D2.1
VLEO Aerodynamics Requirements Document

Project acronym:	DISCOVERER
Grant Agreement:	737183
Project Duration:	1 January 2017 – 31 March 2021 (51 months)
Version:	1.0
Date:	23/03/2018
WP Leader:	Jonathan Becedas [DEIMOS]
Authors:	Gerardo González [DEIMOS] Rosa M. Domínguez [DEIMOS] Irene Vázquez [DEIMOS] Álvaro Braña [DEIMOS] Nicholas H. Crisp [UNIMAN] Jonathan Becedas [DEIMOS]
Due date of deliverable	31/03/2018
Actual submission date	31/03/2018

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AOCS	Attitude and Orbit Control System
AoP	Argument of Perigee
CMG	Control Moment Gyroscope
CoG	Centre of Gravity
ECSS	European Cooperation For Space Standardization
EO	Earth Observation
FMF	Free Molecular Flow
FOV	Field Of View
FOR	Field Of Regard
GSI	Gas-Surface-Interaction
GTO	Geostationary Transfer Orbit
HEO	High Earth Orbit
IFOV	Instantaneous Field Of View
LEO	Low Earth Orbit
LTAN	Local Time of Ascending Node
LTDN	Local Time of Descending Node
MTF	Modulation Transfer Function
OTV	Orbit Transfer Vehicle
P/L	Payload
RAAN	Right Ascension of Ascending Node
S/C	Spacecraft
SAR	Synthetic Aperture Radar
SMA	Semimajor Axes
SSO	Sun-Synchronous Orbit
VHR	Very High Resolution
VLEO	Very Low Earth Orbit

1. INTRODUCTION

This document is the result of an in depth 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. To obtain relevant and sustained results the analysis of the state of the art was first conducted and used to develop a subsequent definition of requirements for mission concepts with enhanced aerodynamics.

The study starts with the establishment of the principles of orbital aerodynamics, directed by the behaviour of a body in free molecular flow, and the analysis of viable aerodynamic control strategies, which are classified into four control methodologies: aerostability, attitude control manoeuvres, orbit control and aeroassisted manoeuvres (Section 2).

To implement those control methodologies, the different aerodynamic technologies were identified and analysed. We established two sets of technologies: aerodynamic geometries and materials; and we evaluated the applicability of these technologies in the Earth Observation field (Section 3).

This led us to analyse the different benefits and challenges of flying at VLEO, and establish a relation with the different applications that can be covered with satellites flying at low altitude (Section 4).

By taking into account the benefits of flying at VLEO (as e.g. the increase of the resolution of images recorded by optical instruments since they are nearer the target, the increase of geospatial position accuracy, the improvement of the signal to noise ratio and the reduction of energy consumption) and the applications that could be covered, we defined four mission concepts with very different platform concepts. These are the following: 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 analysed (Section 5).

Later, 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 (Section 6).

And finally, for the most apt concepts and their applications a set of requirements with emphasis on attitude and orbit control were defined and validated (Section 7). Some additional sections support the content of the document: Section 8 the acknowledgements, Section 9 the references, and Section 10 is a manual explaining the requirements management and the tool used for this purpose, included as an annex to the document.

2. VLEO AERODYNAMICS

The design of a spacecraft for operating in VLEO requires knowledge of the aerodynamic forces and torques caused by 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. By considering this effect in the design of the satellites, the decay effect can either be reduced or compensated for.

The effects of external disturbance torques from aerodynamic forces in orbit was not experienced until the launch of "paddlewheel" satellites in the late 1960s, such as the Explorer VI [1]. 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 [2], in 1977.

The use of aerodynamic torques and forces has subsequently been proposed for a number of different applications in spacecraft orbit and attitude control. In order to implement these control applications a range of control techniques and associated geometries have been conceptualised and developed. Furthermore, materials which can reduce orbital drag and improve atomic oxygen resistance are also under investigation with the potential to support the realisation of these aerodynamic control applications.

Among the aerodynamic control methods proposed so far, both spacecraft aerostability and differential drag manoeuvres have been successfully performed by in orbit missions. However, active aerodynamic attitude control and out-of-plane orbit manoeuvring are still to be demonstrated.

2.1. PRINCIPLES OF ORBITAL AERODYNAMICS

Spacecraft flying in VLEO operate in space conditions, and therefore have to perform under demanding conditions regarding vacuum[1], radiation[2], temperature[3], and effects that materials in space can suffer such as outgassing[4] and electrical charging[5] in order to survive the mission lifetime[6]. In addition, flying at VLEO has additional atmosphere interaction, since its density is higher. However, the atmosphere is not dense enough to be considered as a continuous fluid. For this reason, the flow-regime is typically considered as a free-molecular flow (FMF) rather than a continuum flow regime, which exists at lower atmospheric altitudes. In this FMF regime, the residual atmospheric gas can be considered particulate in nature and features very few collisions between constituent molecules. The 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. A review of different GSI models is presented by Mostaza-Prieto et al. [3].

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. A higher accommodation coefficient increases the angular distribution of the particle reemission from specular reemission towards completely diffuse reemission (see Figure 1). The adsorption of atmospheric

[1] Requirement DISCR030
[2] Requirement DISCR040
[3] Requirement DISCR050
[4] Requirement DISCR060
[5] Requirement DISCR240
[6] Requirement DISCR200

particles onto the spacecraft body causes surface contamination and increases surface accommodation. The surface erosion due to the collisions with energetic and reactive particles (primarily atomic oxygen) can also increase the energy accommodation. Besides, clean surfaces generally have a greater level of quasi-specular reemission, whilst contaminated surfaces have a diffuse distribution of the reemitted particles. The surface adsorption and accommodation were observed to change in function of the orbital altitude and density, and they generally increase at lower altitudes. Typical accommodation coefficients for LEO are in the range 0.85 to 1.00 [4], [5].

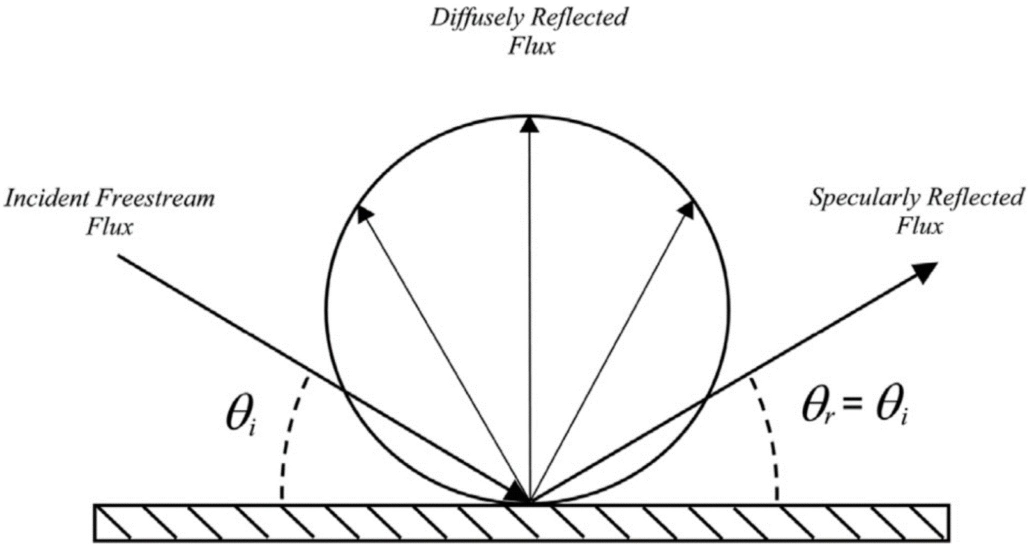


Figure 1: Specular and diffuse reemitted particle fluxes.

As previously introduced, the main aerodynamic force in orbit is drag, which acts opposite to the velocity vector of the satellite. Aerodynamic lift in orbit is much smaller than drag (according to Sentman's GSI model as shown in Figure 2), due to the characteristics of the GSIs and the typically quasi-diffuse distribution of the reemitted particles for most of the surfaces and materials used in LEO satellites. Therefore, a conclusion can be extracted from this figure: a satellite orbiting in VLEO might have the largest surface areas in 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.

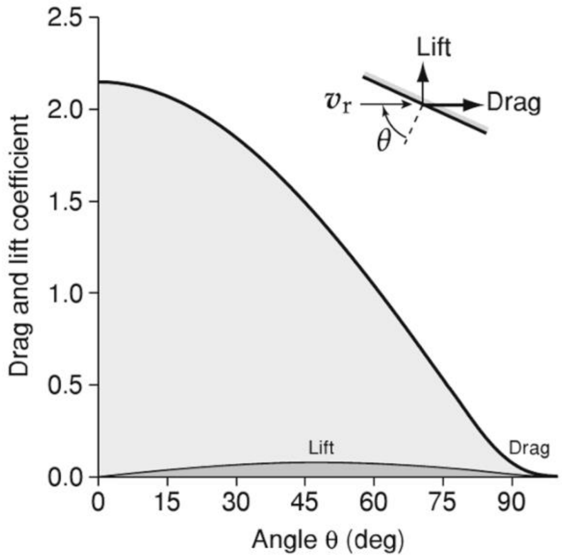


Figure 2: Drag and lift coefficients for a flat-plate at different incidence angle θ calculated by using Sentman's model [6].

2.2. AERODYNAMIC CONTROL

The aerodynamic forces and torques produced by the interaction with the residual atmosphere in LEO can be used to provide stability in orbit, attitude control capabilities, and to perform orbital manoeuvres. Due to the increase in atmospheric density, the magnitude of these effects generally increases with decreasing orbit altitude. Below approximately 400 km these aerodynamic effects are generally the most significant disturbances to the satellite's orbit [1] and may therefore be used to effectively control the attitude or orbital parameters.

2.2.1. Aerostability

The aerodynamic attitude stabilization of a satellite, also known as aerostability, can be a desirable property for vehicles operating in the LEO environment.

In order to achieve static aerostability, the centre-of-pressure of the vehicle should be located behind the centre-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 centre-of-mass of the body forward or by placing additional aerodynamic surfaces towards the aft.

However, whist such a configuration can produce static stability, aerodynamic damping is not sufficient to ensure dynamic stability in the FMF environment of LEO above approximately 160 km and the spacecraft will therefore oscillate about the equilibrium point. An angular damping rate is therefore necessary to support true aerostability and can be provided by either passive methods (e.g. magnetic hysteresis rods or viscous dampers) or active methods (e.g. magnetorquers or reaction/momentum wheels).

A possible solution for an aerostabilized satellite in VLEO would be a satellite provided with stabilizer fins at its aft combined with passive dampers, in order to stabilize the satellite without any power consumption. Some examples of approaches for stabilizing spacecraft by using aerodynamics are described in the following sections.

2.2.1.1. Offset Centre of Mass

The NASA Passive Aerodynamically Stabilised Magnetically-damped Satellite (PAMS) launched in 1996, demonstrated aerostability with a cylindrical vehicle design. In order to provide the restoring torque, the centre-of-mass of the satellite was shifted forward by using a thicker shell at one end of the cylinder, indicated in Figure 3 [7], [8]. This geometry was shown by Rawashdeh and Lumpp [9] to produce restoring pitch torques (normalised to velocity and density) of the order of $1.5 - 2.0\ Nm^2/kg$. For this spacecraft, passive damping in pitch and yaw were provided by internal magnetic hysteresis rods, whilst the roll-axis was not stabilised or controlled.

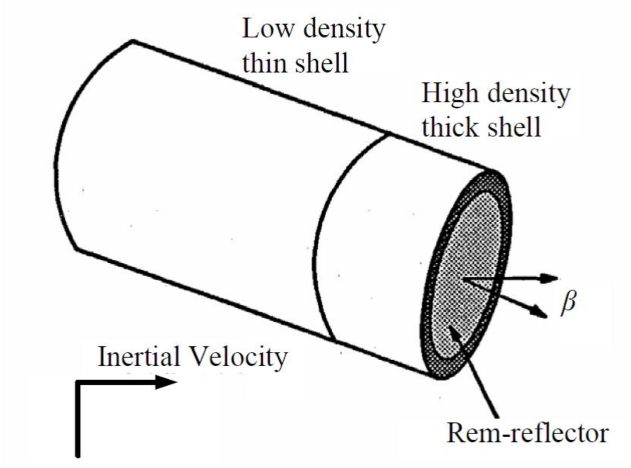


Figure 3: Representation of the NASA Passive Aerodynamically Stabilised Magnetically-damped Satellite (PAMS).

2.2.1.2. Space Arrow

The first demonstration of aerodynamically stabilised satellites was performed by the Soviet Union with the DS-MO satellites, shown in Figure 4. The Cosmos 149 and 320 missions were launched in 1967 and 1970 respectively. They presented an aerodynamic skirt stabilisation device located in the posterior part of the main body, termed a “Space Arrows”. The damping for this mission was provided by two gyroscopes connected to the satellite body through a viscous-spring restraint [10].

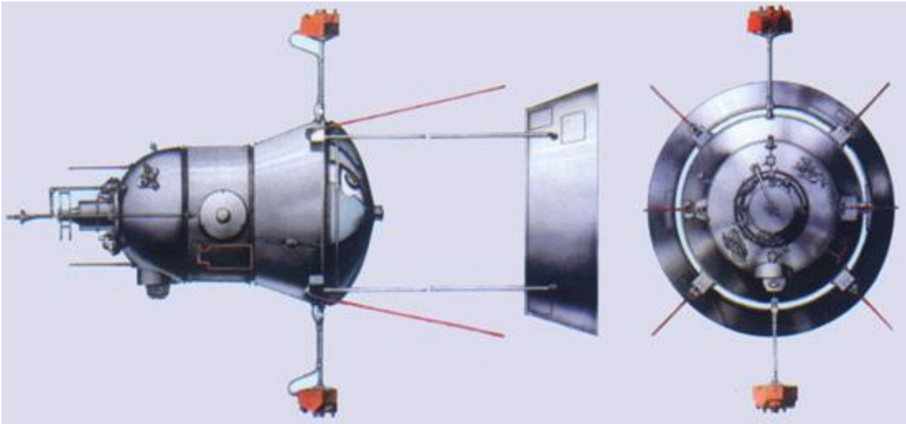


Figure 4: DS-MO "Space Arrow" satellite with aerodynamic skirt stabilisation [image credit: KB Youzhnoie].

2.2.1.3. Aerostable Fins

The ESA Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission launched in 2009, utilised fins/winglets to provide passive stability [11], see Figure 5. However, the attitude of the spacecraft was principally operated in a three-axis stabilised mode using magnetorquer actuators and a range of attitude determination sensors. An ion-propulsion thruster assembly was also utilised to compensate the effects of aerodynamic drag in the in-track direction.

Figure 5: ESA Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) spacecraft [image credit: ESA].

2.2.1.4. Space Darts and Shuttlecocks

More recently, the QbX satellites (also known as Colony-1), launched by the US Naval Research Laboratories in 2010, have demonstrated aerostability on a 3U CubeSat platform. These “Space Dart” satellites, shown in Figure 6, use additional deployable solar-panels in a shuttlecock configuration to provide passive aerodynamic pitch and yaw stability. Active damping was provided by using a combination of three-axis magnetometer, magnetorquers and model-based B-dot control law. Whilst in-orbit results regarding the attitude control performance of the QbX satellites have not been published, the analysis of this design carried out by Armstrong et al. [12] indicated a pointing capability of less than 5° error with respect to the flow. A comparison of control capability at different altitudes also showed that stiff aerodynamic-stabilisation would be available at low-altitudes (torques of 10^{-7} to 10^{-5} Nm at 300 km), whilst at higher altitudes aerodynamic torques would be of similar magnitude to gravity gradient torques (10^{-8} to 10^{-7} Nm at 500 km), thus diminishing control performance.

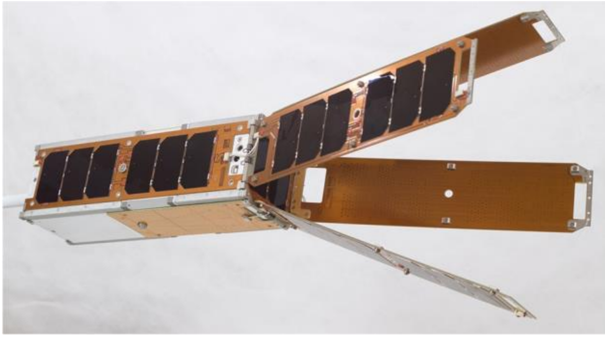


Figure 6: QbX "Space Dart" or shuttlecock design satellite [image credit: Pumpkin].

Further concepts for aerostable satellites including three-axis stabilisation are present in the literature. Psiaki [13] presented the design of a 1U CubeSat with a shuttlecock design of four flexible magnetic “feathers” which provide stability in pitch and yaw. An active system utilising magnetorquers is used to provide damping in the pitch and yaw axes and to provide control in the roll axis. The simulated results for altitudes below 450 km indicate best-case steady-state pointing errors of 2° and worst-case results of approximately 25° in each axis when the aerodynamic twist of the feathers, the off-set of the centre-of-mass, and the classical/parametric resonances are considered.

Rawashdeh and Lumpp [9] considered the design of CubeSats for operation below 500 km using either passive magnetic or active B-dot angular rate damping methods. Two 3U satellites with a shuttlecock configuration (similar to the QbX satellites) were first studied and found to achieve a steady-state tracking accuracy of 10° to 20° using passive damping, and less than 0.1° using active damping. Maximum restoring torques (normalised to velocity and density) of 2.0 Nm^2/kg and approaching 2.5 Nm^2/kg were generated by the four deployable panels (10 x 3 cm) at an angles of 50° and 20° respectively. Secondly a 1U CubeSat with four tape-measure fins (2.5 cm x 2.5 cm) was examined and reported to achieve similar steady-state tracking accuracies with a significantly smaller restoring torques (0.15 – 0.20 Nm^2/kg). The similarity in pointing performance with a substantially smaller area of aerodynamic surface is attributed to the low gravity gradient torques experienced by the 1U CubeSat in comparison to the 3U platform.

The design of an aerostable CubeSat, named ΔDSat, with a configuration of four steerable fins was presented by Virgili Llop et al. [14] , [15]. It is shown in Figure 8. The active magnetic damping produced a pointing capability of less than 2° error with respect to the oncoming flow. An active aerodynamic damping technique was also presented, based on switching the steerable fins from their nominal deflection to higher and lower deflections to control the angular velocities in pitch and yaw. In each case, the roll of the vehicle is controlled using magnetorquers as currently realisable lift-to-drag ratios (<0.1) are not capable of generating the required lift force to provide effective roll control. In the given example the attitude of the spacecraft with respect to the oncoming flow is shown to oscillate with an amplitude of approximately 1° in each axis.

The design of passively aerostable satellites is also investigated by Mostaza-Prieto and Roberts [16]. The static stability of different vehicle shapes is first presented before the dynamic response of a feathered CubeSat design is examined. The effect of varying dynamic pressure was also explored by enabling the identification of the vehicle stability for different orbit regimes.

2.2.1.5. Detumbling

In addition to achieving set pointing angles, the aerostability can be used to assist the detumbling procedure of a spacecraft after launch and release[7]. Typical angular velocities of a spacecraft after the separation with the launcher are of the order of 3 deg/s [17]. A slender-shaped spacecraft provided with stabilizer fins at its tail and a passive damping system would be able to passively align its longitudinal axis with the path direction without any power consumption, performing thus a de-tumbling manoeuvre based on aerodynamic forces.

Hao and Roberts [18] presented a modified B-dot control method to reduce the power required by magnetorquer control actuators by 36% during the detumbling process into a flow-pointing attitude. However this method did not consider the loss of altitude during the extended detumbling process and therefore the reduction of the orbital lifetime.

2.2.2. Aerodynamic Attitude Control Manoeuvres

No active aerodynamic attitude control has been demonstrated in orbit so far. However, a number of studies have investigated attitude control capabilities beyond simple aerostability.

2.2.2.1. Aerodynamic Pointing

The concepts for pointing control by using aerodynamic forces and torques utilise aerodynamic control surfaces, which can enable some attitude control. Two principal configurations have emerged from the previous work on aerostable systems, shuttlecock and feathered panel designs.

Gargasz [19] first considered the shuttlecock configuration for a cubic satellite featuring split moving panels hinged from the top and bottom spacecraft surfaces (Figure 7). This concept enables three-axis control of satellite using only aerodynamic torques. The simulations presented, albeit reduced-order and using limited fidelity models, demonstrate that both three-axis stabilisation and pointing control of up to 5° is feasible from a range of initial conditions using this design. The accommodation coefficients of 0.8 indicating quasi-specular GSIs were assumed in these simulations.

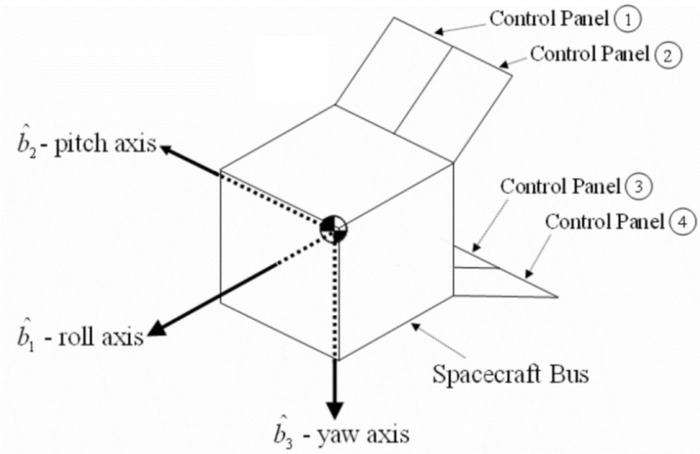


Figure 7: CubeSat concept for 3-axis aerodynamic control.

[7] Requirement DISCR170

The ΔDSat concept introduced by Virgili Llop and Roberts [20] utilises a feathered panel configuration (Figure 8) to enable pointing control of up to 4° with respect to the oncoming flow. The implementing four steerable fins at the tail of the spacecraft would enable control in all the three rotation angles: roll, pitch and yaw. The spins in roll can be achieved by counter-rotating the opposing steerable fins the same angle, generating lift in the opposite direction. This induces a torque that causes a rolling rotation. The spins in pitch and yaw can be performed by a co-rotation of the respective opposing fins, generating a torque, because the centre of aerodynamic pressure is placed behind the spacecraft.

