to 30º > 0.4º/s. |
| **Pointing accuracy** | < 5 arcsec. | < 1.5-2 arcsec. | <108-720 arcsec. | < 36-360 arcsec. |
| **Stability** | 3-axis<br><20-44 µrad/s | 3-axis | 3-axis<br><160 µrad/s | 3-axis |
| **Other control performances**<br><br>**I. Detumbling**<br>**II. Perturbances** | I. Reducing the initial rate under 1 deg/sec each axis within 24 hours protecting Payload from sunlight. | | | |
| | II. Torque of $10^{-4}$ Nm order of magnitude from solar radiation. | II. Torque of $10^{-2}$ Nm order of magnitude from gravity gradient. | II. Torque of $10^{-3}$ Nm order of magnitude from gravity gradient. | II. Torques of $10^{-4}$ Nm order produced by solar radiation, gravity gradient and aerodynamic forces. |

Table 3 collects the common performances for attitude control for the four concepts. The values reflect an average of the representative satellites for each concept (visit https://directory.eoportal.org). The common attitude control performances are described as follows:

- Agility: it is the operational capacity of the satellite to reach certain roll and pitch angles and slew rates.
- Pointing accuracy: Attitude control is responsible for pointing the satellite in the desired direction in the space at any given time. EO usually requires a 3-axis control with pitch, roll and yaw to correct the earth movement.
- Stability: Low (drift) and high frequency (jitter) satellite motions must be considered. In EO applications jitter is the most important in order to avoid blurry acquisition data.
- Other control performances: Detumbling and disturbance torques impact the attitude control and must be compensated.

Every concept presents differences in the orbit and attitude operations. Even when operations are common the performance values are of different magnitude. Besides, the VHR concepts present the most demanding requirements for agility and pointing accuracy. In the case of SAR platforms, the common orbital selection is remarkable: dawn-dusk SSO, which is optimum for the operational concept in terms of reduction of eclipses and energy acquisition optimization.

## 5 ANALYSIS OF EARTH OBSERVATION APPLICATIONS USING AERODYNAMICS TECHNOLOGIES

The previous concepts are here related with the application groups in Table 1 attending to their operations. The relations between concepts and applications are used to conclude in which applications the identified aerodynamic technologies would have the biggest impact. In Table 4 the applications are linked to every platform concept. The selection was made in a qualitative way according to the grade of achievement of the key requirement: spatial resolution, spectral resolution, image quality and agility by every concept and for every application. Notice that forestry, agriculture, crisis response and marine applications are related to all four concepts, while urban applications, which are more tactical, are linked to VHR concepts. In addition, those applications which require covering wide areas of land are covered by optical coverage and SAR concepts.

**Table 4: More frequent EO applications carried out by each platform concept**

| Optical Coverage | Synthetic Aperture Radar | Optical VHR low cost | Optical VHR high performance |
|---|---|---|---|
| Forestry, Agriculture, Crisis response, Marine | | | |
| Land, Atmosphere, Climate change, Water management | | Urban | |

The analysis is concluded by relating the aerodynamic technologies described Section III to the different concepts and the attitude and orbit operations that can be done with them, see Table 5. Most orbit control operations are similar for every defined platform concept and there are clear differences in the attitude control performances requirements for every concept.