Remembering Figure 2, the drag coefficient is always higher than the lift coefficient. Even when the lift coefficient reaches its maximum at 45º deflection, it is of the order of 10^{-1}. Therefore, for manoeuvres that require a high slew rate, this steerable fin approach is not competitive enough, as induced aerodynamic torques are very low. In order to achieve higher torques, larger fins might be used, which, when they are not oriented parallel to the oncoming flow direction, induce a higher drag force which is undesirable for satellite lifetime. Nevertheless, attitude pointing based on aerodynamics is theoretically possible and can have applicability, such as coarse pointing manoeuvres or to reduce the loading on active attitude control systems such as magnetorquers and reaction wheels.

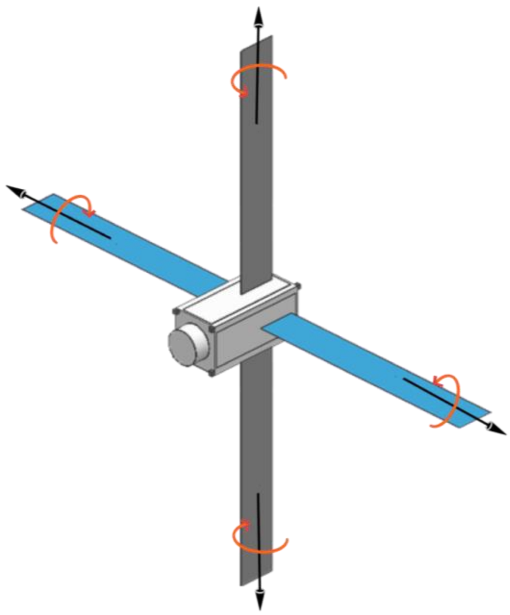


Figure 8: External configuration of the ΔDsat CubeSat.

2.2.2.2. GTO Perigee Raising

Mostaza-Prieto and Roberts [21] presented the design of an optimal attitude manoeuvre with the consideration of the aerodynamic (and gravity-gradient) torques for the low-altitude perigee passage of geostationary satellites during electric orbit raising manoeuvres. Under this approach, the solar arrays are optimally rotated during the perigee pass, taking advantage of the natural environmental torques. This action seems to reduce the requirements on active attitude control actuators (i.e. reaction-wheels) by avoiding saturation and momentum-dumping. The authors proposed that this attitude control augmentation method can support full-electric perigee raising manoeuvres of GEO satellites, resulting in significant mass savings or lifetime extension.

2.2.3. Orbit Control

The drag force is dominant in LEO, resulting from the exchange in the momentum between incident atmospheric particles and the spacecraft surfaces, and therefore acts only opposite to the velocity vector with respect to the atmosphere. The drag force mainly reduces the energy of the orbit and therefore reduces the semi-major axis producing orbital decay. A reduction in orbital eccentricity is also caused due to the relative magnitude of the drag force at apogee and perigee. Comparatively, the aerodynamic lift force in LEO is small (due to the typically high accommodation, diffuse reflection and remission of atmospheric particles), but it can be used to provide both in-plane and out-of-plane forces, affecting the eccentricity, inclination, RAAN, and AoP.

Due to the predominance of drag in LEO, aerodynamic orbit control methods using this force have principally been studied and demonstrated. These manoeuvres 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.

2.2.3.1. Orbit Maintenance

The first work on orbital maintenance using differential drag manoeuvres was presented by Leonard et al. [22] with the aim of reducing the mass/fuel requirements and limiting propulsion system use, which could be inconvenient for close-proximity operations. The feasibility of this concept for control of in-plane separations was considered using two notional satellites which were given additional body panels that could be switched between an attack angle of 0° and 90° to significantly increase the drag force experienced. Later, du Toit et al. [23] proposed that the orientation of the satellite body itself could be used to modulate the drag force experienced and therefore perform constellation maintenance manoeuvres. Numerous studies [24] [25] [26] [27] [28] [29] [30] have further explored these concepts, considering adaptive and optimal control strategies and the role of uncertainties and perturbations including J_2 and variations in the atmospheric density. The main benefits of these operations are reduced propellant expenditure or the capability for in-plane phasing for spacecraft with no propulsion systems. However, consideration must also be given to the significant time-scales which these manoeuvres can take and the loss in orbital altitude and therefore mission lifetime caused by high drag configurations.

Differential drag orbit control manoeuvres in orbit were first demonstrated by the satellites of the ORBCOMM constellation for orbit maintenance [31]. Subsequent demonstration of differential drag manoeuvres for formation-control of nanosatellite-class payloads has also been performed by the AeroCube-4 mission [32] of two 1U satellites with retractable wings for drag modulation and the Planet Labs constellation of “Dove” satellites [33] [34] shown in Figure 9 and Figure 10 respectively. The Dove satellites can be operated in either a high or low drag configuration with an area ratio of approximately 5:1, enabling relative control of the order of 1 km/day^2 to 50 km/day^2 based on altitude and orbit inclination. This constellation deployment capability was presented by Foster et al. [34] for the Flock-1C set of 10 satellites, which were shown to achieve approximately equal in-plane orbital spacing with near-zero relative speeds in a period of 8 months from a common insertion point in a 600 km sun synchronous orbit (SSO).

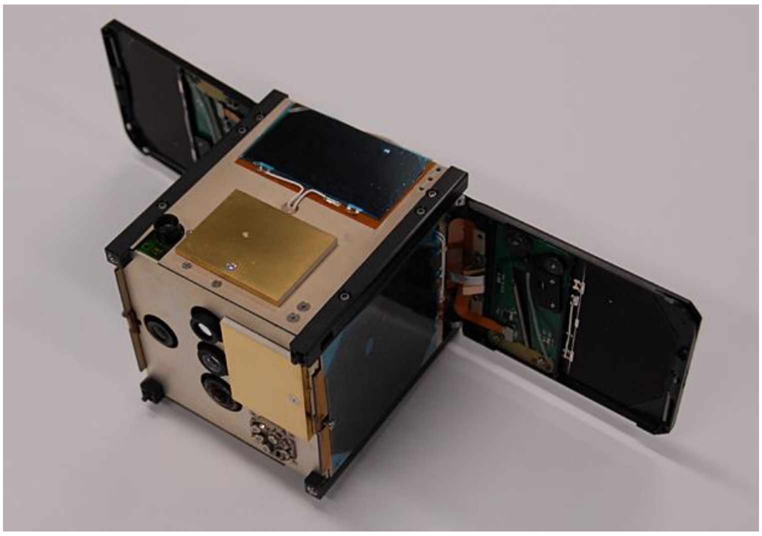


Figure 9: Aerocube-4 with extended wings [image credit: The Aerospace Corporation].

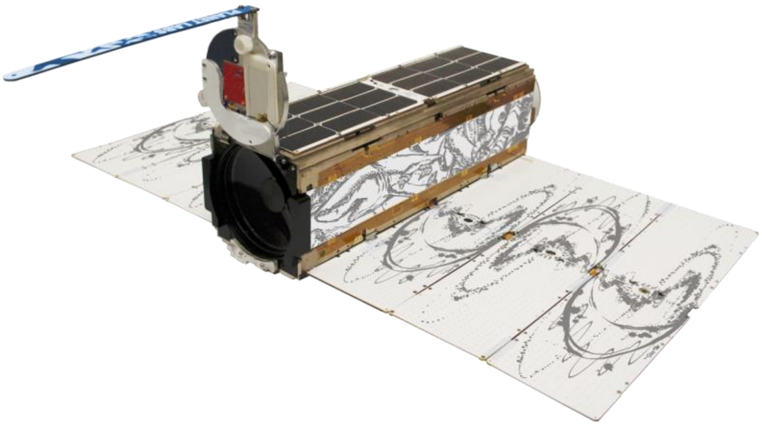


Figure 10: Planet Labs Flock-1 Dove satellite with deployed solar cells [image credit: Planet Labs].

Adjustment of the drag force in orbit was also considered to control the location of the atmospheric reentry interface in place of traditional propulsive methods, first by Patera [35] and then Alemán [36]. These methods presented a significant increase in the drag effect during the final few orbits to adjust the in-track location of the reentry interface. This selection of the reentry interface was considered to reduce the uncertainty and risk of potential property damage or harm to the population in the event that any spacecraft components survive to the reentry. Virgili Llop et al. [37] built upon these earlier works, proposing that the modulation of the drag effect was controlled from higher altitudes, enabling the selection of both the cross-track and in-track reentry interface location.

The use of differential drag was also proposed by Leppinen in [38] to achieve out-of-plane separations between satellites, and to perform the deployment of a multi-plane satellite constellation from a single insertion point. This method utilises the nodal precession (rotation of RAAN) due to Earth's oblateness, causing orbits of different semi-major axis, eccentricity, or inclination to separate over time. Thus, using drag-increasing or deorbit devices the semi-major axis of different satellites can be adjusted in a phased manner enabling control of their planar separation. However, due to the relatively slow differential rate of planar drift of different orbits in LEO, the deployment periods of the order of years are required to achieve meaningful angular separations. Furthermore, a critical trade-off between the initial orbit altitude, required difference in semi-major axis, and useful orbital lifetime exists due to the integral use of orbit decay to execute this method.

2.2.3.2. Differential Lift Manoeuvring

The use of aerodynamic lift in orbit had little attention in the literature for orbit control, due to its low magnitude in comparison to the drag force. Horsley et al. [39] 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 manoeuvres.

2.2.3.3. Descending SSO Inclination Correction

Virgili Llop et al. [40] proposed a method to correct the inclination of descending SSOs due to orbital decay. In this method the production of a lift (side) force was proposed to adjust the orbital inclination as the spacecraft decayed (descended), ensuring that the rate of precession in RAAN was correct and that the orbit remained sun-synchronous. However, they reported that in order to apply this method, a currently infeasible lift-to-drag ratio in the range of 1 to 1.6 was required. Alternatively, a propulsion system which could partially compensate the effect of drag could be used to reduce the lift-to-drag ratio requirement to currently achievable levels. Notice that the direction of the lifting force must alternate each half orbit (at the highest and lowest latitude) to ensure that the cumulative effect on inclination correction is not cancelled out.

2.2.4. Aeroassisted Manoeuvres

Aeroassisted manoeuvres, often referred to as synergetic manoeuvres, using a hybrid combination of propulsive manoeuvring and aerodynamic manoeuvres in the low atmosphere, have also been considered in the literature.

London [41] presented the first work in this area on plane-change manoeuvres, considering the possible propellant savings which could be achieved by first deflecting the spacecraft trajectory into the atmosphere in order to perform aerodynamic manoeuvres before returning the spacecraft to the nominal orbit. Aeroassisted manoeuvres were proposed for in-plane and out-of-plane orbit-change manoeuvres, benefitting from aerodynamic braking and the increased efficiency of manoeuvres at lower periapses. Interplanetary aerocapture and aerobraking manoeuvres were also considered. The foundational work on these aeroassisted manoeuvre concepts was well reviewed by Walberg [42] and by Miele [43].

However, these manoeuvres typically use atmospheric passes with very low altitudes (70 km to 120 km) and are therefore subject to significant dynamic pressure and aerodynamic heating effects [43]. Furthermore, high lift-to-drag ratios, beyond current material and surface capabilities are generally required in order to perform the proposed aerodynamic manoeuvre components.

Aeroassisted manoeuvres have typically been proposed for orbital transfers between LEO and HEO, often for Orbit Transfer Vehicle (OTV) operations. Applications of aeroassisted manoeuvres for operations in only LEO are comparatively sparse, and primarily address out-of-plane transfers.

For a simple plane change manoeuvre in LEO, Miele et al. [44] considered different transfer manoeuvres using aeroassisted trajectories, and concluded that significant energy savings can be made in comparison to the classical three-impulse Hohmann transfer solution. When the effect of atmospheric heating is also considered, the authors indicated that a use of both propulsive and aerodynamic inclination change components provides the best compromise between energy saving and heating requirement. This manoeuvre is executed by first performing an impulsive burn directing the spacecraft into the atmosphere. During the atmospheric passage, a banking angle and aerodynamic lift force are used to achieve the required plane change before propulsive manoeuvres are used to boost the spacecraft back into LEO and re-circularise the orbit. During each impulsive burn a non-tangential component is used to contribute to the total inclination change.

Later, Chen and Yang [45] proposed a similar manoeuvre, but they found that an initial propulsive orbit change manoeuvre to HEO prior to atmospheric re-entry could be used to increase the velocity and minimise the time of the atmospheric passage. They also considered the case of non-planer rendezvous using a simple elliptical phasing orbit prior to the aeroassisted plane change manoeuvre.

Aeroassisted inclination change of small satellites in LEO under heating-rate constraints was considered by Darby and Rao [46], using up to 4 consecutive atmospheric passes. In this study they found that the minimum impulse condition, even under significant heating-rate constraints, resulted in exactly two atmospheric passes.

Bettinger and Black [47] studied the manoeuvring performance of a nominal transatmospheric vehicle (with a hypersonic lift-to-drag ratio of 6) with a focus on responsive overflight of a target location. In this study, aeroassisted trajectories using in-plane phasing and out-of-plane transfers were compared to simple plane change manoeuvres for a range of different ground locations requiring overflight. Aero-assisted in-plane phasing was found to have a low-ΔV requirement (less than 0.5 km/s), albeit with a longer response time than the other methods. Out-of-plane transfers using atmospheric skip entry were also able to provide ΔV savings compared to simple plane change manoeuvres whilst also providing a typically responsive time-of-arrival.

3. AERODYNAMIC TECHNOLOGIES

The generation of aerodynamic forces in orbit is dependent on the characteristics of the materials used in the spacecraft surfaces and in the geometry of the spacecraft with respect to the flow. A range of different external spacecraft geometries have been proposed so far to enable aerodynamic control of spacecraft in VLEO. Furthermore, materials which can provide low-drag characteristics, improve GSIs, or provide increased atomic oxygen resistance are starting to be studied. In all cases, more research is required in aerodynamic technologies considering their applicability, the interactions with the atmosphere, the space conditions and the limited volume and specific loads to support from the launcher vehicle[8,9,10].

3.1. AERODYNAMIC GEOMETRIES

A number of different spacecraft geometries and control surface concepts have been presented with the aim of improving drag characteristics and enabling aerodynamic control and manoeuvring of LEO spacecraft.

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. The ballistic coefficient, the ratio of the spacecraft mass to the product of the drag coefficient and surface area, indicates the aerodynamic properties of a spacecraft; the higher it is, the lower the deceleration caused by drag is [48]. Therefore a high ballistic coefficient is desired. That is achieved by increasing the mass to cross-section area ratio and reducing drag coefficient. Thus, 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 study of low-drag geometry spacecraft for VLEO is presented by Park et al. [49], providing a comparison between geometries with different shaped front surfaces. Notably, when completely diffuse surface reemission characteristics are used, the changes in geometry are not able to meaningfully reduce the drag effects experienced. However, when specular GSI characteristics are considered the drag force can be reduced.

Demonstrated solutions providing aero-stabilisation characteristics have included the aft-located aerodynamic skirt of the DS-MO satellites (Figure 4), the off-centre weighted design of the PAMS mission (Figure 3), the aerodynamic fins used by the GOCE spacecraft (Figure 5), and the shuttlecock design of the QbX satellites (Figure 6). Further proposals include feathered and shuttlecock designs of Psiaki [13] and Rawashdeh and Lumpp [9].

In order to perform differential drag manoeuvring deployable surfaces or variable geometries are required. The Aerocube-4 satellites (Figure 9) have demonstrated the use of deployable wings which increase the cross-sectional area to increase the drag experienced in orbit. Contrastingly, the Planet Labs Dove satellites (Figure 10) utilise active attitude control via a set of four reaction wheel and 3-axis magnetorquers to vary the attitude of the satellite and thus modulate the drag using the extended solar-array area.

[8] Requirement DISCR210
[9] Requirement DISCR220
[10] Requirement DISCR230

To enable further attitude and pointing control using aerodynamic forces, moveable or steerable spacecraft surfaces are required. A 50 cm cubic design featuring a set of four independently movable panels (Figure 7) is proposed by Gargasz [19] with modest pointing control performance (less than 5° with respect to the flow) in 3-axes. Virgili Llop et al. [15] presented an alternative design with a set of four steerable fins (Figure 8) in a feathered configuration. This design has a similar projected pointing capability but improved lifetime due to smaller increment in drag [16].

Geometries for out-of-plane aerodynamic orbit control are comparatively sparse in the literature. The only proposal is presented by Virgili Llop et al. [40] to produce an inclination correction needed to maintain a descending SSO. This wedge-shaped geometry, shown in Figure 11, is designed to have a high and controllable lift-to-drag ratio through yawing about the z-axis. However, this concept assumes that specular reemission of atmospheric particles is achievable, yielding a lift-to-drag ratio of the order of 1.0 to 1.6. Furthermore, in order to provide the appropriate correcting force the wedge must change orientation with respect to the flow during each passage over the highest and lowest latitude. With presently available materials Virgili Llop et al. [40] indicate that drag-compensating propulsion is required to implement the proposed configuration for inclination correction of descending SSOs.

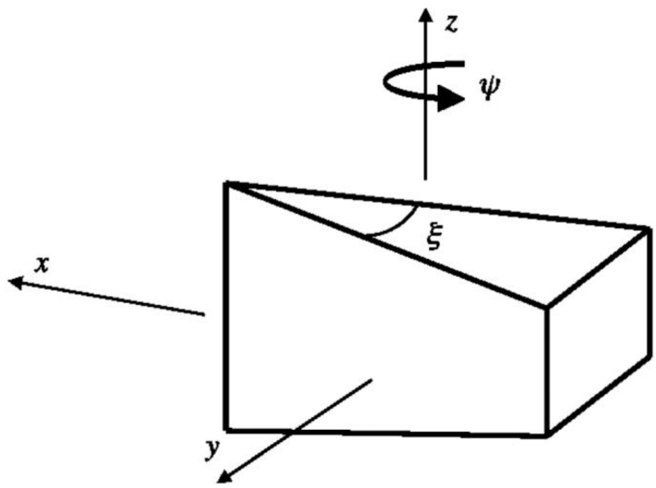


Figure 11: Proposed spacecraft geometry for descending SSO inclination correction.

3.2. MATERIALS

Due to the nature of GSI in orbit and degradation of spacecraft surfaces through adsorption and erosion, new materials are being sought which can improve spacecraft aerodynamic qualities. Materials and surface finishes which have lower surface accommodation coefficients, can encourage specular and quasi-specular particle reemission, and are resistant to contamination and erosion are therefore of key interest.

Atomic oxygen, generated by the photo-dissociation of diatomic oxygen by ultraviolet radiation, is high a highly reactive species and is the most abundant atmospheric constituent between approximately 150 km to 650 km in the LEO regime [50], [51]. Materials which are resistant adsorption and erosion by atomic oxygen have therefore formed the bulk of research in this area so far.

Numerous protective mechanisms and surface coatings for atomic oxygen protection were discussed by Reddy [50]. 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. [51] and Samwel [52].

3.3. APPLICATION OF AERODYNAMIC TECHNOLOGIES TO EARTH OBSERVATION

Due to the relative infancy of aerodynamic control in orbit beyond aerostability, most studies to date have not focused on any specific application or mission type. However, some studies of aerodynamic control and associated technologies indicate benefits which apply particularly to Earth Observation missions.

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. Using aerodynamic control surfaces, coarse pointing capability of up to 5° (with respect to the oncoming flow) in pitch and yaw is expected to be achievable with existing materials.

The method for descending SSO inclination correction presented by Virgili Llop et al. [40] is particularly applicable to Earth Observation missions which often occupy these orbits to take advantage of the regularity in local time of ascending node and therefore solar illumination angle. However, a lift-to-drag ratio in the range of 1 to 1.6 is required.

Differential lift orbit control methods have also been proposed for Earth Observation constellation maintenance. Li and Mason [28] and Foster et al. [34] presented the in-plane constellation maintenance of the Planet Labs Flock constellation for Earth Observation. Similarly, Leppinen [38] proposed a similar method enabling a multi-plane constellation to be deployed from a single insertion point, enabling optimisation of the constellation revisit time. However, the slow differential rate of planar drift of different orbits in LEO, deployment periods of years' duration are required to achieve meaningful angular separations.

To date, these studies have generally investigated these control methods without focusing on a particular application or mission type. However, concepts which are of particular interest or applicability to Earth Observation missions have begun to emerge, enabling wider and extended operations in VLEO.

At present, much of the literature and most of the in-orbit demonstrations have focused on the development of aerostability, enabling stable attitude in low altitude orbits without the use of other attitude control hardware. The use of aerodynamic forces for orbital station-keeping and constellation maintenance have also been demonstrated in orbit. These methods have enabled systems to reduce propellant consumption or eliminate the propulsion system use entirely, but at the expense of lengthy deployment periods and potentially significant reduction in orbital lifetime. In comparison, active aerodynamic attitude control and pointing has seen less attention and has yet to be demonstrated in orbit. Furthermore, the available literature indicates that pointing control capability is limited with currently characterised materials and that the use of aerodynamic control without any other support technology may be unreliable given the variability and uncertainty of the atmospheric density. Further research in this field has to be done.

4. EARTH OBSERVATION APPLICATIONS

In general, circular SSO orbits at altitudes between 600 km and 1000 km are 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. A 500 km orbit altitude provides consistent illumination conditions as well as a low altitude decay caused by the atmospheric drag [53]. Furthermore, recent studies have introduced the potential benefits of orbiting at VLEO [54], where the atmospheric drag is increased and the spacecraft flight dynamics is dominated by the aerodynamics forces.

The following sections expose the advantages of orbiting at VLEO for Earth Observation applications and the challenges which need to be overcome to enable reasonable operations. Finally, different EO applications are presented in order to assess the adequacy of operations in VLEO.

4.1. BENEFITS OF VLEO

4.1.1. Increased Resolution of Optical Payloads

The angular resolution can be defined as the capability of the system to resolve separate points that are located at an angular distance. Considering a telescope as the optical system, the optical resolution can be defined as the ability to resolve remote objects at a short distance and reproduce them into individual elements of the image. This performance is characterised by Rayleigh criterion, which states that the minimum separation between two points of light in order to be distinguished by an observer is the radius of the Airy Disc, defined as:

$$r = 1.22\,\frac{\lambda}{D} \tag{5.1}$$

Here, r is the radius of the Airy Disc, λ is the wavelength of the light and D is the aperture diameter of the telescope.

Considering diffraction through a circular Rayleigh aperture, the angular resolution can be rewritten:

$$\alpha = 1.22\,\frac{\lambda}{D} \tag{5.2}$$

Here, α is the angular resolution, λ is the wavelength of the light and D is the aperture diameter of the telescope.

Regarding Earth Observation missions, two system factors are defined in order to assess the on ground target resolution. First of all, the Ground Resolution Distance (GRD) can be defined as the size of the smallest element distinguishable on acquired imagery, as shown in Figure 12.

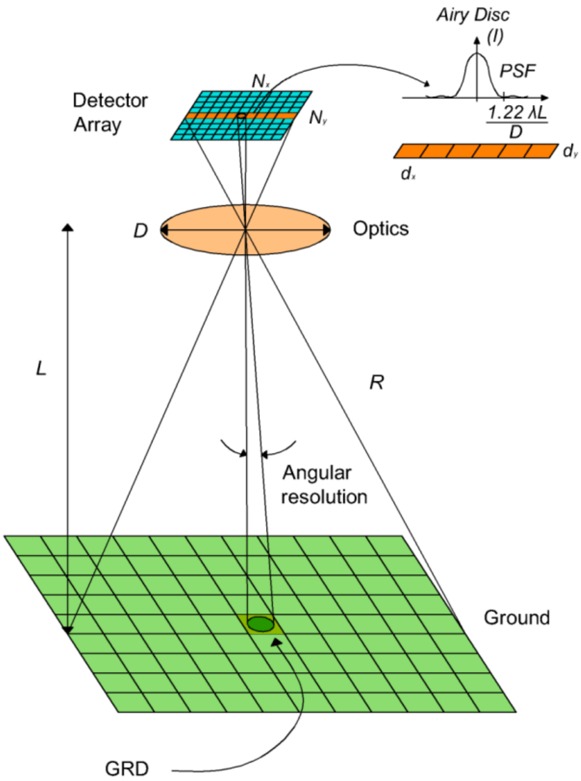


Figure 12: Ground Resolution Distance (GRD) outline.

Hence, equation 3.1 can be transformed to express the GRD as follows:

$$GRD = 1.22\,\frac{H \times \lambda}{D} \tag{5.3}$$

The parameter GRD is the Ground Resolution Distance, H is the altitude, λ is the wavelength of the light and D is the aperture diameter.

Secondly, the Ground Sample Distance (GSD) can be defined as the projection of a single pixel on the ground, shown in Figure 13 and expressed as:

$$GSD \propto \frac{d \times H}{F} \tag{5.4}$$

where d is the pixel size, H is the altitude and F is the focal length of the telescope.

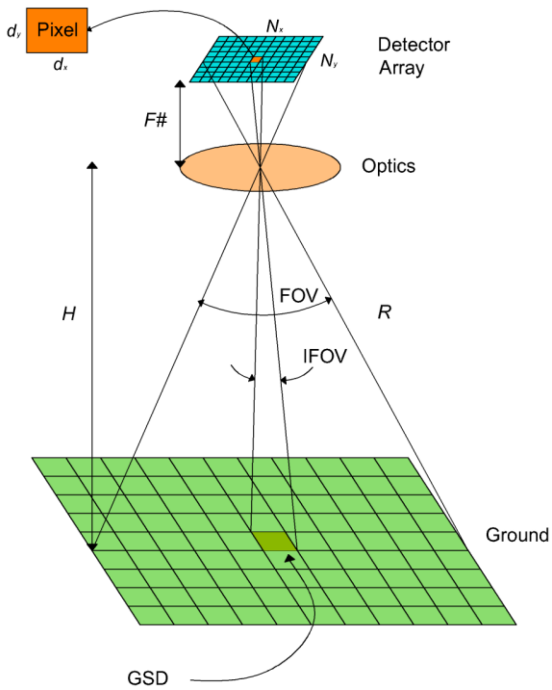


Figure 13: Ground Sampling Distance (GSD) outline.

Therefore, from equations 5.3 and 5.4 and considering fixed optical parameters, a reduction in the orbit altitude will automatically increase the GRD and the GSD and the resolution of the spacecraft, for instance.

In addition, Figure 14 shows the relation between the telescope aperture and the GSD for several orbit altitudes explained before. Regarding a constant aperture value in the graphic, a lower orbit altitude results in a better resolution which the system could provide without any modifications to the optical payload. Furthermore, if the Earth Observation mission requires reaching a certain system resolution, lower orbits will lead to smaller apertures, which also means smaller instruments, usually related to a cost reduction.

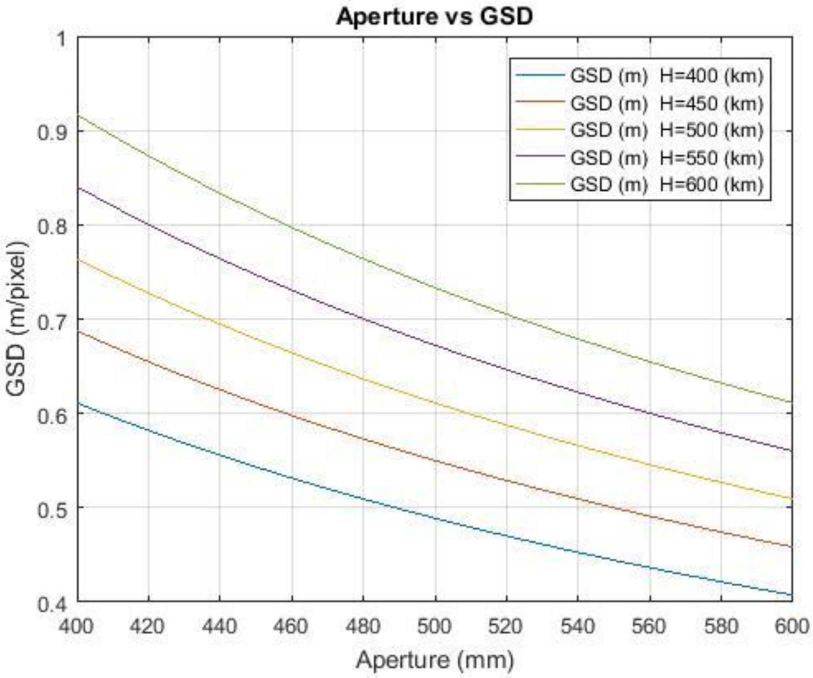


Figure 14: Aperture vs GSD.

4.1.2. Increased Radiometric Performance

Radiometry is often defined as a set of techniques used to measure electromagnetic radiation, including visible light. The energy collected by on-board sensors not only depends on the energy emitted or reflected from the observed target, but also on other factors such as the sensor response, atmosphere conditions (aerosols or fog, among others) or sun sensors geometry.

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, meaning the orbit altitude, as expresses equation 5.5.

$$P \propto \frac{1}{H^2} \tag{5.5}$$

Therefore, VLEO does not affect the sensor features but improves the power density of the received signal. Regarding optical payloads as well as radars, the main advantage is the improvement of signal to noise ratio (SNR) [53]. Another benefit is the power consumption reduction, which is especially important for transmission subsystems. Finally, due to the fact that at lower orbit altitudes the same results can be obtained with less sensitive instruments, the instrument cost could be reduced compared to traditional orbit missions.

4.1.3. Increase in available launch mass

Flying at VLEO can also increase the available mass to be launched. This is the consequence of the reduction in altitude and the equivalent mass to be launched with the same propellant of injecting the satellites in a lower orbit can be increased. This relation is exponential in circular orbits, i.e. the mass that a launcher is capable of injecting into a circular orbit decreases exponentially as the orbit altitude increases [55].

4.1.4. Non disposal manoeuvre is required at EOL

The ESA guidelines related to Clean Space state as follows [56]:

"It is recommended that satellites and orbital stages be commanded to re-enter Earth's atmosphere within 25 years of mission completion, if their deployment orbit altitude is below 2000 km (in the LEO region)."

Currently, most satellites are operating in high altitude orbits. In order to de-orbit the satellite, some sort of device is required such as a propulsion system to perform a de-orbit burn or a drag sail.

Flying in VLEO, the spacecraft can take advantages of drag for re-entry purposes. At this altitude the atmospheric drag is sufficiently strong to cause a re-entry before the intended end of the mission (in a 400 km orbit the lifetime is not typically higher than 3 years [53]).

4.1.5. Low risk of collision with space debris

Nowadays, the space debris rate around the Earth has dramatically increased. More than half century of space activities have resulted on more than 6000 satellites placed into orbit, of which less than a thousand remain still operational [57].

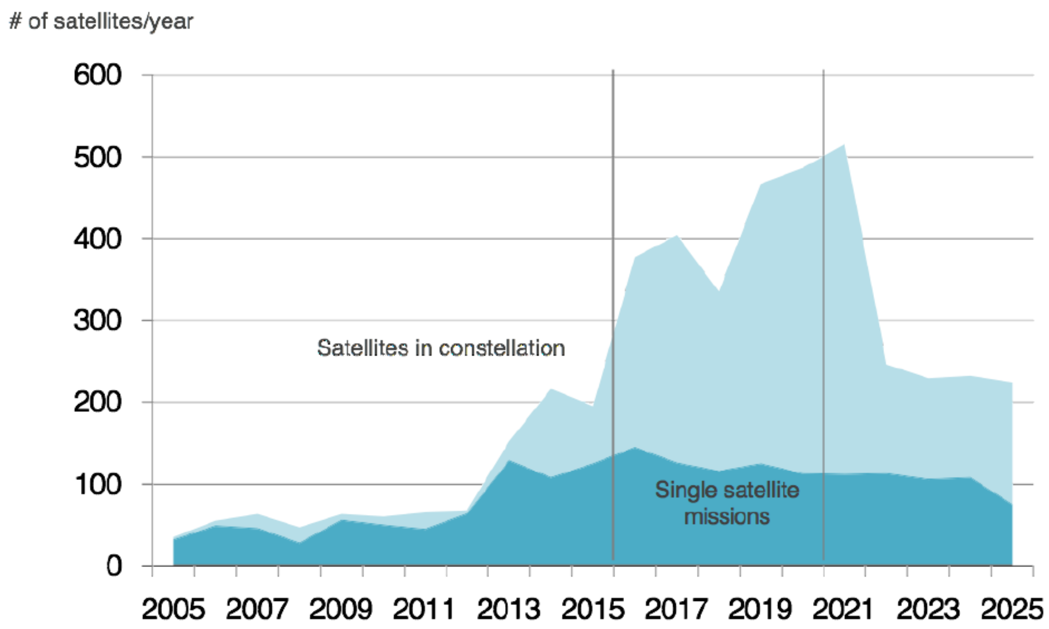


Figure 15: Number of satellites per year from 2005 to 2025 [image credit: ESA].

Approximately, a third part of these objects are in orbits above 500 km in altitude. Space debris is recognised as a major risk to space missions: an object of 1 cm in length can generate the energy equivalent to an exploding hand-grenade when impacting a satellite.

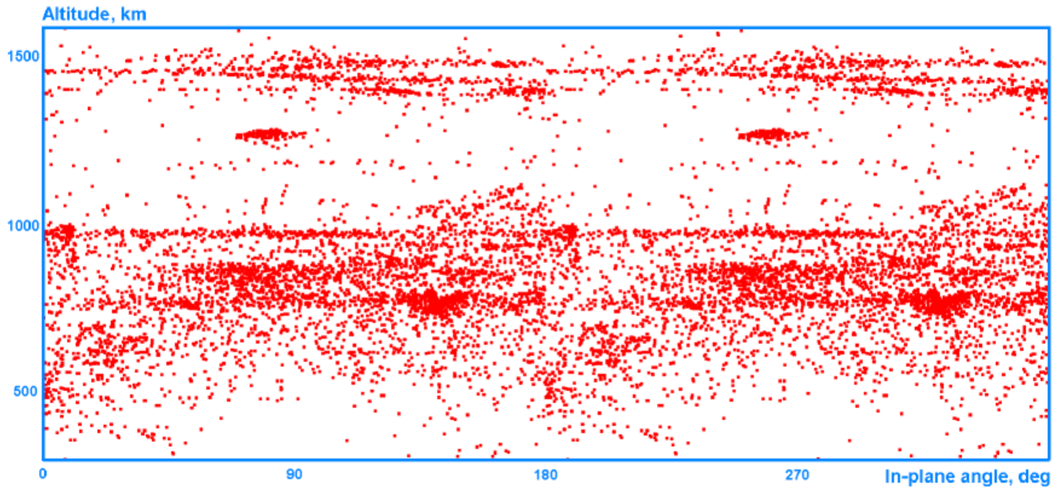


Figure 16: Space debris in LEO [58].

Orbiting at VLEO could reduce the probability of collision with space debris due to the fact that debris have a higher rate orbital decay in VLEO orbits, hence the orbit will clear itself faster than higher orbits.

4.1.6. Increase of Geospatial Position Accuracy

Orbiting at VLEO, 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 of interest is also reduced. This leads to more a more accurate geolocation of collected imagery and data.

4.1.7. Disruptive Propellant Systems

Traditionally, rocket engines are the most common propulsion systems used to maintain a stable altitude and extend the on-orbit lifetime. However, the propellant required for these manoeuvres causes an increase in spacecraft mass and can introduce more complexity in the system design.

Regarding the environment at VLEO, Singh [59] suggested that propellant could be collected from the remaining atmosphere particles at these altitudes. On-orbit collecting systems could reduce the spacecraft mass leading to smaller and less expensive satellites. In addition, another advantage could be the possibility of including more instruments or larger apertures.

4.1.8. Low Radiation Levels

Radiation in Earth orbit has its origin in particles trapped by the Earth's magnetic field (Van Allen Belts), solar particles, and cosmic rays. Very low orbits are mainly affected by Van Allen Belts and cosmic rays.

Lower orbits are protected from solar radiation by the inner Van Allen belt and the Earth magnetic field (Figure 17). Flying at lower altitude also protects the spacecraft from a greater proportion of solar activity effects, such as solar flares and coronal mass ejection. However, cosmic rays, which consist of high energetic particles, originate outside the Solar System. Intense ionizations can be caused while they are passing through matter. The Earth's magnetic field provides only partial protection from cosmic rays in lower orbits.

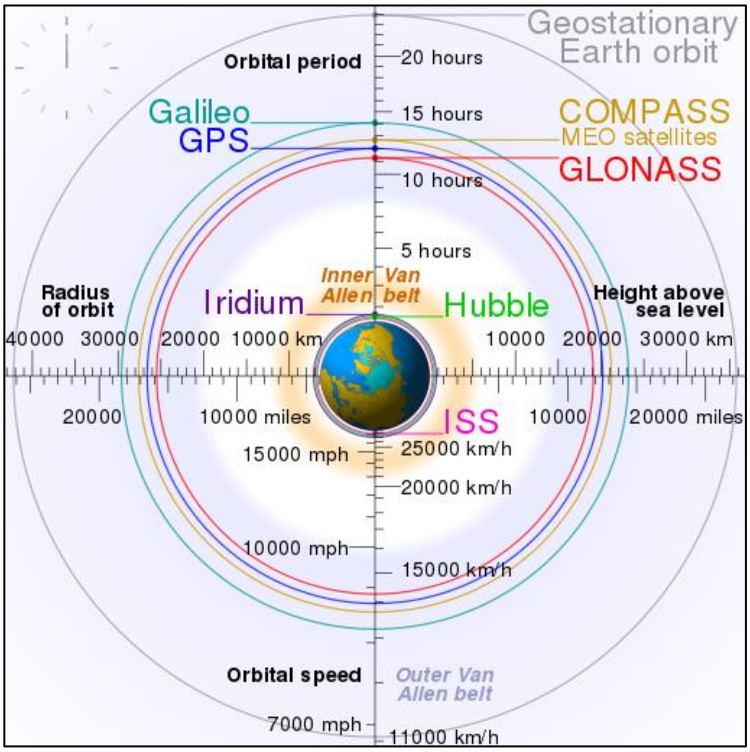


Figure 17: Description of several satellites orbits [image credit: North_pole_february_ice-pack_1978-2002.png by Geo Swan].

4.2. CHALLENGES OF FLYING IN VLEO

4.2.1. Earth's Atmosphere

The density of the atmosphere decreases exponentially with increasing altitude, as the study carried out by Llop [53] shows in Figure 18.

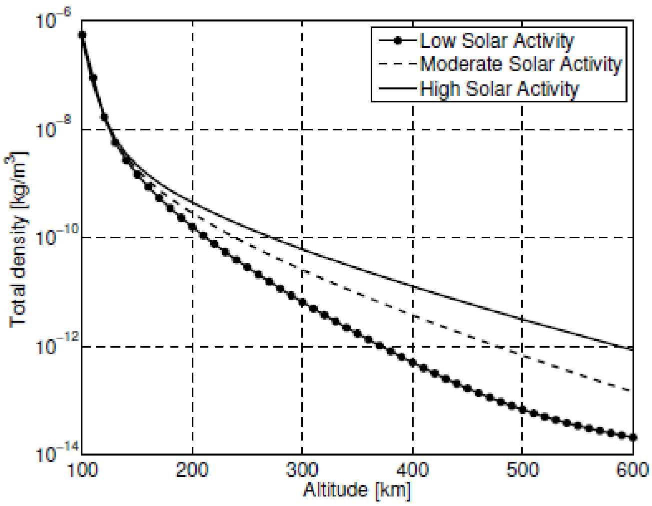


Figure 18: Variation of the atmosphere density with the altitude for different solar activities [53].

The strongest natural force at 500 km altitude is the Earth's gravity, even though the atmospheric drag is still significant. Furthermore, at 450 km the aerodynamic drag is strong enough to dominate the orbital dynamics compared to other disturbances. To avoid spacecraft decay in less than 5 years, several changes in traditional spacecraft design are necessary. At this altitude, the spacecraft is located in the Heterosphere in which the composition is dominated by ionized species. The resulting effects are as follows [53]:

- Aerodynamic forces: the drag is the main aerodynamic force, causing the orbital decay.
- Surface corrosion: the atomic oxygen, which is the major constituent from 200 km to 600 km orbit altitude, reacts with the materials, leading to surface and sensor performance degradation.
- Spacecraft charging[11]: some gas particles which might be adsorbed are electrically charged. Thus the spacecraft can become charged which can damage sensitive spacecraft components.

4.2.2. Communication Windows

At lower altitudes the available windows for data downlink to a given ground station are reduced as the time of passage becomes shorter due to elevation angle constraints and increased orbital velocity. Considering the same data generation, the access duration reduction requires faster data downloading rates, representing a major design driver. One solution could be selecting higher bandwidth communications subsystems. Another alternative could be transmitting through communication relay satellites orbiting in GEO, which allow extended communications windows [53].

4.2.3. Revisit Time

The revisit time is defined as the period, typically measured in days, between two consecutive opportunities of acquiring the same target The field of view (FOV) is a sensor performance parameter and differs from the field of regard (FOR) which is a platform performance parameter. The capable revisit time is therefore usually different from the time between two consecutive target acquisitions. As a result, the revisit time depends on the platform tilting capability, as shows Figure 19:

[11] Requirement DISCR240

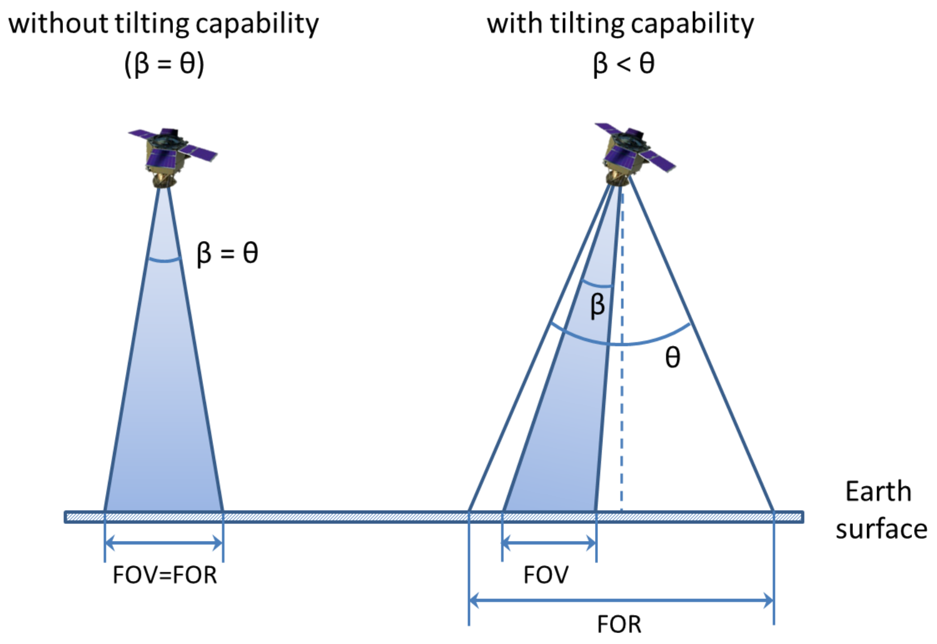


Figure 19: Tilting capability.

Regarding small tilting angles capabilities and very wide FOV, the FOR computation will strongly depend on the FOV. However, this kind of design is not common in high resolution applications taking into account that platform tilting operational capability could exceed ±45 deg.

In the case of a satellite with no tilting capability, the FOV will be equal to the FOR and, thus, the revisit time will also be equal to the orbit repeat cycle. In the case of orbits with 1 day of repeating ground tracks (the satellite overflies the same targets in each orbit per day), some points could remain uncovered.

Aside from these particularities, higher altitudes allow shorter mean revisit time because of the increase of both the FOV and the FOR with the altitude for a same sensor and tilting performances, respectively. In fact, for SSO the maximum revisit time at 600 km is around 6 days at the equator, while at 400 km it is about 7 days. The maximum revisit time not only depends on altitude, but also on overlapping between consecutive orbits and on repeating cycles, so the relation between the altitude and the maximum revisit time is not as direct as for mean revisit time.

To sum up, VLEO presents a drawback for those applications which demand very frequent revisit time.

4.3. EO APPLICATIONS OF VLEO

In general, flying at lower altitudes is convenient for missions in which high precision is needed. Table 1 shows some feasible EO applications for VLEO orbits which are classified into 6 different groups. In addition, some EO performance parameters are included to order to characterise each application. Finally, the last column in the table refers to the adequacy of VLEO:

- **Low**: the application can be successfully performed flying either at VLEO or at LEO. However, due to some performances such as coverage or revisit time, selecting conventional Low Earth Orbit could be recommended regarding complexity or cost.

- **Medium**: the altitude is not as relevant as other factors in order to select the most suitable orbit for this application, thus VLEO could be appropriate for such cases.
- **High**: orbiting at VLEO instead of at traditional LEO could maximise the benefits explained above.