**Table 5: Relation between aerodynamic technologies and platform concepts through operations**

<table>
<tr><th></th><th>Optical coverage</th><th>Optical VHR high perform.</th><th>Optical VHR low cost</th><th>SAR</th></tr>
<tr><td>Orbit maintenance</td><td colspan="4">Aerodynamic geometries: Aerodynamic forces for orbital station-keeping.</td></tr>
<tr><td>Collision avoidance</td><td colspan="4" rowspan="2">Aerodynamic geometries: Aerodynamic forces for altitude variation.</td></tr>
<tr><td>Nominal orbit insertion</td></tr>
<tr><td>Rephasing</td><td colspan="4">Aerodynamic geometries: Aerodynamic forces for constellation maintenance.</td></tr>
<tr><td>Deorbiting</td><td colspan="4">Aerodynamic geometries: Creation of aerodynamic forces for deorbiting.</td></tr>
<tr><td>Agility</td><td colspan="4">N/A: The very low lift-to-drag ratios do not provide similar performance to classical technologies.</td></tr>
<tr><td>Pointing accuracy</td><td colspan="4">Aerodynamic Control Surfaces: Up to 5deg in pitch and yaw. With four steerable fins and active dumping up to 1deg of attitude control seems achievable with respect to the oncoming flow.</td></tr>
<tr><td>Stability</td><td rowspan="2">Aerodynamic skirt, Off-center weighted design, Aerodynamic fins, Shuttlecock design: Torques up to $10^{-7}$ Nm at 500km.</td><td colspan="2" rowspan="2">N/A: Generated torques are not enough to stabilize nor correct great perturbances.</td><td rowspan="2">Aerodynamic skirt, Off-center weighted design, Aerodynamic fins, Shuttlecock design: Torques up to $10^{-5}$ Nm at 300km.</td></tr>
<tr><td>Other control performances: detumbling and perturbances</td></tr>
</table>

For instance, orbit maintenance can be improved in all four concepts by incorporating in the platform some aerodynamic geometries that make the platform more aerodynamic with the objective of reducing drag forces, such as to increase the ballistic coefficient, or use drag and lift forces to support orbit corrections when propulsion is used. Besides, collision avoidance, nominal orbit insertion, rephasing and deorbiting can be supported by aerodynamic geometries making use of drag forces mainly. However, using aerodynamic geometries that make use of drag and lift forces directly affect to orbit decay, and for instance to the lifetime of the satellite if the altitude loss is not recovered by a propulsion system.

The expected performances of the aerodynamic technologies in both orbit and attitude control operations can be used to make a selection of those techniques that can potentially be used for the different mission concepts.

In the case of agility, the use of aerodynamic technologies do not provide higher performance than classical attitude control methods (as e.g. reaction wheels or control moment gyros), however they can be used in combination with them to improve the overall performance, for example to recover reaction wheels from saturation. Nevertheless, they could be used alone to provide pointing accuracy in the order of 5 degrees in pitch and yaw angles, to stabilize optical coverage and SAR concepts and to do detumbling or compensate external perturbations up to $10^{-5}$ Nm.

## 6. CONCLUSIONS

On the one hand, optical coverage and SAR concepts focus in the same group of applications. On the other hand, VHR low cost and VHR high performance missions share the same group of applications between them.

The analysis concluded that optical coverage and SAR concepts seem to be the most appropriate to use aerodynamic technologies, while VHR concepts impose very demanding requirements in agility and pointing accuracy which cannot be provided by aerodynamic technologies alone with the existing technology. Most promising aerodynamic technologies are related to the configuration design of the platform body and addition of aerodynamic surfaces to perform aerostability operations and disturbance torques mitigation applied to Optical Coverage and SAR missions. Aerodynamic technologies can also be used for orbit control operations such as orbit maintenance, collision avoidance, nominal orbit insertion, rephasing and deorbiting. However, because of the increase in drag forces, these maneuvers would be lengthy in time and would reduce the orbital lifetime, demanding additional propulsion for altitude maintenance.

In terms of attitude control operations the current SoA and research on aerodynamic technologies conclude that there are not suitable aerodynamic technologies at this moment to cover demanding agility operations in orbit, as the provided slew rates do not fulfil the attitude requirements of commercial missions, which can be easily fulfilled with reaction wheels and control moment gyros. However, they could be used for aerodynamic trim if they are combined with traditional actuators. For instance, attitude pointing based on aerodynamics is theoretically possible and can have applicability, such as coarse pointing maneuvers or reduce the load supported by reaction wheels.

Aerodynamic geometries such as the aerodynamic skirt, off-centre weighted design, aerodynamic fins and shuttlecock design could be of interest in the case of aerostability and mitigation of disturbance torques for Optical Coverage and SAR missions. Besides an increase of the ballistic coefficient would reduce the drag and increase lifetime. The same effect would have further research with specular materials.

Improvement in the previous described technologies is expected to be achieved within the DISCOVERER European H2020 project to improve EO applications with satellites flying in VLEO.

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