Furthermore, apart from remote sensing, some communications applications, for instance telecommunication and mobile data services, can also take advantage of VLEO due to the extensive benefits explained before [60] [61] [62].

Table 1: Feasible EO applications for VLEO.

Group	Application	GSD	Sensor	Revisit time	Spectral Frequency	VLEO Adequacy
Forest	Forest Management	0.5-10m	HYP[1]/MS[2]/PAN[3]	1.5months-1year	Red (630-690nm)	High
Agriculture	Precision Agriculture (Fertilizer optimization, pesticide metering, irrigation planning)	2.5-100m	HYP/MS/PAN	5days-1month	Coastal Band (400-450nm) Green (520-600nm)	High
Agriculture	Illicit crops detection (surveillance)	1-30 m	SAR[4]	< 1 day	Optical/NIR	Medium
Agriculture	Crop type and health	2.5-100m	HYP/MS	5days-1month	Coastal Band (400-450nm) Red Edge (650-760nm)	High
Agriculture	Chlorophyll	2.5-100m	HYP/MS	5days-1month	Coastal Band (400-450nm) Red (630-690nm)	High
Agriculture	Vegetation Land Cover & Analysis	2.5-100m	HYP/MS	5days-1month	Green (520-600nm) Red (630-690nm)	High
Agriculture	Leaf or canopy differences	2.5-100m	HYP/MS	5days-1month	Coastal Band (400-450nm) Red Edge (650-760nm)	High
Water Management	Snow and lake cover	>5m	HYP/MS	10hours-1month	Near IR (760-900nm) Mid IR (1550-1750nm)	Low
Water Management	Water properties	>5m	HYP/MS	10hours-1month	Blue-Green (450-520nm)	Low
Water Management	Oceanography	>25m	HYP/MS	1week-2months	Blue-Green (450-520nm)	Low
Land	Minerals	>10m	HYP/MS	1year-10years	Red (630-690nm)	Low
Land	Soils	>10m	HYP/MS	1year-10years	Red (630-690nm) Mid IR (1550-1750nm)	Low
Land	Sediments	>10m	HYP/MS	1year-10years	Blue-Green (450-520nm)	Low
Land	Mapping	0.5-100m	MS/PAN/SAR	1year-10years	-	Medium
Atmosphere	Meteorology	>100m	HYP/MS/SAR	1hours-1day	-	Low
Climate change	Greenhouse		HYP/MS	-	-	Low
Crisis Response	Insurance risk modelling	1-10m	MS/PAN	2hours-1day	-	Low
Crisis Response	Volcanic eruptions	>7.5m	MS/PAN/SAR	2hours-2days	Thermal Infrared	Low

Group	Application	GSD	Sensor	Revisit time	Spectral Frequency	VLEO Adequacy
Crisis Response	Forest fires	>7.5m	MS/PAN	2hours-2days	Thermal Infrared	Low
Crisis Response	Flood Risk Analysis	5-10m	MS/PAN	1day/1year		Low
Crisis Response	Large-scale damaging weather-related events	>7.5m	MS/PAN	2hours-2days	Thermal Infrared	Low
Urban	Traffic	0.5-1.5m	PAN	30minutes-1day	-	Low
Urban	Urban Development	0.1-10m	MS/PAN	1year-10years	-	High
Urban	Intelligence Services	0.5-10m	MS/PAN	-	-	High
Marine	Maritime surveillance	1-30 m	SAR	10minutes-1month	Optical / Infrared	Medium
Marine	Phytoplankton	>100 m	HYP/MS/PAN	>1 year	Optical / Infrared	Low
Marine	Oil spill monitoring and response	1-30m	MS/PAN/SAR	< 1 day	Optical / Infrared/ Thermal Infrared	Low
Marine	Fishing Activity	1-30m	SAR	10minutes-1mont	Optical	Medium
Marine	Dredging operations	>30m	HYP/MS/PAN	3 hours	Optical/NIR	Low
Marine	Port security	< 30m	SAR	10minutes-1month	Optical / Infrared	Medium
Marine	Piracy Monitoring	1-30 m	SAR	< 1 day	Optical/NIR	Medium
Marine	Port activity and economics	<1m – 5m	MS/SAR	hours- 1 month	Optical/NIR	Medium

[1] HYP: Hyperspectral
[2] MS: Multispectral
[3] PAN: Panchromatic
[4] SAR: Synthetic Aperture Radar

5. EARTH OBSERVATION OPERATIONS

Part of the evaluation of the aerodynamic technologies to be implemented in operational systems is the analysis of the operations that can be done with such technologies if they are competitive in comparison with classical AOCS subsystems. From this analysis requirements related to the operations can be extracted.

5.1. MISSION CONCEPTS

Four concepts have been selected in accordance to both the benefits of flying at VLEO and the set of applications that can be covered, both analysed in section 4. For instance, the closest distance to the target increases the resolution of optical payloads, increases the geospatial precision accuracy and increases the radiometric performance and as a consequence it improves the signal to noise ratio in both optical payloads and radars, and reduces the power consumption. Then three different optical concepts, focused on high resolution applications, and one radar concept were selected to exploit the benefits and applications of flying at VLEO. Optical low resolution concepts do not present particular operational benefits for flying at VLEO. In fact, the reduction of the orbit altitude can dramatically reduce the swath and increase the revisit time which are critical design drivers of these types of systems.

Four representative mission concepts have therefore been selected to evaluate the applicability of aerodynamic technologies and control:

- Optical coverage
- Optical VHR high performance
- Optical VHR low cost
- Synthetic Aperture Radar

5.1.1. Optical coverage concept

In this concept, we considered that the spacecraft carries an optical payload. The objective is to record the surface characteristics of large targets such as regions, countries or coast profiles. For this application, a wide swath is usually required. Thus related attitude control requirements are not very demanding, while image stabilization is enhanced. The acquisition planning can be defined during the design of the orbit, and agility is often not required since nadir pointing is the most frequent pointing mode. The following representative examples can be considered:

- *Deimos-1*

Deimos-1[12] is the first Spanish Earth Observation satellite. It is the result of a partnership formed by Deimos Imaging of Boecillo-Valladolid, which used to be a subsidiary of Elecnor Deimos before its sale to Urthecast Corp, and Surrey Satellite Technology Ltd (SSTL).

Launched in 2009, with an expected lifetime of 10 years, it is the Spanish member of the Disaster Monitoring Constellation (DMC). It is a source of medium resolution data (22 m) with a large range of visual field (660 km swath), providing yearly coverage of Sub-Saharan Africa to the European GMES/Copernicus program since 2010 and cloud-free coverage of the United States

[12] https://directory.eoportal.org/web/eoportal/satellite-missions/d/deimos-1

every two weeks to United States Department of Agriculture (USDA) during the crop season since 2011. Figure 20 depicts an artistic view of the satellite.

Figure 20: Deimos 1 artistic view.

- *Sentinel-2*

Sentinel-2[13] is a multispectral operational imaging mission within the GMES (Global Monitoring for Environment and Security) programme, jointly implemented by the EC (European Commission) and ESA (European Space Agency) for global land observation at high resolution with high revisit capability [63].

Launched in 2015, Sentinel-2 provides enhanced continuity of data and complements SPOT and Landsat missions. See Figure 21 for an artistic view.

Figure 21: Sentinel-2 artistic view [image credit: ESA, Airbus DS (eoPortal)].

- *Flock constellation*[14,15,16]

Planet Labs is a private start-up company of San Francisco which aim to deploy the largest constellation of Earth-imaging satellites. Their nanosatellites are meant to be low-cost, rapidly

[13] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-2
[14] https://directory.eoportal.org/web/eoportal/satellite-missions/f/flock-1
[15] https://www.planet.com/pulse/a-look-back-planets-progress-in-2014/
[16] https://www.itu.int/en/ITU-R/space/workshops/2015-prague-small-sat/Presentations/Planet-Labs-Safyan.pdf

deployable, and capable of taking pictures of the Earth providing a spatial resolution of 3 – 5 m. On January 2015, a total of 40 Flock 1 nanosatellites were deployed from the International Space Station and 11 Flock 1c nanosatellites into SSO on a Dnepr. Figure 22 shows a set of Flock satellites.

Figure 22: Flock 1 nanosatellites [image credit: Planet Labs (eoPortal)].

5.1.2. Optical VHR high performance concept

This group of satellites are part of EO missions with tactical purposes that make use of optical payloads with very high resolution integrated on very agile platforms. Attitude requirements (agility, slew rate, and stability among others) are very demanding for these missions as well as orbit control for precise location when imaging. In this case, the following spacecraft can be considered as examples:

- *Pleiades-HR*

Pleiades-HR[17] is a constellation of two satellites owned by CNES [64]. This mission follows the SPOT programme. These satellites provide VHR imagery. They have very agile platforms, enabling global coverage, short revisit time and daily observation accessibility. The overall objectives of Pleiades are the following:

- Provision of an optical high-resolution panchromatic (0.7 m) and multispectral (2.8 m) imagery with high quality product standards in terms of resolution and high image location accuracy.
- Global coverage and daily observation accessibility to any point on Earth, providing more than 250 images/day with each satellite.
- Service provision of the "level-2 products" to customers consisting of a panchromatic image with a merged multispectral image orthorectified on a Digital Terrain Matrix.
- Provision of stereo imagery (up to 350 km x 20 km or 150 km x 40 km) and mosaic imagery with size up to 120 km x 120 km.

[17] https://directory.eoportal.org/web/eoportal/satellite-missions/p/pleiades

- The satellites are required to support risk management support services in terms of observation coverage (this requires an agile spacecraft design, a responsive operational concept, and a sufficient ground segment). Figure 23 shows an artistic view of a Pleiades satellite.

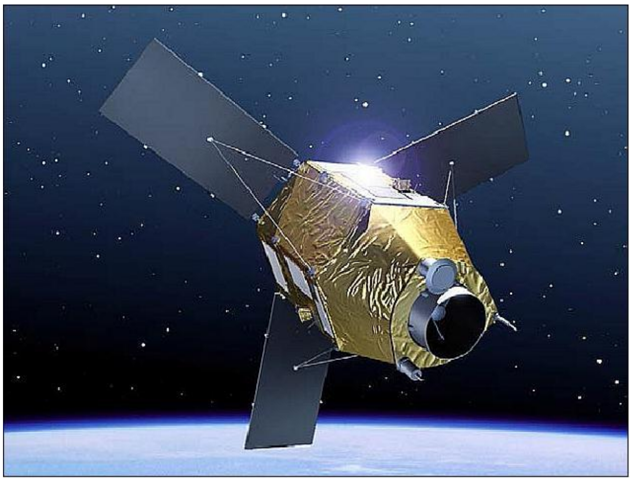


Figure 23: Pleiades artistic view [image credit: CNES (eoPortal)].

- *WorldView-4*

WorldView-4[18] is the latest high resolution satellite of the DigitalGlobe WorldView programme. Currently, WorldView-4 completed its testing and calibration phase and began serving its first direct access customer on February 1st 2017. Lockheed Martin is the prime contractor of the WorldView-4 spacecraft. WorldView-4 will provide map-accurate images with a new high-resolution camera provided by Harris Corporation. In addition to delivering critical geospatial situational awareness and global security information to intelligence analysts, war fighters and decision makers, commercial users will also benefit from access to imagery from WorldView-4, see Figure 24.

Figure 24: WorldView-4 artistic view [image credit: Lockheed Martin, Digital Globe (eoPortal)].

[18] https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-4

5.1.3. Optical VHR low cost concept

This mission concept shares the objectives of Optical VHR high performance satellites. However it is considered relevant to make the distinction that low cost missions can reach high performance with smaller, lighter, cheaper and simpler platforms:

- *Deimos-2*

  Deimos-2[19] was tested and integrated in Deimos Satellite Systems premises in Puertollano. Currently Deimos-2 is owned and operated by Deimos Imaging.

  Launched in June 2014, Deimos-2 was the first Spanish very-high resolution Earth Observation satellite, producing multispectral images with a resolution of 75 cm per pixel. It is one of the very few privately-owned submetric satellites in the world (Figure 25).

Figure 25: Deimos 2 in the clean room of Elecnor Deimos (Puertollano, Spain).

- *RapidEye*

  RapidEye [20] is a full end-to-end commercial Earth Observation system comprising a constellation of five minisatellites, a dedicated SCC (Spacecraft Control Centre), a data downlink ground station service, and a full ground segment designed to plan, acquire and process up to 5 million km^2 of imagery every day to generate unique land information products.

  Owned and operated by BlackBridge, the main objective is to provide a range of Earth observation products and services to a global user community, covering markets as agriculture, environment, forestry, mapping, intelligence and defence, security and emergency or virtual simulation.

[19] http://www.elecnor-deimos.com/project/deimos-2/
[20] https://directory.eoportal.org/web/eoportal/satellite-missions/r/rapideye

All the five satellites shared the same launcher. The launch took place on August 2008. Figure 26 shows the RapidEye satellites.

Figure 26: RapidEye constellation [image credit: BlackBridge (eoPortal)].

- *SkySat constellation*

SkySat[21] is a commercial Earth observation microsatellite of Skybox Imaging Inc, which was owned as Terrabella by Google and which now is owned by PlanetLabs. It collects high resolution panchromatic and multispectral images of the Earth. The Skysat provides imagery and video. Figure 27 shows an artistic view of the SkySat.

Figure 27: SkySat deployed configuration [image credit: SkyBox Imaging (eoPortal)].

5.1.4. Synthetic Aperture Radar (SAR) concept

Apart from optical payloads, 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:

[21] https://directory.eoportal.org/web/eoportal/satellite-missions/s/skysat

- *TerraSAR-X:*

  TerraSAR-X1[22] is a German satellite mission developed by BMBF (German Ministry of Education and Science) and DLR (German Aerospace Centre). The main objective is to acquire multi-mode and high-resolution X-Band data for several applications, such as geology, climatology, oceanography or natural disasters assessment.

  The science potential of the mission is given by:

  - The high geometric and radiometric resolution (experimental 300 MHz mode for very high range resolution).
  - The single, dual and quad polarization mode capability.
  - The capability of multi-temporal imaging.
  - The capability of repeat-pass interferometry.
  - The capability of ATI (Along-Track Interferometry).

  The TerraSAR-X1 launch took place on June, 2007. Figure 28 shows an artistic view.

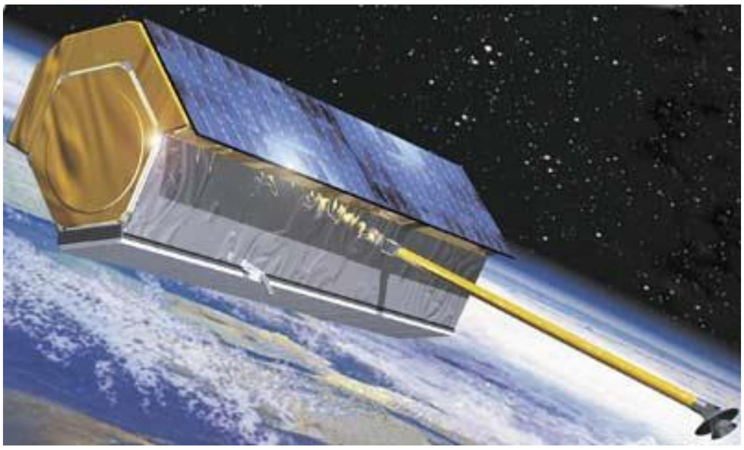


Figure 28: TerraSAR-X artistic view [image credit: Astrium (Gunter's Space Page)].

- *Sentinel-1*

  Sentinel-1[23] is one of the components of the Copernicus missions (before called GMES), which is the European contribution to GEOSS (Global earth Observation System of Systems). Sentinel-1 consists of a two satellite constellation (Sentinel-1A and Sentinel-1B) sharing the same orbital plane and separated by 180 deg orbital phasing difference in order to provide a continuous coverage of Earth surface for radar mapping with independent performance capabilities and enhanced revisit frequency and reliability.

  By using a C-Band SAR, Sentinel-1 provides continuous Earth's surface data in order to cover several applications such as monitoring ice zones, artic environment, natural hazards,

[22] https://directory.eoportal.org/web/eoportal/satellite-missions/t/terrasar-x
[23] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-1

mapping land surfaces (forests, oil and water, agriculture) or maritime and coastal surveillance.

The Sentinel-1A and Sentinel-1B launches took place on April 2014 and on April 2016 respectively (Figure 29).

Figure 29: Sentinel-1 artistic view [image credit: ESA, TAS-I (eoPortal)].

- *EnviSat*

EnviSat[24] is an Earth observation mission of ESA. The overall objectives are the following: studying and monitoring the Earth's environment on various scales, from local through regional to global; monitoring and management of the Earth's resources, both renewable and non-renewable; continuation and improvement of the services provided to the worldwide operational meteorological community; contribution to the understanding of the structure and dynamics of the Earth's crust and interior.

EnviSat carries 10 instruments onboard, one of them is ASAR (Advanced Synthetic Aperture Radar) which operate at C-band in a wide variety of modes. ASAR ensures continuity with the image mode (SAR) and the wave mode of the ERS-1/2 AMI. It features enhanced capability in terms of coverage, range of incidence angles, polarisation, and modes of operation. ASAR could detect changes in surface heights with sub-millimetre precision. The main application fields are the following: Landscape Topography), Snow and Ice , Ocean Currents and Topography, see Figure 30 for an artistic view.

[24] https://directory.eoportal.org/web/eoportal/satellite-missions/e/envisat

Figure 30. EnviSat artistic view [image credit: ESA (eoPortal)]

- *COSMO-SkyMed Second Generation (CSG) Constellation*

Italy's second generation COSMO-SkyMed[25] is a constellation of two satellites. The objective is to improve the quality of the imaging service, providing the end users with enhanced capabilities in terms of higher number of images and image quality (with larger swath and finer spatial and radiometric resolution) with respect to the current COSMO-SkyMed constellation, referred to as CSK. The CSG requirements call for additional capabilities (e.g. full polarimetric SAR acquisition modes) granting a greater operative versatility, both in terms of programming capability and the effective sharing of the system resources among different typologies of users requesting images of different characteristics.

The satellites will be positioned in the same sun-synchronous orbit as the first-generation satellites. Each satellite will provide synthetic aperture radar (SAR) imagery of the earth's surface for defence and security, seismic hazard analysis, disaster monitoring and agricultural mapping applications.

The CSG mission has been conceived, according to the requirements stated by ASI (Agenzia Spaziale Italiana) with funding of the Italian Ministry of Defence (I-MoD), at the twofold need (civil/defence) of ensuring operational continuity to the currently operating "first generation" CSK constellation, while achieving a generational step ahead in terms of functionality and performances. In order to ensure operational continuity, the new CSG satellites will be ready for operations in time to replace the CSK satellites whenever they are being progressively phased out at the end of their lifetime, see Figure 31.

[25] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cosmo-skymed-second-generation

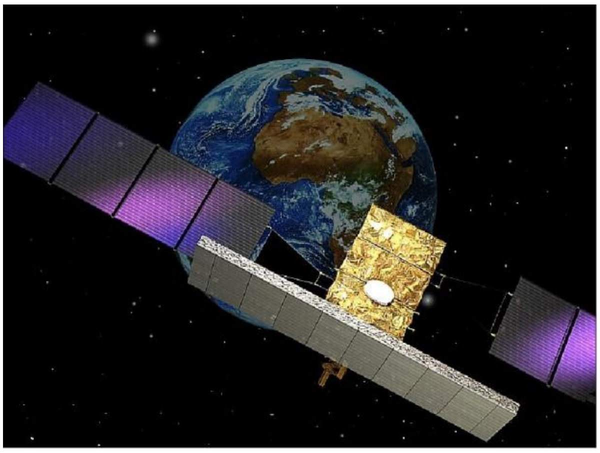


Figure 31. COSMO-SkyMed Second Generation [image credit:ASI (eoPortal)]

5.2. ORBIT CONTROL OPERATIONS

Orbit control performances have been classified for individual analysis into the following categories: orbit maintenance, collision avoidance, nominal orbit insertion, rephasing, and deorbiting.

5.2.1. Orbit maintenance

Maintenance of the nominal orbit is usually paramount for any spacecraft, particularly for EO missions[26]. Exposure conditions for image acquisition and fine adjustments of the optical systems among other reasons, require the orbit to be maintained within a narrow range of altitudes, inclinations or LTAN/LTDN (see Figure 32 for an explanation about ascending and descending concepts).

There exist multiple contributions to change the shape and location of an orbit, including the non-spherical nature of the Earth, gravitational effects of the sun and the moon, or the solar radiation pressure [65]. However, the perturbation with the greatest contribution in VLEO is the atmospheric drag. In Table 2 orbital parameters and lifetime are collected for optical coverage missions, the same for Optical VHR High performance missions in Table 3, Optical VHR Low Cost missions in Table 4 and SAR missions in Table 5.

All these tables are based on eoPortal web page[27].

Table 2: Orbit maintenance performances in Optical coverage missions.

Satellite	Orbit and lifetime
Deimos-1	SSO, altitude = 661 km, inclination = 98 deg, LTAN is at 10:39 hours. 5 years lifetime (8 years of operation in July 2017).
Sentinel-2	SSO, altitude = 786 km, inclination = 98.5 deg with 10:30 hours LTDN. Design

[26] Requirement DISCR070
[27] https://directory.eoportal.org

	lifetime of 7 years with propellant for 5 more years
Flock constellation	11 Flock 1c: near-circular orbit of 630 km with an inclination of 98 deg and an LTAN of 10:30 hours. 40 Flock 1 (Launched from ISS): 400 km circular orbits (inclination of ~52 deg). 3 years predicted lifetime.

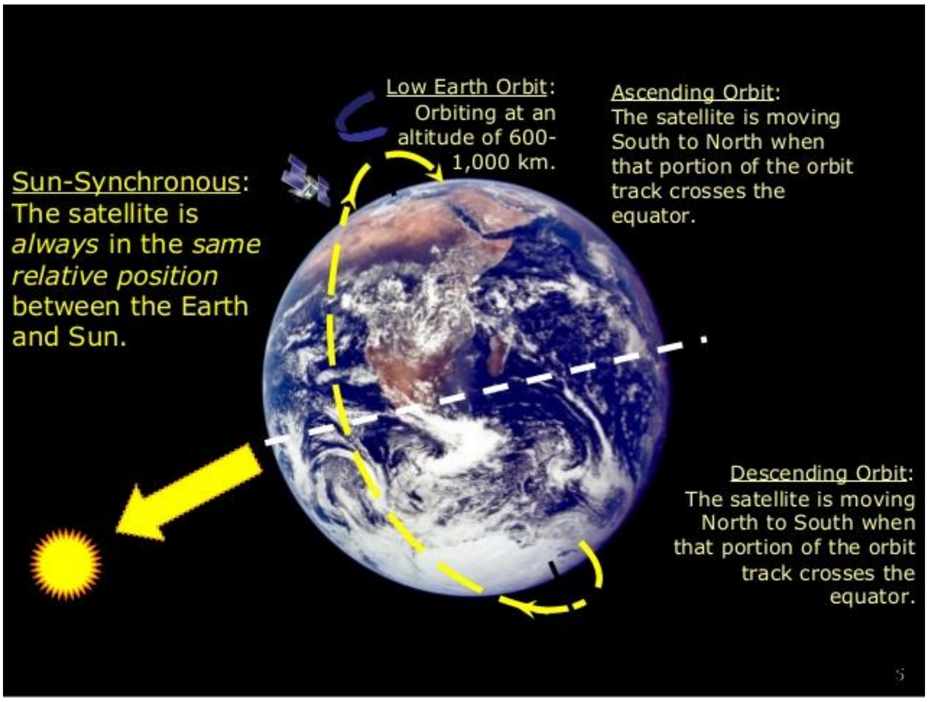


Figure 32: SSO ascending/descending explanation [image credit: SlideShare, Ghasssan Hadi].

Table 3: Orbit maintenance performances in Optical VHR High performance missions.

Satellite	**Orbit and lifetime**
Pleiades	Sun-synchronous phased orbits (180 deg phasing, 14 and 15/26 rev/day), altitude = 694 km, inclination = 98.2 deg, local equator crossing time on a descending node at 10:30 hours. Design lifetime: 5 years.
WorldView-4	SSO, altitude = 617 km, inclination = 98 deg, period = 97 minutes, LTDN at 10:30 hours, effective revisit time capability ≤ 3 days. Design lifetime of 7 years. Service lifetime is expected o be extended up to 10 or 12 years.

Table 4: Orbit maintenance performances in Optical VHR Low Cost missions.

Satellite	**Orbit and lifetime**
Deimos-2	Sun-synchronous near-circular orbit, nominal altitude of 630 km, inclination of 98 deg, nominal LTAN at 10:30 hours. 4-day revisit time enabled by the ±45 deg maximum off-nadir pointing capability. Nominal mission lifetime of 7 years with a goal of 10 years.
RapidEye	Nominal circular SSO, 630 km altitude, 11:00 hours equator crossing time on descending node. Design lifetime of 7 years.
SkyBox Constellation	Sun-synchronous near-circular orbit, altitude = 600 km, inclination = 97.8 deg, LTDN = 10:30 hours. 4 years lifetime.

Table 5: Orbit maintenance performances in SAR missions.

Satellite	**Orbit and lifetime**
TerraSAR-X	Sun-synchronous circular dawn-dusk orbit with a local time of ascending node at 18:00 hours (± 0.25 h) equatorial crossing, average altitude 514.8 km (505-533 km), inclination = 97.44 *deg*, nominal revisit period of 11 days. Almost 10 years of lifetime.
Sentinel-1	Sun-synchronous near-circular dawn-dusk orbit, altitude = 693 km, inclination = 98.18 deg, LTAN = 18:00 hours. 7 years lifetime.
EnviSat	Near-circular sun-synchronous orbit; altitude = 800 km; LTDN = 10 hours, inclination = 98.55 deg, orbit period = 100.6 minutes, exact repeat cycle of 35 days. 5 years lifetime.
COSMO-SkyMed Second Generation (CSG)	Circular sun-synchronous dawn-dusk orbit, nominal altitude = 619.6 km, inclination = 97.86 deg, with LTAN at 6:00 hours. All spacecraft of the SAR constellation will be positioned in the same orbital plane. 7 years lifetime.

As exposed, the typical mission lifetime values of EO satellites are between 4 and 10 years. In Figure 33 the altitude history of a satellite with a nominal altitude of 350 km and an area to mass ratio of 0.01 m^2/kg is shown, computed with the simulation software DAS 2.0.2. Lowering orbit altitude to this representative VLEO altitude value leads to drastically reduce the satellite lifetime to about 6 months.

This issue could be solved by reducing the area to mass ratio of the spacecraft (i.e. to increase its ballistic coefficient) as much as possible or by using a propulsion system for drag compensation and orbit maintenance.

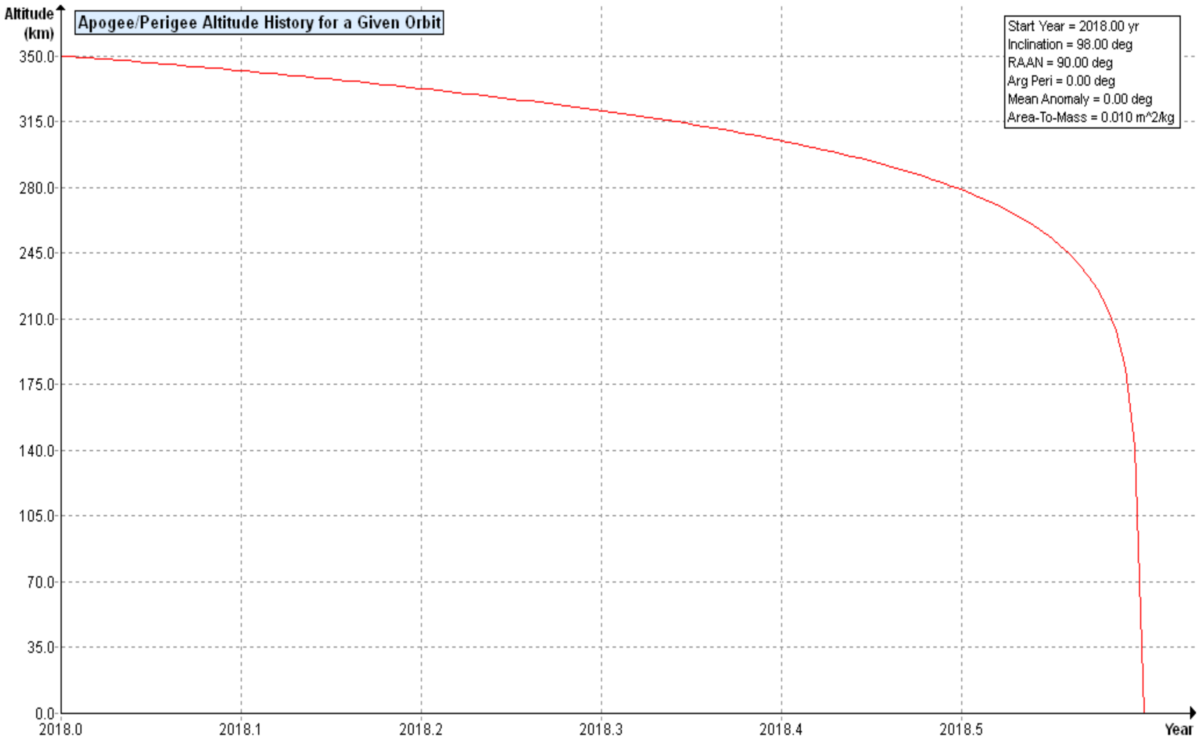


Figure 33: Altitude history of a satellite with an area to mass ratio of 0.01 m^2/kg.

5.2.2. Collision avoidance

A typical design consideration is to estimate two collision manoeuvres per year. It has to be noted that not all the collision alerts lead to a collision manoeuvre as it depends on considerations about collision probability, impact in the mission operations, and the accepted risk level by the satellite operators[28].

5.2.3. Nominal orbit insertion

Primary payloads in a space launch have a key advantage in the orbit insertion but, launch injection errors have to be considered in the design[29]. Satellites can take advantage of secondary-payload launches to reduce mission costs but the differences between the injection and nominal mission orbit (altitude, inclination, and eccentricity among others) require correction by a manoeuvre campaign during the early mission stages.

As input for the design, the following values can be considered[30]:

- Launch injection errors: ± 25 km Semi Major Axis (SMA), ± 0.1 deg inclination.
- Nominal orbit acquisition (if required): ± 50 km SMA, ± 1 deg inclination.

[28] Requirement DISCR080
[29] Requirement DISCR090
[30] http://www.spacex.com/

5.2.4. Rephasing

Phasing is the relative position between satellites of a constellation in the orbit. Phasing maintenance is called rephasing. As an example, the RapidEye mission has the following phasing requirement: *The satellite constellation shall be controlled so that the satellite ground tracks are nominally equally spaced at the equator. The ground track spacing shall be maintained within +/-10% of the distance between the ground tracks (3σ), relative to the nominal position* [66].

When orbiting, phasing variations take place continuously as each satellite could have slightly different altitudes, drag coefficient and, therefore, orbital velocity. In the moment a rephasing manoeuvre is considered for a satellite, the common practice is to increase the orbit altitude to adjust the satellite velocity with reference to the nominal orbit. The variation between this new velocity and the one in the nominal orbit will provide a continuous variation in phasing until the next rephasing would be needed.

Although each mission could have very different rephasing needs, RapidEye calculations will be used to set an estimation of the frequency and the altitude variation required. For this mission, it is concluded that two rephasing manoeuvres[31] are required per year to move the satellite around 200 m above the nominal orbit [66].

5.2.5. Deorbiting

Space debris is a current concern, especially in most populated regions as Geosynchronous or SSO around 600 km altitude. Space organisms and Agencies as ESA and NASA have developed a list of guidelines referred to space debris mitigation in which one of the classical statements is that each satellite in LEO should be able of re-entering in less than 25 years after the end of operations[32]. This is usually achieved thanks to atmospheric drag in low orbit although spacecraft with propulsion system commonly include this functionality in their delta-V budget.

5.3. ATTITUDE CONTROL OPERATIONS

Attitude control is one of the many functions typically implemented in an EO platform, consisting of pointing angles, stability, slew rates, and other performances related to where and how the satellite is pointing at a given target. Attitude control is not only used for image acquisition but also for detumbling following launch vehicle separation, optimizing solar energy acquisition, and firing operations among other activities.

Figure 34 shows the classical on-body frame with the definition of the three important slew angles for imaging operations which is demanded in many missions.

[31] Requirement DISCR100
[32] Requirement DISCR110

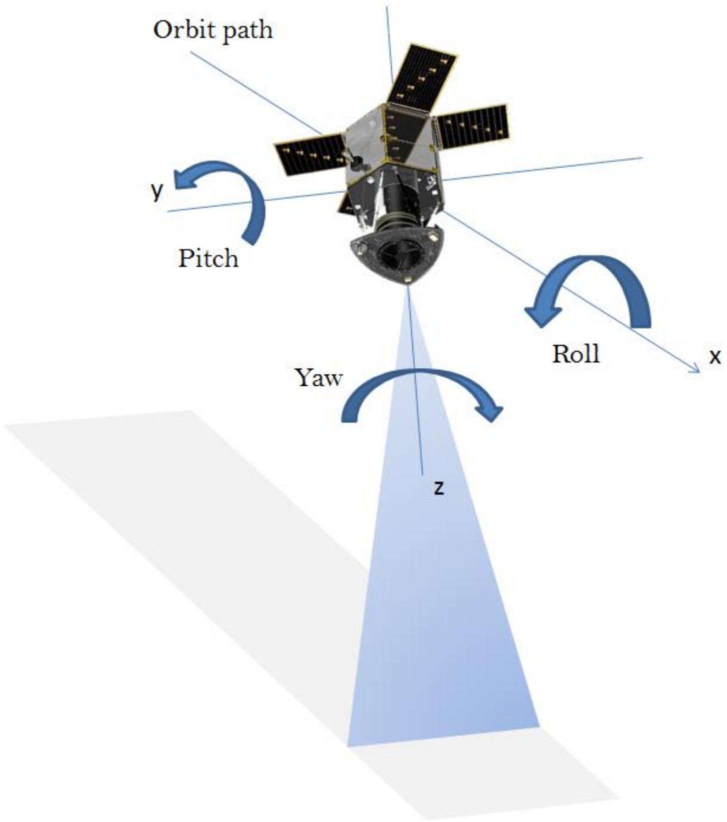


Figure 34: On-body frame axes and slew angles.

- Roll: allows the satellite to point at different places inside its field of regard. It is used to acquire images the satellite is not going to overfly in a current orbit.

- Pitch: in this case, the pitch angle allows the satellite to take images of already overflown targets or not reached yet by pointing at different places into the orbit projection in the Earth. This is commonly used to make stereo acquisitions or tessellation to increase the swath (width) of the final imagery products.

The combined use of roll and pitch is also frequent in agile spacecraft to improve the possibilities of the mission plan and widen the area in which a target can be acquired, allowing also better performance in a multipointing acquisition mode.

- Yaw: this is also an important slew angle as it is used for geometrical corrections motivated by the Earth rotation during the acquisition of strips.

5.3.1. Agility

Earth observation satellites usually perform a 3-axis attitude control. This is required by the pointing performances and operational concepts (slew, yaw steering corrections, solar acquisition optimization and payload protection against sun pointing)[33]. With the term “agility” in this document we refer to operational limitations of a platform to reach certain angles in roll and pitch but, even more important in some missions, to the slew rates.

[33] Requirement DISCR120

Apart from coverage missions, which are optimized for nadir pointing, agility is one of the most important platform performances for the other mission concepts. Maximum angles in roll and pitch for image acquisition and angular velocities (together with acceleration and stabilization times) derive the maximum performance for multipointing, stereo, tristereo, or mosaicking. Yaw steering performance is used for optical acquisition[34]. It is a required manoeuver to achieve a correct acquisition of a target on Earth as it rotates during the image operation.

5.3.2. Pointing accuracy

Most demanding pointing requirements in the selected mission concepts arise from the need to make the payload point to a particular ground target. Although solar array pointing or orbit manoeuvres are also demanding, the accuracy in these cases is generally not so precise as the requirements of targeting Earth subjects of some meters from several hundred kilometres. The pointing requirement values are related to the field of view, as the aim is to place the target within it. For example, if FOV is four times a 3σ pointing error, it is expected to place the target within the FOV with a 6σ probability, which is quite acceptable. In addition, if some image acquisition requires overlap of several images, pointing requirements can be motivated by the accuracy in the overlap to avoid the acquisition of large overlapping areas. Typical values for the pointing accuracy in this case are around 10% to 20% of the FOV.

5.3.3. Stability

Satellite stability is commonly analysed by separating stability for high frequencies, known as jitter, and for low frequencies, drift [48].

- Jitter is an angle bound or angular rate limit on short-term, high-frequency motion. It is usually specified to keep the spacecraft motion from blurring sensor data. In Earth observation, the jitter is commonly defined as a function of the spatial resolution, which often is derived as a modulation transfer function (MTF) of the system. The MTF degradation due to jitter must be limited to a certain percentage of the instantaneous field of view (IFOV), depending of the minimum MTF value desired at the Nyquist frequency. The rough order of magnitude for jitter is around 1 deg/s, although very high resolution missions need more precise stability.

- Drift is a limit on slow, low-frequency vehicle motion. Drift is not a major concern for image acquisition as it takes short times to record an image, although in large and continuous periods of acquisition it must be taken into account. Drift is of the order of 1 deg/hour.

5.3.4. Other control performances

Other attitude control parameters exist which are not so frequently utilised during the mission or have lower impact in the attitude control requirements. Detumbling after launch separation or a temporal loss of satellite control and internal and external disturbance torques are here analysed to evaluate precisely their impact in attitude needs:

Detumbling: Apart from the common detumbling after launch separation, uncontrolled tumbling of a spacecraft may result from collision, malfunction, or other disabling event associated with the application of a large disturbing torque or breakup of a vehicle[35]. In the attitude control requirements definition, this performance has to be considered as it could be one of the most demanding manoeuvres in the mission.

[34] Requirement DISCR190
[35] http://www.spacedaily.com/reports/Detumbling_a_Spacecraft_999.html

The spacecraft angular rates after the separation due to stabilization errors and disturbances induced by the separation process are as follows: $\omega_x < 2.0$ deg/s, $\omega_y < 3.0$ deg/s, $\omega_z < 3.0$ deg/s. The time required for reducing the initial rate under 1 deg/s in each axis shall be within 24 hours. Furthermore, the sensor shall be protected against direct Sun illumination so the satellite shall be capable of manoeuvring the attitude during detumbling whilst protecting the payload from sunlight.

- Control of internal disturbance torques [48]:
    - Uncertainty in centre of gravity.
    - Thruster misalignment
    - Mismatch of thruster outputs
    - Rotating machinery
    - Liquid sloshing
    - Dynamics of flexible bodies
    - Thermal shocks on flexible appendages

  Spacecraft designers shall minimize internal disturbances through careful planning and precise manufacturing. This may increase costs, although it is important to trade the minimization of these disturbances against the degradation in satellite performance. In most cases, some of these disturbances are not included or are limited by avoiding components such as rotating machinery, liquids, flexible bodies, or appendages in the design. The remainder require the design, fabrication and integration of the spacecraft with the aim of reducing the possible impact.

- Control of environmental disturbance torques:

  In order to achieve a proper and accurate attitude control and determination, external disturbances must be minimized by the AOCS. An estimation of possible external disturbance torques is described herein and calculations included in Table 6.

    - Magnetic field: disturbance caused by the magnetic field of the Earth, see Figure 35 for a visual representation of the Earth`s magnetic field. It is strongly influenced by the orbit altitude, the residual spacecraft magnetic dipole and the orbit inclination. The torque caused by the magnetic field (T_m) can be estimated as:

$$Tm = DB \tag{6.15}$$

where *D* is the residual magnetic dipole moment of the spacecraft and *B* the magnetic field of the Earth.

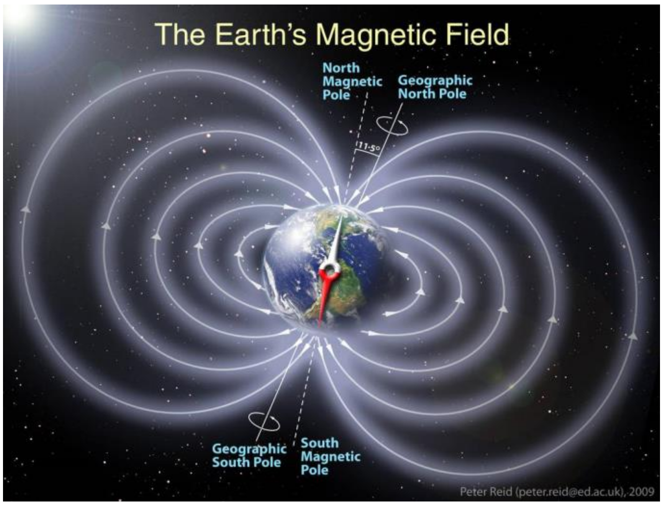


Figure 35: Earth Magnetic Field [image credit: Peter Reid, NASA].

If the orbit is considered to be polar as it is the worst case for magnetic field torque, the magnetic field can be approximated as:

$$B = \frac{2M}{R^3} \quad (6.16)$$

where M is the magnetic moment of the Earth, M = 7.96 x 10^{15} T·m^2 and R the radius from the centre of the Earth to the orbit of the spacecraft in m. Depending on the spacecraft size and the magnetic dipole compensation mechanisms, the value of D is in the range of 0.1 to over 20 A·m^2. For small satellites without compensating mechanisms D = 1 A·m^2 is a typical value, while big satellites are expected to compensate the magnetic dipole. For this estimation we can consider D = 1 A·m^2 to be representative enough for all the mission cases considering that the aim is to provide a calculation of a rough order of magnitude for this torque.

Thus, for an orbit altitude of 400 km and a residual magnetic dipole moment of the spacecraft of 1 A·m^2, and considering a mean radius of the Earth of 6371 km, the value estimated for the torque would be $T_m = 5.128 \cdot 10^{-5}$ N·m.

- Solar radiation: a spacecraft with deployable solar panels present a higher component of solar radiation force. The flying orientation prioritizes the solar power acquisition, which implies that solar panels are perpendicular to the sun radiation vector, maximizing this effect. However, panel disposition is usually a symmetric configuration so no torque is produced. This disturbance produces a cyclic torque if the spacecraft is Earth-oriented or constant if sun-oriented. Depending on the spacecraft geometry, the surface reflectivity, and the centre of gravity location the solar radiation becomes representative for satellites with large areas exposed to the sun. The torque caused by solar radiation is expressed as:

$$T_S = \frac{F_S}{c} A_S (1+q)(c_{sp} - c_g) cos(i) \quad (6.17)$$

where T_S is the torqued caused by the solar radiation, F_s is the solar constant (1367 W/m^2), c is the speed of light (3 x 10^8 m/s), A_s the exposed surface area, q the surface reflectance factor (in the range of 0 to 1, commonly 0.6), c_{sp} the location of the centre of solar pressure, c_g the centre of gravity and *i* the angle of incidence of the Sun.

- Gravity gradient: this disturbance affects to satellites with agility that deviate from the nadir axis when taking imagery. Apart from this deviation angle, the disturbance caused by the gravity gradient also depends on the spacecraft moments of inertia, and hence on its geometry and the orbit altitude. The gravity gradient has more influence on satellites with large differences between the inertia in yaw axis and inertia in pitch or roll axis, this is, satellites with elongated shapes in the nadir axis, such as WorldView. The torque caused by the gravitational effect is estimated as follows:

$$T_g = 3\mu|I_z - I_y|sin(2\theta)/2R^3 \tag{6.17}$$

  where μ is the standard gravitational parameter, i.e $\mu = GM$, where G is the universal gravitational constant (6.674 x 10^{-11} Nm^2/kg^2) and M the mass of the Earth (5972 x 10^{24} kg); R is the distance from the centre of the Earth to the orbit of the satellite; I_z and I_y are the moments of inertia; and θ the deviation from nadir axis. Notice that with pitch or roll angles of 45º, the spacecraft experiences the maximum torque.

- Aerodynamic: this disturbance appears in satellites that have a surface that is not aligned with the CoG. This creates a torque caused by the aerodynamic drag. As in the case of solar radiation, solar panels can induce this torque although a symmetric configuration will prevent from this disturbance:

$$T_a = 0.5\rho V^2 C_d A(c_{pa} - c_g) \tag{6.18}$$

  where T_a is the aerodynamic torque, ρ is the atmospheric density, C_d is the drag coefficient, A is the exposed surface area, V is the spacecraft velocity, c_{pa} is the centre of aerodynamic pressure and c_g is the centre of gravity.

In Table 6, rough order of magnitude estimation of every disturbance is shown for each type of mission. The worst case scenarios are included. All the torque values are estimated supposing that the orbit altitude is 400 km.

Table 6: External disturbance torques.

Disturbance	**Optical coverage**	**Optical VHR high performance**	**Optical VHR low cost**	**SAR**
Magnetic field	5 x 10^{-5} N·m	5 x 10^{-5} N·m	5 x 10^{-5} N·m	5 x 10^{-5} N·m

Disturbance	Optical coverage	Optical VHR high performance	Optical VHR low cost	SAR
Solar radiation	Sentinel-2 has an important influence of the torque induced by the solar radiation due to its unique solar panel. 10^{-4} Nm	Owing to the usual symmetry of the solar panels mounted on this type of satellites the torque caused by solar radiation can be neglected.	These satellites try to leverage the maximum solar energy. Their solar panels are arranged symmetrically, so although the solar force is high, the torque is not significant.	The most representative case is EnviSat. It has a unique solar panel creating an asymmetry. Also its huge size increases the value of the torque induced by the solar radiation. 10^{-4} Nm
Gravity gradient	This type of satellite does not usually have agility. Moreover, they tend to have not-elongated shapes, so the torque induced by the gravity gradient can be neglected.	Due to its elongated shape, WorldView-4 is the most critical satellite in study, in terms of gravity gradient. Also, its weight and size lead to a high torque. 10^{-2} Nm	Deimos-2 does not have a big difference between its height and width, but it can have the maximum angle agility at 45 deg. 10^{-3} Nm	Although it is not usual to find SAR satellites having its long axis oriented towards nadir, COSMO-SkyMed and Sentinel 1 are shaped along it and have large slew capabilities, so the gravity gradient could be a factor to consider. 10^{-4} Nm

Disturbance	Optical coverage	Optical VHR high performance	Optical VHR low cost	SAR
Aerodynamic	The Sentinel-2 deployed solar panel is not perpendicularly oriented to the velocity vector, so it does not have influence on the aerodynamic torque. Other coverage satellites have symmetrical shapes, so the aerodynamic torque can be neglected.	The same argument as exposed in case of solar radiation about the symmetry can be used to neglect the aerodynamic torque.	The telescope of Deimos-2 may induce aerodynamic torques because of the asymmetry it has. 10^{-5} Nm	Due to its deployed solar panel, EnviSat is subdued to an aerodynamic torque. The hypothetical decrease of the altitude orbit up to 400 km should be kept in mind. 10^{-4} Nm

With all this information, it is possible to evaluate which torque disturbances are of largest magnitude and will have to be considered for each type of mission concept:

- Optical coverage: attending to the evaluated disturbances, and mainly based on Sentinel 2 shape and operation, the torque disturbance by solar radiation pressure is the largest one that should be compensated in orbit with a defined pointing direction during operations. The order of magnitude is 10^{-4} Nm.

- Optical VHR High performance: with the current SoA, this mission concepts requires platforms over 1000 kg. The shape and size of the representative satellites that have been analysed imply that the gravity gradient is relevant, especially when acquiring images with big roll or pitch angles in which the z axis of the body frame has the maximum separation from nadir pointing. This disturbance torque is in the 10^{-2} Nm order if elongated platforms are used.

- Optical VHR low cost: with the same operational concept as the VHR high performance, gravity gradient is again the largest disturbance torque although smaller platforms in terms of mass and size are used. In this case the torque is of the order of 10^{-3} Nm.

- SAR: specific conditions are presented in SAR missions, such as the typical use of a dawn-dusk orbit to minimize eclipses and maximize solar energy acquisition. This is the reason why a single solar panel is common, breaking the typical symmetry in a satellite, as it is the case for EnviSat. This asymmetry generates torque disturbances by solar radiation and atmospheric drag of the order of 10^{-4} Nm. This is the same order as for gravity gradient induced torque analysed in the flight configuration of Sentinel 1 and Cosmo Skimmed Seconda Generazione. Both of them have large agility thanks to the use of Control Moment Gyros (CMG).

In Table 7, Table 8, Table 9 and Table 10, real values of agility, pointing accuracy and stability for representative spacecraft in the selected mission concepts are collected. Although specific information for every mission is not easily achievable (due to lack of information, different definitions, variability in units) the main objective is to present a general view for each concept that allows us to extract representative performances of attitude control.

Table 7: Attitude control performances in Optical coverage missions.

Satellite	Agility	Pointing accuracy	Stability
Deimos-1	3-axis control.	No strict requirements on pointing control due to the wide swath it has.	A gravity gradient boom is used to provide a high degree of platform stability, constraining the body-rotation rates to < ±2.5 mdeg/s (44 µrad/s)
Sentinel-2	3-axis control with cross-track pointing capability for event monitoring. Slew rate < 0.5 deg/s.	20 *m*, < 5 arcsec	≤ 20 µrad/s (3σ)
Flock constellation	3-axis control. Permanent magnet locked and axis-aligned to the Earth's magnetic field (being nadir pointing twice per orbit)	The alignment of the magnetic field is about 1 deg at any point.	Large stability provided by magnetorquers.

Table 8: Attitude control performances in Optical VHR High performance missions.

Satellite	Agility	Pointing accuracy	Stability
Pleiades	3-axis control. Up to 60 deg in roll and pitch in 25 s (2.4 deg/s).	< 2 arcsec.	3-axis stabilized.
WorldView-4	3-axis control. 200 km in 10.6 s (1.7 deg/s)	< 1.5 arcsec.	3-axis stabilized.

Table 9: Attitude control performances in Optical VHR Low Cost missions.

Satellite	Agility	Pointing accuracy	Stability
Deimos-2	3-axis control. ±45 deg pointing in cross-track (maximum). ±30 deg pointing in cross-track (nominal), > 1 deg/sec slew rate.	0.03 deg (108 arcsec) in all axes.	3-axis stabilized. 0.009 deg/s (3σ) (157 µrad/s).
RapidEye	3-axis control. Cross track off-pointing up to ±20 deg.	0.2 deg (720 arcsec) (3σ).	3-axis stabilized.
SkyBox Constellation	3-axis control.	0.1 deg (360 arcsec).	3-axis stabilized.

Table 10: Attitude control performances in SAR missions.

Satellite	Agility	Pointing accuracy	Stability
TerraSAR-X	3-axis control. Slew rate < 0.4 deg/s, ±30 deg off nadir.	65 arcsec (3σ).	3-axis stabilized.
Sentinel-1	3-axis control.	0.01 deg (36 arcsec).	3-axis stabilized.
EnviSat	3-axis control.	< 0.1 deg (360 arcsec) (3σ).	3-axis stabilized.
COSMO-SkyMed Second Generation (CSG)	3-axis control.	High pointing accuracy.	3-axis stabilized.

5.4. OPERATIONS SUMMARY

In summary, the main performances of an EO platform for orbit and attitude control have been analyzed. The state of the art for four different mission concepts has been studied, considering relevant mission examples. Table 11 includes a proposal for the desired performances for orbit control and Table 12 for attitude control. The figures are based on the collected information for each concept.

The main conclusions extracted from this study are as follows:

- Every mission concept presents differences in the orbit and attitude operations. Even when some of are common the performance values are of different magnitude, e.g. slew rates or pointing accuracy.
- The VHR mission concept presents the most demanding requirements for agility and pointing accuracy because of the application fields. In the case of VHR low-cost satellites, the aim is to achieve similar performance, whilst reducing costs and energy consumption. This leads to a slight relief in terms of the low-cost mission agility requirements.
- In the case of SAR missions the common orbital selection is notable: Dawn-dusk SSO, which is optimum for the operational concept in terms of reduction of eclipses and energy acquisition optimization.
- In general, for VLEO deorbiting in 25 years after the end of operations is easily achievable.
- In order to attain typical EO mission lifetime values, satellites in VLEO must be provided with a propulsion system for drag compensation and orbit maintenance. Furthermore, the spacecraft ballistic coefficient must be increased as much as allowed by the payload.

Table 11: Orbit control performances summary.

		Optical coverage missions	**Optical VHR high performance missions**	**Optical VHR low cost missions**	**SAR missions**
Orbit control	**Orbit maintenance**	Orbit maintenance is performed during 3-7 years of lifetime, depending on the mission. The typical orbit is SSO with LTAN/LTDN 10:30.	Orbit maintenance is performed during 5-7 years of lifetime, depending on the mission. The typical orbit is SSO with LTAN/LTDN 10:30.	Orbit maintenance is performed during 4-7 years of lifetime, depending on the mission. The typical orbit is SSO with LTAN/LTDN 10:30.	Orbit maintenance is performed during 5-10 years of lifetime depending on the mission. Typical orbit is SSO dawn/dusk with LTAN/LTDN 06:00.
	Collision avoidance	2 collision manoeuvres per year.	2 collision manoeuvres per year.	2 collision manoeuvres per year.	2 collision manoeuvres per year.
	Nominal orbit insertion	+/- 50 km SMA, +/- 1 deg inclination.	+/- 50 km SMA, +/- 1 deg inclination.	+/- 50 km SMA, +/- 1 deg inclination.	+/- 50 km SMA, +/- 1 deg inclination.
	Rephasing	Two manoeuvers per year to replace the satellite at a certain altitude above the nominal orbit.	Two manoeuvers per year to replace the satellite at a certain altitude above the nominal orbit.	Two manoeuvers per year to replace the satellite at a certain altitude above the nominal orbit.	Two manoeuvers per year to replace the satellite at a certain altitude above the nominal orbit.
	Deorbiting	Re-entering in less than 25 years after the end of operations.	Re-entering in less than 25 years after the end of operations.	Re-entering in less than 25 years after the end of operations.	Re-entering in less than 25 years after the end of operations.

Table 12: Attitude control performances summary.

		Optical coverage missions	Optical VHR high performance missions	Optical VHR low cost missions	SAR missions
Attitude control	**Agility**	3-axis control, > 0.5 deg/s[36].	3-axis control. Up to 60 deg with 1.7-2.4 deg/s.	3-axis control. Up to 45 deg. > 1 deg/s.	3-axis control. Up to 30 deg[37] > 0.4 deg/s.
	Pointing accuracy	< 5 arcsec[38].	< 1.5-2 arcsec.	< 108-720 arcsec.	< 36-360 arcsec.
	Stability	3-axis stabilized. < 20-44 µrad/s[39].	3-axis stabilized.	3-axis stabilized. <160 µrad/s.	3-axis stabilized.

[36] Requirement DISCR140
[37] Requirement DISCR130
[38] Requirement DISCR150
[39] Requirement DISCR160

	Other control performances I.Detumbling **II.Perturbances**	I.Reducing the initial rate under 1 deg/sec each axis within 24 hours protecting P/L from sunlight[40] [41]. II.Compensating a torque of 10^{-4} Nm order from Solar Radiation.	I.Reducing the initial rate under 1 deg/sec each axis within 24 hours protecting P/L from sunlight. II.Compensating a torque of 10^{-2} Nm order from Gravity Gradient.	I.Reducing the initial rate under 1 deg/sec each axis within 24 hours protecting P/L from sunlight. II.Compensating a torque of 10^{-3} Nm order from Gravity Gradient.	I.Reducing the initial rate under 1 deg/sec each axis within 24 hours protecting P/L from sunlight. II. Compensating torques of 10^{-4} Nm order produced by Solar Radiation, Gravity Gradient and Aerodynamic forces[42].

[40] Requirement DISCR170
[41] Requirement DISCR250
[42] Requirement DISCR180

6. ANALYSIS OF EO WITH ENHANCED AERODYNAMICS AND TECHNOLOGIES

6.1. APPLICATIONS FOR EARTH OBSERVATION

With regards to the use of aerodynamic technologies, consideration of the atmosphere density is paramount to achieving good results as it has a strong impact on the values of the applicable forces and torques. Thus the applicability of aerodynamic technologies is mainly restricted to VLEO. In terms of EO applications for general missions (without considering any filter by altitude), it is possible to identify a number of different groups:

- **Forest**: forest management requires ground resolutions between VHR (~1 m) and medium resolution (>10 m). Multiple bands are commonly used in the payloads including hyperspectral sensors.
- **Agriculture**: this is a very heterogeneous group of applications that includes precision agriculture, illicit crop detection, measurements of chlorophyll and vegetation identification among others. In this case not only visible but also SAR payloads are used with a very wide range of resolutions.
- **Water Management**: snow and lake covers, water properties management or oceanography are classified in this group. Typically medium to low resolution are required, so VLEO is not identified as the best option as payload precision is not the main design driver.
- **Land**: mineral analysis, sediment control, soil management and mapping are included. Apart from wide swath images required for mapping in which resolution is not a driver, typically resolution for these land applications ranges from medium resolution at around 10 m to very high precision images below 1 m (0.5 m for traffic applications).
- **Atmosphere:** meteorology applications commonly use very low resolution and very wide swath. In principle, VLEO does not present relevant advantages for these missions.
- **Climate change:** this is similar to the previous case.
- **Crisis response:** this group includes useful applications for prediction of natural disasters such as flood risk analysis, monitoring of volcanic eruptions or forest fires, and also for post-event tasks such as damage assessment. Although frequent revisit time is an important parameter for this applications (which VLEO does not generally enhance), the required resolution now is a key driver that make lower orbits very useful for this purpose.
- **Urban:** This group of applications are the most representative for VHR missions. With requirements below 1 m and reaching 0.5 m of GSD this group includes traffic, urban development and intelligence services that would benefit from very low orbits.
- **Marine:** Several applications are included here such as maritime surveillance, oil spill monitoring and response, fishing activity monitoring, port security, or piracy monitoring. They make use of medium-to-high resolution (from 30 m to about 1 m or better) with very demanding revisit time periods. VLEO can be a good solution due to the spatial resolution improvement, but requires additional complements (such as multiple satellites in form of swarms or constellations) to improve temporal resolution.

Considering now the four mission concepts already presented in Section 5.1, it is useful to match these concepts with the applications groups presented above. These pairs of concepts and applications will then be used to conclude in which applications the identified aerodynamic technologies will have the biggest impact.

Four different mission concepts were selected to analyse a wide set of requirements:

- Optical coverage: typically missions with low or no agility performances, payload without very high pointing precision and very high resolution, but with very wide footprints to optimise the volume of the acquired area.
- Optical VHR high performance: Very high resolution is the key parameter, also the revisit time so it is common the use of constellations such as Pleiades and WorldView. The spectral resolution is also important so multiple payloads are commonly included in the satellite.
- Optical VHR low cost: the resolution and the revisit time are very demanding requirements, however pointing accuracy requirements are less demanding. Again constellations are common to improve the acquisition frequency (as e.g. RapidEye and DMC). The spectral bands are typically restrained to RGB and Panchromatic, which limits some applications.
- Synthetic Aperture Radar: SAR payloads have applications as all-weather capable, day-night operable and are complementary of optical applications as radar is sensitive to dielectric constant, surface roughness, penetration, and slope, among other parameters.

In Table 13 the applications associated to every concept are indicated. The selection has been made in a qualitative way according to the grade of achievement of the key requirements (spatial resolution, spectral resolution, image quality and agility) by every concept and for each application.

Table 13: EO applications carried out by the mission concepts.

	Optical Coverage	Optical VHR high performance	Optical VHR low cost	Synthetic Aperture Radar
Forestry	✔	✔	✔	✔
Agriculture	✔	✔	✔	✔
Water Management	✔			✔
Land	✔			✔
Atmosphere	✔			✔
Climate change	✔			✔
Crisis Response	✔	✔	✔	✔
Urban		✔	✔	
Marine	✔	✔	✔	✔

6.2. AERODYNAMIC TECHNOLOGIES APPLIED TO IN ORBIT OPERATIONS

The term "aerodynamic technologies" is used to define several manners of creating, modifying and even preventing forces due to the satellite environment, specifically due to the residual atmosphere present in Earth orbits. The generation of aerodynamic forces in orbit is dependent on the material characteristics and the geometry of the spacecraft with respect to the atmospheric flow. Aerodynamic technologies have been divided into the following categories:

- Aerodynamic geometries
- Materials

6.2.1. Aerodynamic geometries

Several spacecraft configurations are applied in flying satellites whose designs are derived not only from drag characteristics but also from calculations about volume optimization, sun-power acquisition, structural properties or payload constraints.

From an aerodynamic point of view, the main objective of a geometric design shall be the improvement of drag characteristics and manoeuvring of the spacecraft.

Drag reduction

Considering VLEO, atmospheric density causes an increase in the decay rate compared to operation at higher altitudes, leading to lifetime reduction. The ballistic coefficient is a measure of the aerodynamic properties of the platform; the higher it is the lower the deceleration caused by the drag. High ballistic coefficients are achieved by increasing the mass to cross-section area ratio and reducing drag coefficient. Thus, platforms might be as compact as possible and slender shaped in the axis coincident with the velocity direction.

Further information and references about low-drag geometries are given in Section 3.1.

Spacecraft Manoeuvring

Manoeuvring using aerodynamic technologies requires the generation of forces or torques. While drag force is easy to achieve and differential drag manoeuvring has been demonstrated with some positive results, the use of lift at orbit altitudes is not so promising because of the simultaneous generation of undesired drag. The very low lift-to-drag ratios do not provide optimal performance for aerodynamic technologies when applied to some operations in which a lift force is required, as for example, orbit maintenance, collision avoidance, nominal orbit acquisition, and in general operations in which the orbital energy increases as a consequence of increasing the altitude. Within DICOVERER reflecting materials will be researched to increase the lift-to-drag ratios. It is expected that these technologies improve manoeuvring.

In Section 2.2 and in Section 3.1 implemented solutions and designs of aerodynamic technologies to perform in orbit operations were introduced:

- Aerostabilisation:
  - Aerodynamic skirt of DS-MO satellites.
  - Off-centre weighted design of the PAMS mission.
  - Aerodynamic fins in GOCE spacecraft.
  - Shuttlecock design of the QbX satellites.
- Drag increase oriented to speed orbital decay:

  - Deployable wings to increase the cross-sectional area in Aerocube-4.
- Pointing control in 3-axes (although these designs have the counterpart of increasing drag):
  - Set of four independently movable panels.
  - Set of four steerable fins in feathered configuration.
- Out-of-plane aerodynamic orbit control:
  - A wedge-shaped geometry to have a high and controllable lift-to-drag ratio through yawing about z-axis in order to perform inclination corrections to maintain a descending SSO. This solution requires drag-compensating propulsion.
- GTO perigee raising assistance:
  - Use of aerodynamic (and gravity-gradient) torques for the low-altitude perigee passage of geostationary satellites during electric orbit raising manoeuvres.
- Orbit/constellation maintenance:
  - Differential drag manoeuvres to perform constellation maintenance manoeuvres. The primary benefits of these operations are a reduction of propellant expenditure and the capability for in-plane phasing for spacecraft with no propulsion systems, however they take long times of operation and reduce orbital altitude and lifetime.
- Reentry control:
  - Drag adjustments through a configuration that allows drag modulation.
- Aeroassisted manoeuvres:
  - Hybrid combination of propulsive manoeuvring and aerodynamic manoeuvres in the low atmosphere. This requires thermal protection.

6.2.2. Materials

The study of new materials is proposed to improve the spacecraft aerodynamics, directly impacting on the performance of aerodynamic geometries (e.g. body shape, fins, panels). Currently, research is focused on the following:

- Lower surface accommodation coefficients
- Encouraging of specular and quasi-specular particle reemission
- Resistance to contamination and erosion. Materials which are resistant to adsorption of and erosion by atomic oxygen

6.3. ENHANCED AERODYNAMICS AND TECHNOLOGIES PERFORMANCE

Due to the reduced maturity of aerodynamic control in orbit regarding aerostability, most of the studies have not focused on specific applications or mission type. However, some studies of aerodynamic control and associated technologies indicate benefits that particularly apply to Earth Observation missions.

At altitudes under approximately 400 km the aerodynamic effects are in general the most significant disturbance and may be used to control the attitude of the satellite. In VLEO, aerostable designs and low-drag geometries may increase orbital lifetimes and attitude stability.

The use of aerodynamic forces for orbital station-keeping and constellation maintenance have also been demonstrated in orbit. These methods can reduce propellant consumption or eliminate propulsion system, but lengthy deployment periods and significant reduction of orbital lifetime are the main drawbacks.

Active aerodynamic attitude control and pointing are yet to be demonstrated in orbit. In addition, the available literature indicates that pointing control capability is limited with currently characterised materials and that the only use of aerodynamic control may be unreliable given the significant variability and uncertainty of atmospheric density.

Aerodynamic technologies performances

The following performance parameters have been derived from the study performed in Section 2. VLEO Aerodynamics:

- Using aerodynamic control surfaces, coarse pointing capability of up to 5° (with respect to the oncoming flow) in pitch and yaw is expected to be achievable.
- For aerostability, a shifted forward CoM allows pitch torques of the order of 1.5 – 2.0 Nm^2/kg. An analysis of the control capability at different altitudes also showed that stiff aerodynamic-stabilisation would be available at low-altitudes (torques of 10^{-7} to 10^{-5} Nm at 300 km), whilst at higher altitudes aerodynamic torques would be of similar magnitude to gravity gradient torques (10^{-8} to 10^{-7} Nm at 500 km).
- Two 3U satellites with a shuttlecock configuration were first studied by Rawashdeh and Lumpp [9]. They found a steady-state tracking accuracy of 10° to 20° using passive damping and less than 0.1° using active damping. In addition, a 1U CubeSat with four tape-measure fins (2.5 cm x 25 cm) was examined and reported to achieve similar steady-state tracking accuracies with a significantly smaller restoring torques (0.15 – 0.20 Nm^2/kg).
- A configuration of four steerable fins was presented by Virgili Llop et al. [14] [15]. Active magnetic damping was demonstrated to produce a pointing capability of less than 2° error with respect to the oncoming flow. An active aerodynamic damping technique was also presented, performing an amplitude of approximately 1° in every axis.

In addition to the concepts previously presented, satellite designs which make special consideration for the dynamics in VLEO or feature novel aerodynamic technologies can be considered, for example the wedge-shaped satellite design presented by Virgili Llop et al. [40] enabling out-of-plane orbit manoeuvring.

For satellites featuring conventional momentum-exchange attitude control actuators (reaction wheels, CMGs), aerodynamic surfaces could be used to provide natural desaturation capability, thus reducing requirements on these actuators and the power requirements for magnetorquers [67]. Moving aerodynamic surfaces could also be used to vary the stability of a satellite between different configurations, allowing for increased agility (slew rates) for pointing when required and increased stability at other times. Moving surfaces could also be used to provide “aerodynamic trim”, rejecting or mitigating the effects of environmental torques on the satellite body and thus further reducing the requirements on active attitude actuators.

An alternative “aerodynamic disc” geometric concept (shown in Figure 36) can enable the satellite to remain area-invariant with respect to the flow when performing pitching and rolling manoeuvres using conventional attitude control actuators. This allows satellites with telescopes to perform slewing manoeuvres without incurring any change in cross-sectional area or aerodynamic condition and therefore avoid potentially disturbing or resisting torques which might otherwise increase the demand on the on-board attitude actuation and control systems. Furthermore, if the centre of mass of the spacecraft is also located at the geometric centre, unwanted yawing torques can also be eliminated. This condition can be described as neutral stable, where the aerodynamic moment coefficients are equal to zero and do not change with the angle with respect to the flow. Net forces will be still generated, principally drag. However, by selection of the roll/yaw orientation of the spacecraft, side-forces could be utilised over time to enable propellant-free orbit-change manoeuvres.

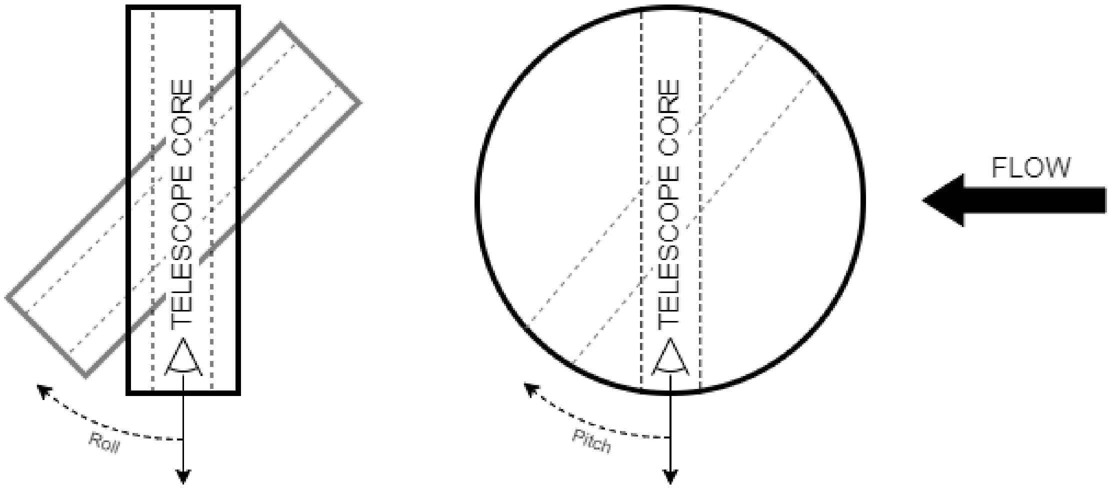


Figure 36. "Aerodynamic Disc" Geometric Concept

Such geometry may also provide insensitivity to thermospheric gusts, which may produce unwanted body rotations and structural vibrations affecting imaging quality. For such geometry, the surface area in contact with the oncoming flow may be increased, but the projected area will remain similar to that of conventional designs. A reconsideration of classical satellite structural configurations and location of supporting subsystems may reduce this impact. Further, inflatable or deployable structures could also be considered to reduce volume for launch, whilst the development of low-drag surfaces and materials would enable longer mission lifetimes without compensating propulsion systems.

6.4. AERODYNAMIC TECHNOLOGIES APPLIED TO THE MISSION CONCEPTS

By considering the four mission concepts and the analysis of the current state of the art in aerodynamic technologies we can define which technologies are most applicable to each mission.

From Section 5.4, we concluded that most orbit control operations are similar in each defined mission concept (with the exception of lifetime values) and that there are clear differences in the attitude control performances requirements for each concept. 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, see Table 14.

Table 14. Relation between aerodynamic technologies and mission concepts through operations.

<table>
<tr><th colspan="2"></th><th>Optical coverage missions</th><th>Optical VHR high performance missions</th><th>Optical VHR low cost missions</th><th>SAR missions</th></tr>
<tr><td rowspan="5">Orbit control operations</td><td>Orbit maintenance</td><td colspan="4">Aerodynamic geometries: Creation of aerodynamic forces for orbital station-keeping at the expense of lengthy deployment periods and potentially significant reduction in orbital lifetime.</td></tr>
<tr><td>Collision avoidance</td><td colspan="4" rowspan="2">Aerodynamic geometries: Creation of aerodynamic forces for altitude increase with significant reduction in orbital lifetime caused by drag increase.</td></tr>
<tr><td>Nominal orbit insertion</td></tr>
<tr><td>Rephasing</td><td colspan="4">Aerodynamic geometries: Creation of aerodynamic forces for constellation maintenance at the expense of lengthy deployment periods and potentially significant reduction in orbital lifetime.</td></tr>
<tr><td>Deorbiting</td><td colspan="4">Aerodynamic geometries: Creation of aerodynamic forces for deorbiting.</td></tr>
<tr><td rowspan="4">Attitude control operations</td><td>Agility</td><td colspan="4">N/A: The very low lift-to-drag ratios do not provide optimal performances for aerodynamic technologies applied to agility operations.</td></tr>
<tr><td>Pointing accuracy</td><td colspan="4">Aerodynamic Control Surfaces: Up to 5deg (coarse pointing) 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-centre weighted design, Aerodynamic fins, Shuttlecock design: Generation of torques up to 10^{-7} Nm at 500km.</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td><td rowspan="2">Aerodynamic skirt, Off-centre weighted design, Aerodynamic fins, Shuttlecock design: Generation of torques up to 10^{-5} Nm at 300km.</td></tr>
<tr><td>Other control performances</td></tr>
</table>

N/A: *Not applicable aerodynamic technologies for the operation and mission concept.*

We can conclude the following, relating aerodynamic technologies VLEO, platform concepts, and applications:

- Optical Coverage and SAR concepts focus in the same group of applications (although specific outputs from these missions are dedicated to different processed products).
- VHR with low cost and VHR high performance missions focus on the same group of applications.
- Optical Coverage and SAR concepts seem to be the most appropriate concepts to make use of aerodynamic technologies for flying at VLEO, while VHR low cost and VHR high performance impose very demanding agility and pointing accuracy, which cannot be provided by aerodynamic technologies. Therefore, the most promising aerodynamic technologies are related to the configuration design of the platform body and addition of aerodynamic surfaces with the aim of performing aerostability operations and disturbance torques mitigation applied to Optical Coverage and SAR missions.
- Aerodynamic technologies can be used for orbit control operations such as orbit maintenance, collision avoidance, nominal orbit insertion, rephrasing and deorbiting. However, because of the increase in drag forces, these manoeuvres would be lengthy in time and would reduce the orbital lifetime, demanding additional propulsion for altitude maintenance.
- In the case of the deorbiting manoeuvre, the drag increase is an advantage, and it can reduce the propellant budget dedicated to this end-of-life manoeuver for all the mission concepts. Nevertheless, operating a satellite in VLEO guarantees for almost any size of spacecraft a natural decay before 25 years.
- In terms of attitude control operations the current SoA and research on aerodynamic technologies conclude that they are not suitable for agility operations as the slew rates provided do not fulfil the attitude requirements of commercial missions as reaction wheels and control moment gyros can. They could be used for aerodynamic trim if they are combined with traditional actuators. Further research can be done here, but the satellite complexity and risk would increase as well.
- Aerodynamic control surfaces can provide a coarse performance in pointing accuracy for every mission concept.
- Aerodynamic technologies 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.
- The groups of applications that would benefit from the use of aerodynamic technologies in this field are the following (extracted from the applications relation with mission concepts in Table 13):
    - Forestry
    - Agriculture
    - Water Management
    - Land
    - Atmosphere
    - Climate change
    - Crisis Response
    - Marine
- Attitude pointing based on aerodynamics is theoretically possible and can have applicability, such as coarse pointing manoeuvres or reduce the load supported by reaction wheels.
- Alternatively, a propulsion system which could partially compensate the effect of drag could be used to compensate the drag forces produced by the low lift-to-drag ratio of the aerodynamic technologies applied to agility operations.

From these results a list of requirements is extracted in the following section.

7. AERODYNAMIC REQUIREMENTS FOR EO APPLICATIONS AND PLATFORM CONCEPTS

In this section a list of requirements for attitude and orbit control systems is included. The requirements have a unique identifier code and are classified into different groups:

- Attitude control: Requirements applied to attitude control devices.
- Orbit control: Requirements applied to orbit control devices.
- A&O control: Requirements applied to both attitude and orbit control devices.

Every requirement is also classified as operational (specifications, environment adaptability) or functional (performances for the system). Annex A describes the requirements management manual and tool.

These requirements have been commonly covered by Attitude and Orbit Control Subsystem (AOCS) and Propulsion Subsystem (PS). In the frame of this project, the aim is to enhance the performance of satellites flying at VLEO by means of aerodynamic technologies. The use of these technologies is therefore subjected to the achievement of the requirements.

According to the results shown in Section 6.4, the required parameters of some performance requirements are based on the state of the art of Optical Coverage and SAR missions. Both mission concepts seem to be the most appropriate to use aerodynamic technologies in VLEO. Some functional and operational requirements are derived from other analysis in this document as referenced for each requirement in the rationale.

Other requirements are extracted from existing missions (also analysed in this document) or standards for attitude control requirements, such as ECSS:

- Values for mass allocation of attitude and orbit control devices are obtained from Deimos-2 as reference mission[43, 44].
- The requirement of a safe mode[45] was derived from ECSS-E-ST-60-30C. This implies that attitude control shall provide autonomous capability to reach and control safe pointing and angular rates to ensure the integrity of the spacecraft vital functions.

[43] Requirement DISCR010
[44] Requirement DISCR020
[45] Requirement DISCR260

Table 15: Attitude and orbit control requirements for aerodynamic technologies.

ID	Group	Type	Name	Description	Rationale	Status	Verification	Remarks
DISCR010	Attitude control	Operational	Attitude control devices mass	Devices for attitude control shall have a maximum mass of 12% of satellite mass.	Aerodynamic technologies shall be competitive compared to classical subsystems. Typical mass allocation for Attitude control subsystem could be a limit in order to make fair comparisons. Percentage estimation comes from ACS mass allocation in Deimos-2 mission as indicated in the introduction of Section 7 Aerodynamic Requirements for EO Applications and Platform Concepts.	Validated	T and RD	Some aerodynamic technologies consist on specific shape of the structure or the use of existing elements as deployable solar panels. In this situation this requirement shall not be applied to these elements as a whole but to the modifications as joints or mechanisms not included in a classical design.
DISCR020	Orbit control	Operational	Orbit control devices Mass	Devices for orbit control shall have a maximum mass of 10% of satellite mass.	Aerodynamic technologies shall be competitive compared to classical subsystems. Typical mass allocation for Orbit control subsystem could be a limit in order to make fair comparisons. Percentage estimation comes from Propulsion Subsystem mass allocation in Deimos-2 mission as indicated in the introduction of Section 7 Aerodynamic Requirements for EO Applications and Platform Concepts.	Validated	T and RD	Some aerodynamic technologies consist on specific shape of the structure or the use of existing elements as deployable solar panels. In this situation this requirement shall not be applied to these elements as a whole but to the modifications as joints or mechanisms not included in a classical design.
DISCR030	A&O Control	Operational	Vacuum	Devices for attitude and orbit control shall operate in vacuum environment.	Satellite operational environment is especially unpleasant because of gravity absence conditions, vacuum, thermal gradients or radiation. From Section 2.1 Principles of Orbital Aerodynamics.	Validated	T	Space environment conditions depend on the orbit so they shall be documented for each specific mission in the Satellite Environmental Specifications Document.

ID	Group	Type	Name	Description	Rationale	Status	Verification	Remarks
DISCR040	A&O Control	Operational	Radiation	Devices for attitude and orbit control shall be designed to withstand the total radiation dose expected during the mission.	Satellite operational environment is especially unpleasant because of gravity absence conditions, vacuum, thermal gradients or radiation. From Section 2.1 Principles of Orbital Aerodynamics.	Validated	T	Space environment conditions depend on the orbit so they shall be documented for each specific mission in the Satellite Environmental Specifications Document.
DISCR050	A&O Control	Operational	Temperature	Devices for attitude and orbit control shall be designed to withstand the temperature variation range expected in the nominal orbit.	Satellite operational environment is especially unpleasant because of gravity absence conditions, vacuum, thermal gradients or radiation. From Section 2.1 Principles of Orbital Aerodynamics.	Validated	T	Space environment conditions depend on the orbit so they shall be documented for each specific mission in the Satellite Environmental Specifications Document.
DISCR060	A&O Control	Operational	Outgassing	Attitude and orbit control devices shall be composed of very low outgassing materials.	In space some materials have outgassing effects, reducing performances and increasing the risk of material depositions in other elements as lenses, mechanisms... From Section 2.1 Principles of Orbital Aerodynamics.	Validated	T	
DISCR070	Orbit control	Functional	Orbit Maintenance	Orbit control shall maintain the orbital parameters during the whole mission.	Orbit control is in charge of the necessary orbit corrections and altitude maintenance. From Section 5.2.1 Orbit maintenance.	Validated	A	Orbital parameters range allowed are defined for each mission. Depending on the amplitude of this range, frequency of manoeuvres is determined.
DISCR080	Orbit control	Functional	Collision avoidance	Orbit control shall be able of performing two collision avoidance manoeuvres per year.	Two collision avoidance per year is a typical estimation considered for DeltaV calculation in preliminary designs. From Section 5.2.2 Collision avoidance.	Validated	A	
DISCR090	Orbit control	Functional	Nominal orbit insertion	Orbit control shall carry the satellite from injection to nominal orbit.	Differences between injection and nominal orbits are estimated in +/-50km in SMA and +/-1deg in inclination although it depends on the mission purpose and the launch conditions. From Section 5.2.3 Nominal orbit insertion.	Validated	A	

ID	Group	Type	Name	Description	Rationale	Status	Verification	Remarks
DISCR100	Orbit control	Functional	Rephasing	Orbit control shall perform at least two manoeuvers per year to rephase the satellite.	In order to change the true anomaly of a satellite, orbit control shall rise the altitude to change the orbital period. Then, orbital decay or a second manoeuver replaces the satellite in the nominal orbit with the target true anomaly.	Validated	A	
DISCR110	Orbit control	Functional	Deorbiting	Orbit control shall allow to re-entry in less than 25 years after the end of operations.	This is a common guideline from several space agencies and organisations to reduce space debris in most populated orbits as indicated in Section 5.2.5 Deorbiting.	Validated	A	
DISCR120	Attitude control	Functional	3-axis Control	Attitude control shall perform 3-axis control of the satellite	3-axis control is performed in all the mission concepts analysed. From 5.3.1 Agility.	Validated	T and RD	
DISCR130	Attitude control	Functional	Agility	Attitude control shall perform up to 30 deg of slew in all angles	This requirement comes from identified SAR missions in Table 12.	Validated	T and RD	
DISCR140	Attitude control	Functional	Slew rate	Attitude control shall perform slew rates higher than 0.5deg/s in all axes	This requirement comes from identified optical coverage missions in Table 12.	Validated	T and RD	
DISCR150	Attitude control	Functional	Pointing accuracy	Attitude control shall have a pointing accuracy better than 5 arcsec	This requirement comes from identified optical coverage missions in Table 12.	Validated	T	
DISCR160	Attitude control	Functional	Stability	Attitude control shall have a stability better than 20 µrad/s in all axes	This requirement comes from identified optical coverage missions in Table 12.	Validated	T	
DISCR170	Attitude control	Functional	Detumbling	Attitude control shall reduce the angular velocity under 1 deg/sec within 24 hours after launch vehicle separation	Attitude control is in charge of stabilising the platform in case it is tumbling when separated from launch vehicle. From Section 2.2.1.5 Detumbling and missions in Table 12.	Validated	A	

ID	Group	Type	Name	Description	Rationale	Status	Verification	Remarks
DISCR180	Attitude control	Functional	Perturbations	Attitude control shall compensate other environmental torques not used for control.	Solar radiation, gravity gradient or aerodynamic forces produce perturbations that affect satellites for optical coverage and SAR missions. Values are shown in Table 12.	Validated	A	
DISCR190	Attitude control	Functional	Yaw steering	Attitude control devices shall be capable of compensating the Earth rotation effect during imaging	Yaw steering is required to compensate the effect of Earth rotation when payload is acquiring images as explained in Section 5.3.1 Agility.	Validated	A	
DISCR200	A&O Control	Functional	Lifetime	Attitude and orbit control devices shall have the same lifetime as the rest of the platform	Attitude and orbit control devices are expected to operate during the whole mission including the disposal. From Section 2.1 Principles of Orbital Aerodynamics.	Validated	T and RD	
DISCR210	A&O Control	Operational	Design loads	Attitude and orbit control devices shall withstand the maximum loads imposed by the launch vehicle.	The maximum loads expected during a mission take place typically during the launch. From the introduction of Section 3 Aerodynamic Technologies	Validated	T	
DISCR220	A&O Control	Operational	Natural frequencies	Attitude and orbit control devices shall have natural frequencies bigger than the imposed by the launch vehicle both in longitudinal and lateral axis.	In order to avoid resonances. This is common in all missions. From the introduction of Section 3 Aerodynamic Technologies.	Validated	T	
DISCR230	A&O Control	Operational	Deployable devices	Attitude and orbit control devices that require to be deployed in operation must be stored during launch.	Volume in launch vehicle is usually very constrained so satellite envelope must be reduced as much as possible. From the introduction of Section 3 Aerodynamic Technologies.	Validated	RD	

ID	Group	Type	Name	Description	Rationale	Status	Verification	Remarks
DISCR240	A&O Control	Operational	Space charging protection	Attitude and orbit control devices that include mechanical parts shall be electrically connected to mechanical structures with resistance less than 10 mOhm.	Grounding is required as space charging protection. From Section 2.1 Principles of Orbital Aerodynamics and Section 4.2.1 Earth's Atmosphere. The resistance value comes from Deimos-2 mission.	Validated	T	
DISCR250	Attitude control	Functional	Payload protection	Attitude control devices shall protect the payload from direct sunlight.	Direct exposure to sunlight can damage photodetectors in the sensor of the payload. From missions in Table 12.	Validated	T	
DISCR260	Attitude control	Functional	Safe Mode	Attitude control shall provide autonomous capability to reach and control safe pointing and angular rates to ensure the integrity of the spacecraft vital functions.	Extracted from ECSS-E-ST-60-30C as indicated in the introduction of Section 7 Aerodynamic Requirements for EO Applications and Platform Concepts.	Validated	T	Major anomalies are defined for each mission.

8. ACKNOWLEDGEMENT AND DISCLAIMER

The DISCOVERER project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.

This publication reflects only the authors' views and the European Commission is not liable for any use that may be made of the information contained therein.

9. REFERENCES

[1] NASA, “Spacecraft Aerodynamic Torques,” 1971.

[2] B. K. Ching, D. R. Hickman and J. M. Straus, “Effects of atmospheric winds and aerodynamic lift on the inclination of the orbit of the S3-1 satellite,” *Journal of Geophysical Research,* vol. 82, p. 1474, 1977.

[3] D. Mostaza-Prieto, B. P. Graziano and P. C. E. Roberts, “Spacecraft drag modelling,” *Progress in Aerospace Sciences,* vol. 64, pp. 56-65, 2014.

[4] K. Moe and M. M. Moe, “Gas–Surface Interactions and Satellite Drag Coefficients,” *Planetary and Space Science,* vol. 53, pp. 793-801, 2005.

[5] M. D. Pilinski, B. M. Argrow and S. E. Palo, “Semiempirical Model for Satellite Energy-Accommodation Coefficients,” *Journal of Spacecraft and Rockets,* vol. 47, pp. 951-956, 2010.

[6] EelcoNieningDOORNBOS, Thermospheric Density and Wind Determination from Satellite Dynamics, Delft: IpskampDrukkers, 2011.

[7] R. R. Kumar, D. D. Mazanek and M. L. Heck, “Simulation and Shuttle Hitchhiker validation of passive satellite aerostabilization,” *Journal of Spacecraft and Rockets,* vol. 32, pp. 806-811, 1995.

[8] R. R. Kumar, D. D. Mazanek and M. L. Heck, “Parametric and classical resonance in passive satellite aerostabilization,” *Journal of Spacecraft and Rockets,* vol. 33, pp. 228-234, 1996.

[9] S. A. Rawashdeh and J. E. Lumpp, “Aerodynamic Stability for CubeSats at ISS Orbit,” *Journal of Small Satellites,* vol. 2, pp. 85-104, 2013.

[10] V. A. Sarychev, S. A. Mirer, A. A. Degtyarev and E. K. Duarte, “Investigation of equilibria of a satellite subjected to gravitational and aerodynamic torques,” *Celestial Mechanics and Dynamical Astronomy,* vol. 97, pp. 267-287, 2007.

[11] M. R. Drinkwater, R. Haagmans, D. Muzi, A. Popescu, R. Floberghagen, M. Kern and M. Fehringer, “The GOCE Gravity Mission: ESAŚ First Core Earth Explorer,” in *3rd International GOCE User Workshop*, Frascati, 2007.

[12] J. Armstrong, C. Casey, G. Creamer and G. Dutchover, “Pointing Control for Low Altitude Triple Cubesat Space Darts,” in *23rd Annual AIAA/USU Conference on Small Satellites*, Logan, 2009.

[13] M. L. Psiaki, “Nanosatellite Attitude Stabilization Using Passive Aerodynamics and Active Magnetic Torquing,” *Journal of Guidance, Control, and Dynamics,* vol. 27, pp. 347-355, 2004.

[14] J. Virgili Llop, P. C. E. Roberts, S. Hobbs and J. Kingston, “Aerostability for Low Altitude Flying CubeSats,” in *2nd IAA Conference on University Satellite Missions and Cubesat Workshop*, Rome, 2013.

[15] J. Virgili Llop, P. C. E. Roberts and Z. Hao, “Aerodynamic Attitude and Orbit Control Capabilities of The ∆Dsat CubeSat,” in *37th Annual AAS Guidance and Control Conference*, Breckenridge, 2014.

[16] D. Mostaza-Prieto and P. C. E. Roberts, “Methodology to Analyze Attitude Stability of Satellites Subjected to Aerodynamic Torques,” *Journal of Guidance, Control, and Dynamics,* vol. 39, pp.

437-449, 2016.

[17] International Space Company Kosmotras, “Space Launch System DNEPR User's Guide,” Moscow, 2001.

[18] Z. Hao and P. C. E. Roberts, “Using Aerodynamic Torques To Aid Detumbling Into an Aerostable State,” in *67th International Astronautical Congress*, Guadalajara, 2016.

[19] M. L. Gargasz, “Optimal Spacecraft Attitude Control Using Aerodynamic Torques,” 2007.

[20] J. Virgili Llop and P. C. E. Roberts, “ΔDsat, a QB50 CubeSat mission to study rarefied-gas drag modelling,” *Acta Astronautica,* vol. 89, pp. 130-138, 2013.

[21] D. Mostaza-Prieto and P. C. E. Roberts, “Perigee Attitude Maneuvers of Geostationary Satellites During Electric Orbit Raising,” *Journal of Guidance, Control, and Dynamics,* pp. 1-12, 2017.

[22] C. L. Leonard, W. M. Hollister and E. V. Bergmann, “Orbital Formationkeeping with Differential Drag,” *Journal of Guidance, Control, and Dynamics,* vol. 12, pp. 108-113, 1989.

[23] N. J. du Toit and Daniel, J. J. du Plessis and W. H. Steyn, “Using Atmospheric Drag for Constellation Control of Low Earth Orbit Micro-satellites,” in *10th Annual AIAA/USU Conference on Small Satellites*, Logan, 1996.

[24] G. B. Palmerini, S. Sgubini and G. Taini, “Spacecraft Orbit Control using Air Drag,” in *56th International Astronautical Congress*, Fukuoka, 2005.

[25] R. Bevilacqua and M. Romano, “Rendezvous Maneuvers of Multiple Spacecraft Using Differential Drag Under J2 Perturbation,” *Journal of Guidance, Control, and Dynamics,* vol. 31, pp. 1595-1607, 2008.

[26] C. Lambert, B. S. Kumar, J. F. Hamel and A. Ng, “Implementation and performance of formation flying using differential drag,” *Acta Astronautica,* vol. 71, pp. 68-82, 2012.

[27] O. Ben-Yaacov and P. Gurfil, “Long-Term Cluster Flight of Multiple Satellites Using Differential Drag,” *Journal of Guidance, Control, and Dynamics,* vol. 36, pp. 1731-1740, 2013.

[28] A. S. Li and J. Mason, “Optimal Utility of Satellite Constellation Separation with Differential Drag,” in *AIAA/AAS Astrodynamics Specialist Conference*, San, 2014.

[29] L. DellÉlce and G. Kerschen, “Optimal propellantless rendez-vous using differential drag,” *Acta Astronautica,* vol. 109, pp. 112-123, 2015.

[30] L. Mazal, D. Pérez, R. Bevilacqua and F. Curti, “Spacecraft Rendezvous by Differential Drag Under Uncertainties,” *Journal of Guidance, Control, and Dynamics,* vol. 39, pp. 1721-1733, 2016.

[31] A. W. Lewin, “Low-Cost Operation of the ORBCOMM Satelliet Constellation,” in *11th Annual AIAA/USU Conference on Small Satellites*, Logan, 1997.

[32] J. W. Gangestad, B. S. Hardy and D. A. Hinkley, “Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats,” in *27th Annual AIAA/USU Conference on Small Satellites*, Logan, 2013.

[33] C. R. Boshuizen, J. Mason, P. Klupar and S. Spanhake, “Results from the Planet Labs Flock Constellation,” in *28th Annual AIAA/USU Conference on Small Satellites*, Logan, 2014.

[34] C. Foster, H. Hallam and J. Mason, “Orbit determination and differential-drag control of Planet Labs cubesat constellations,” *Advances in the Astronautical Sciences,* vol. 156, pp. 645-657,

2016.

[35] R. Patera, “Drag Modulation as a Means of Mitigating Casualty Risk for Random Reentry,” in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, San, 2005.

[36] S. Alemán, “Satellite Reentry Control via Surface Area Amplification,” 2009.

[37] J. Virgili Llop, P. C. E. Roberts and N. C. Hara, “Atmospheric Interface Reentry Point Targeting Using Aerodynamic Drag Control,” *Journal of Guidance, Control, and Dynamics,* vol. 38, pp. 403-413, 2015.

[38] H. Leppinen, “Deploying a single-launch nanosatellite constellation to several orbital planes using drag maneuvers,” *Acta Astronautica,* vol. 121, pp. 23-28, apr 2016.

[39] M. Horsley, S. Nikolaev and A. Pertica, “Small Satellite Rendezvous Using Differential Lift and Drag,” *Journal of Guidance, Control, and Dynamics,* vol. 36, pp. 445-453, 2013.

[40] J. Virgili Llop, P. C. E. Roberts, K. Palmer, S. Hobbs and J. Kingston, “Descending Sun-Synchronous Orbits with Aerodynamic Inclination Correction,” *Journal of Guidance, Control, and Dynamics,* vol. 38, pp. 831-842, 2015.

[41] H. S. London, “Change of Satellite Orbit Plane by Aerodynamic Maneuvering,” *Journal of the Aerospace Sciences,* vol. 29, pp. 323-332, 1962.

[42] G. D. Walberg, “A Review of Aeroassisted Orbit Transfer,” in *9th Atmospheric Flight Mechanics Conference*, San, 1982.

[43] A. Miele, “The 1st John V. Breakwell Memorial Lecture: Recent advances in the optimization and guidance of aeroassisted orbital transfers,” *Acta Astronautica,* vol. 38, pp. 747-768, 1996.

[44] A. Miele, W. Y. Lee and K. D. Mease, “Optimal trajectories for LEO-to-LEO aeroassisted orbital transfer,” *Acta Astronautica,* vol. 18, pp. 99-122, 1988.

[45] H. Chen and D. Yang, “Nonplanar LEO-LEO aeroassisted space rendezvous,” *Aircraft Engineering and Aerospace Technology,* vol. 79, pp. 22-34, 2007.

[46] C. L. Darby and A. V. Rao, “Minimum-Fuel Low-Earth-Orbit Aeroassisted Orbital Transfer of Small Spacecraft,” *Journal of Spacecraft and Rockets,* vol. 48, pp. 618-628, 2011.

[47] R. A. Bettinger and J. T. Black, “Comparative Study of Phasing, Atmospheric Skip Entry, and Simple Plane Change Maneuvers,” *Journal of Spacecraft and Rockets,* vol. 51, pp. 1965-1975, 2014.

[48] J. R. Wertz and W. J. Larson, Space Mission Analysis and Desing, 3rd ed., United States of America: Space Technology Library, 2013.

[49] J. H. Park, R. S. Myong, D. H. Kim and S. W. Baek, “Aerodynamic shape optimization of space vehicle in very-low-earth-orbit,” in *29th International Symposium on Rarefied Gas Dynamics*, Xi'an, China, 2014.

[50] M. R. Reddy, “Review effect of low earth orbit atomic oxygen on spacecraft materials,” *Journal of Materials Science,* vol. 30, pp. 281-307, 1995.

[51] B. A. Banks, S. K. Miller and K. de Groh and Kim, “Low Earth Orbital Atomic Oxygen Interactions with Materials,” in *2nd International Energy Conversion Engineering Conference*, Providence, 2004.

[52] S. W. Samwel, “Low Earth Orbital Atomic Oxygen Erosion Effect on Spacecraft Materials,” *Space Research Journal,* vol. 7, pp. 1-13, 2014.

[53] J. V. Llop, “Spacecraft Flight in the Atmosphere,” Cranfield University, Cranfield, 2014.

[54] J. Virgili Llop, P. C. E. Roberts, Z. Hao, L. Ramio Tomas and V. Beauplet, “Very Low Earth Orbit mission concepts for Earth Observation: Benefits and challenges,” in *12th Reinventing Space Conference*, London, 2014.

[55] J. V. Llop, “Very Low Earth Orbit mission concepts for Earth Observation. Benefits and challenges,” London, 2014.

[56] E. S. Agency, “Mitigating Space Debris Generation,” ESA, 14 April 2017. [Online]. Available: http://www.esa.int/Our_Activities/Operations/Space_Debris/Mitigating_space_debris_generation. [Accessed 03 August 2017].

[57] E. S. Agency, “ESA,” 2016. [Online]. Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space/CleanSat. [Accessed 18 August 2016].

[58] J. Pearson, “Active Debris Removal: EDDE, the ElectroDynamic Debris Eliminator,” Mountain View, 2010.

[59] L. A. Singh, “Very Low Earth Orbit Propellant Collection Feasibility Assessment,” Georgia Institute of Technology, Georgia, 2014.

[60] G. Maral, “Low Earth satellite system for communicatiobns,” *International Journal of Satellites Communications,* vol. 9, no. 4, pp. 209-225, 1991.

[61] SUPARCO, “The National Space Agency of Pakistan,” SUPARCO, 8 March 2017. [Online]. Available: http://www.suparco.gov.pk/pages/applications-satellite.asp. [Accessed 8 March 2017].

[62] ESA, “Telecomunications & integrated applications,” ESA, 03 April 2013. [Online]. Available: http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Orbits. [Accessed 03 April 2013].

[63] G. Weidermann, W. Gockel, S. Winkler, J. M. Rieber, B. Kraft and D. Reggio, “The Sentinel-2 satellite attitude control system - challenges and solutions,” 9th International ESA Conference on Guidance, Navigation & Control Systems, Porto, Portugal, 2014.

[64] L. Lebègue, G. D. Ph. Kubik, D. F and T. N, “Using exotic guidance for Pleiades-HR image quality calibration,” Centre National d'Etudes Spaciales, Toulouse, 2018.

[65] Argonne National Laboratory, “Design Requirementes for Orbit Maintenance of SPS Elements,” DOE/NASA, Argonne, 1980.

[66] J. Ling and E. Hsueh, “Fuel minimization for constellation phasing maintenance of multi classes of low-cost satellites,” National Space Organization, Taiwan, 2006.

[67] D. Mostaza-Prieto, "Characterisation and Applications of Aerodynamic Torques on Satellites," *The University of Manchester,* 2017.

[68] E. Doornbos, Thermospheric Density and Wind Determination from Satellite Dynamics, Delft: IpskampDrukkers, 2011.

10. ANNEX A: REQUIREMENTS MANAGEMENT MANUAL AND TOOL

10.1. ACRONYMS

A	Analysis
I	Inspection
RD	Review of Design
RM	Requirements Management
SaaS	Software as a Service
T	Test

10.2. INTRODUCTION

The aim of this report is the selection of a requirements management tool to be used in DISCOVERER. Several options are listed and the selection of the tool to work with is justified in this document.

The selected tool is introduced with emphasis on the generated requirements matrix together with a brief user's manual.

10.3. REQUIREMENTS MANAGEMENT TOOLS

In the design of complex systems, requirements management is an essential task that must not be ignored. Lots of professional requirements management (RM) tools are available[46], although a high specialized one might not be always the best option.

In the scope of DISCOVERER, the main functions that this tool has to offer are the following:

- Requirements definition: the RM tool shall allow writing and editing requirements in a simple way.
- Agile requirements visualization: possibility of making a search by keywords is also mandatory to allow to the DISCOVERER team the visualization of requirements in an agile manner.
- Easy access to the tool: in a project like DISCOVERER in which several partners work together from different locations, the use of tools with remote access is mandatory. This is one of the most important demands for the RM tool and maybe the one that make us decided for a specific tool instead of others.
- Good, nice and cheap: is also desirable.

[46] See http://makingofsoftware.com/resources/list-of-rm-tools

10.3.1. Identification

Accordingly to the previous list and based on our experience, two options have been pre-selected for use as the DISCOVERER requirements tool.

10.3.1.1. 3SL Cradle

"*Cradle is a tool to load, create, inter-link and publish information for all stages in a systems engineering project using agile, iterative or phase-based approaches and using any process. It is completely user-definable, scalable, flexible and secure. It can be deployed locally in your organisation or project, deployed to remote sites or partners, or delivered through SaaS from any private or public cloud.*"[47]

Cradle is a professional tool for requirements management widely used in Deimos projects. The Deimos team has experience in the use of this tool and its functionalities go beyond the needs of this project. The main disadvantage of Cradle is that it has limitations to work collaboratively from different locations. This would require new license acquisition and availability for remote access to Deimos servers. We also consider that it is a tool that requires certain knowledge that would have to be shared with the team, increasing the original dedication to these tasks.

10.3.1.2. Google Sheets

As an example of a non-specific RM tool, Google Sheets has been considered as the best option to configure an all-purpose tool as an RM tool. The main drawback is the non-specific functionalities for requirements management, which forces us to design a simple requirements matrix with all the fields that we will need for each item. Other important aspects such as identification, traceability, and verification can be managed in different ways, as the addition of cells with an elements selection or adding new fields for each requirement. The main advantage of this option is that the whole team can easily access the system with a Gmail account from each working place to edit, comment, suggest, or revise. Furthermore, it is free.

10.3.2. Selection

Summarising, Google Sheets will be used as the tool for RM in DISCOVERER. A professional tool is not considered as an option as they usually demand previous knowledge and the acquisition of licenses, apart from the difficulties to access from different places. Out of the non-specific tools, Google Sheets is the most friendly (as they are similar to the well-known Excel tool by Microsoft) and configurable, they offer an easy access from any place and have no costs.

10.4. DISCOVERER REQUIREMENTS TOOL – BRIEF USER'S MANUAL

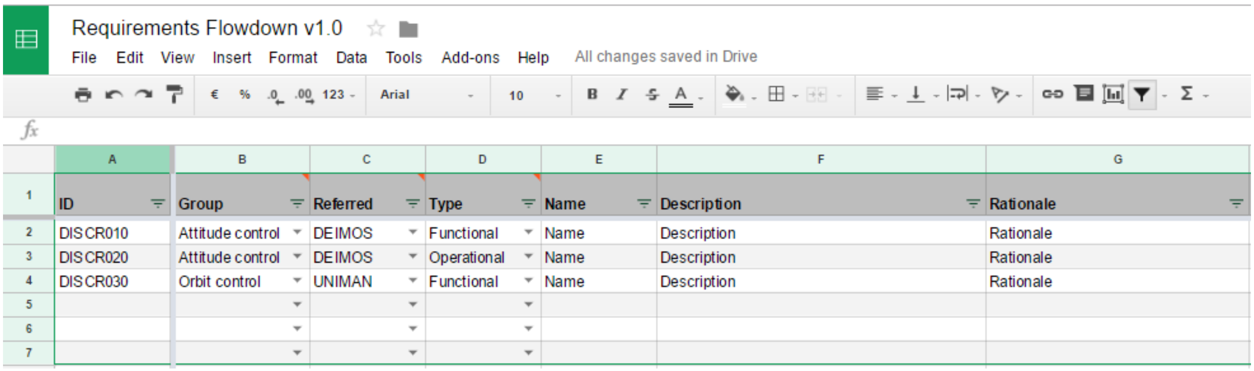
"*Requirements Flowdown*" file has been already created in Google Drive and is ready to be shared with all the ReDSHIFT team:

[47] See https://www.threesl.com/en/cradle/index.php for more information about Cradle software and its characteristics.

https://docs.google.com/spreadsheets/d/13_SS9plgafzkHS69YDRlBY9CaDM-Q24-Yqq6eeOT3QA/edit#gid=0https://docs.google.com/spreadsheets/d/1jehJTsYaGZGegr08E0PNOnaOxk41e9Z5myNvoSUaTYs/edit?usp=sharing

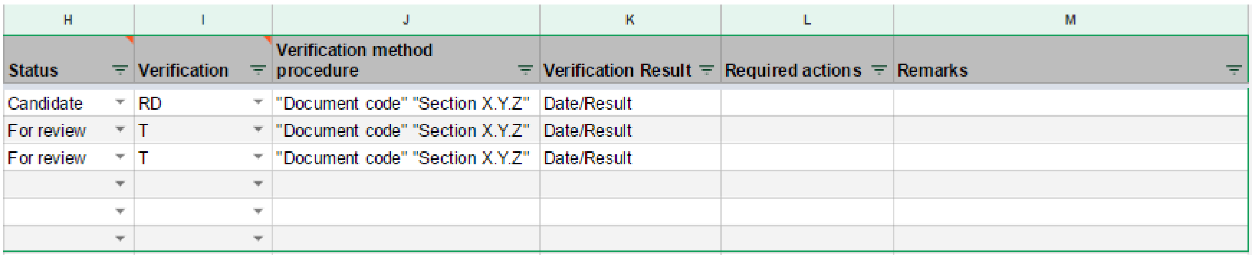
10.4.1. General view

When a user accesses to the sheet, the view must be similar to Figure 37 and Figure 38. This is the requirements matrix and also a “Notes” sheet is included in the same file with the information of some fields that may require explanation.



ID	Group	Referred	Type	Name	Description	Rationale
DISCR010	Attitude control	DEIMOS	Functional	Name	Description	Rationale
DISCR020	Attitude control	DEIMOS	Operational	Name	Description	Rationale
DISCR030	Orbit control	UNIMAN	Functional	Name	Description	Rationale

Figure 37: Requirements matrix view I (From column A to G).



Status	Verification	Verification method procedure	Verification Result	Required actions	Remarks
Candidate	RD	"Document code" "Section X.Y.Z"	Date/Result		
For review	T	"Document code" "Section X.Y.Z"	Date/Result		
For review	T	"Document code" "Section X.Y.Z"	Date/Result		

Figure 38: Requirements matrix view II (From column H to M).

10.4.2. Requirement fields

Apart from the first row with the title of each field, a requirement per row is included. Each item collects several fields that are here described:

- **ID:** Code for the unambiguous identification of each requirement: DISCRXXX

Note: Each requirement shall have a three digit number (XXX). It is preferably to use only the first two digits in first versions and reserve the last one for the addition of requirements in advanced phases of the project, the inclusion of items without renumbering being possible.

- **Group:** Classification of the requirements in technological fields:
  - Attitude control: For requirements concerning the attitude control performances of the spacecraft.
  - Orbit control: For requirements related to the orbital control of the mission (orbit maintenance, collision avoidance, deorbiting…)
  - A&O Control: For requirements that apply to both attitude and orbit control.

- **Referred:** Referred partner for consultation.
- **Type:** Classification of the requirements by areas [1]:
  - Functional: define how well the system must perform to meet its objectives.
  - Operational: define how the system operates.
- **Name:** name of the requirement.
- **Description:** description of the requirement. Example: *The mass of the system shall be less than 50 kg.* It shall contain a responsible or subject (The mass of the system) with the main action in an active way preferably (shall be less than 50kg) and avoiding ambiguous terms.[48]
- **Rationale:** brief description of the origin of the requirement. Typically a constraint in a test facility, a company strategic decision or the state of the art.
- **Status:** status of the requirement into the following flow chain:
  - Candidate: the author of the requirement shall set the requirement as "candidate" during its elaboration.
  - For Review: when the author considers the requirement is mature enough to be revised by Systems Engineering.
  - Validated: Validated requirement. To be verified.
  - Compliant: verified requirement.
  - Non-compliant: requirement that has not passed the verification procedure.
- **Verification:** selection of verification method for each requirement.
  - (T) Test: verification method by measurement of product performance and functions under representative simulated environments.
  - (A) Analysis: verification method performing a theoretical or empirical evaluation.
  - (RD) Review of design: verification method using approved records or evidence that unambiguously shows that the requirement is met. Examples: design documents, design reports, technical descriptions, engineering drawings.
  - (I) Inspection: verification method by visual determination of physical characteristics.
- **Verification method procedure:** reference to the document (or section) that includes the verification method procedure.
- **Verification result:** date and result of the verification. The result could be a numerical value or Pass/Fail.
- **Required actions:** possible action derived from the verification.
- **Remarks:** any note or remark that could be useful.

10.4.3. Other functionalities

All the fields are deployable in the row A, which allows searching for specific data as the Group or the Verification Result, among others.

Google Sheets allow adding comments in any cell to open a discussion or make a suggestion. A mail alert will then be sent to the creator of the sheet. It is possible to include more people to be alerted of

[48] For more information about how writing good requirements see http://homepages.laas.fr/kader/Hooks.pdf

the generated comment by adding the sequence "+" plus "*mail of the addressee"* as shown in Figure 39.

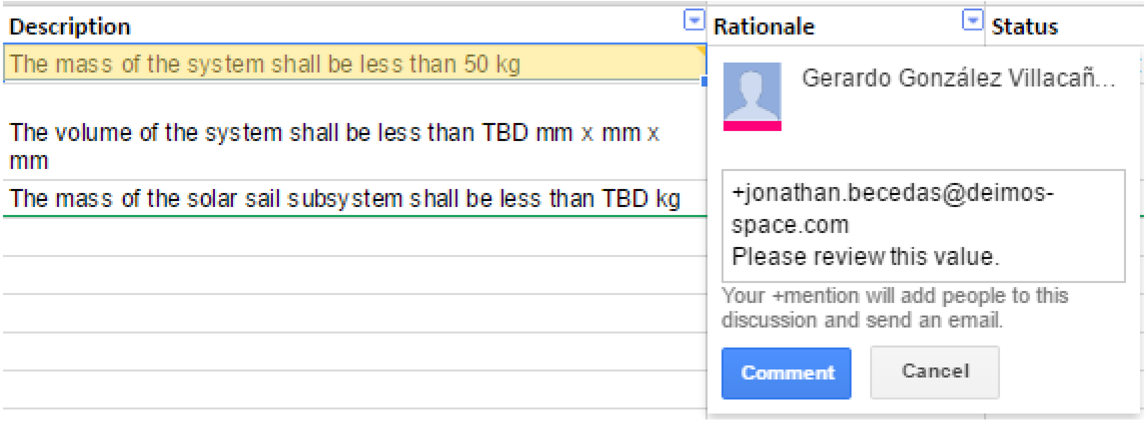


Figure 39: Example of comment with addressee.

10.5. CONCLUSIONS

Google Sheets have been selected as the DISCOVERER tool for requirements management. A combination of multiple and configurable functionalities, price and user-friendly tool has been the main characteristics considered in the selection.

The simple configuration of the requirements matrix has been presented together with a user's manual with the basic knowledge required to make use of the tool.

10.6. REFERENCES

[1] Wertz et al., "Space Mission Analysis and Design", *Space Technology Library*, United States of America, 11th ed., 1999.