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Launch, Operations, and First Experimental Results of the Satellite for Orbital Aerodynamics Research (SOAR)

Nicholas H. Crisp[a]*, Alejandro Macario-Rojas[a], Peter C.E. Roberts[a], Steve Edmondson[a], Sarah J. Haigh[a], Brandon E.A. Holmes[a], Sabrina Livadiotti[a], Vitor T.A. Oiko[a], Katharine L. Smith[a], Luciana A. Sinpetru[a], Jonathan Becedas[b], Valeria Sulliotti-Linner[b], Simon Christensen[c], Virginia Hanessian[c], Thomas K. Jensen[c], Jens Nielsen[c], Morten Bisgaard[c], Yung-An Chan[d], Georg H. Herdrich[d], Francesco Romano[d], Stefanos Fasoulas[d], Constantin Traub[d], Daniel Garcia-Almiñana[e], Silvia Rodriguez-Donaire[e], Miquel Sureda[e], Dhiren Kataria[f], Badia Belkouchi[g], Alexis Conte[g], Simon Seminari[g], Rachel Villain[g]

[a] The University of Manchester, *Oxford Road, Manchester, M13 9PL, United Kingdom*
[b] Elecnor Deimos Satellite Systems, *Calle Francia 9, 13500 Puertollano, Spain*
[c] GomSpace A/S, *Langagervej 6, 9220 Aalborg East, Denmark*
[d] Institute of Space Systems (IRS), University of Stuttgart, *Pfaffenwaldring 29, 70569 Stuttgart, Germany*
[e] UPC-BarcelonaTECH, *Carrer de Colom 11, 08222 Terrassa, Barcelona, Spain*
[f] Mullard Space Science Laboratory (UCL), *Holmbury St. Mary, Dorking, RH5 6NT, United Kingdom*
[g] Euroconsult, *86 Boulevard de Sébastopol, 75003 Paris, France*
* Corresponding Author: nicholas.crisp@manchester.ac.uk

Abstract

The Satellite for Orbital Aerodynamics Research (SOAR) is a 3U CubeSat that has been designed to investigate the aerodynamic performance of different materials at low orbital altitudes. The spacecraft has been developed within the scope of DISCOVERER, a Horizon 2020 project that aims to develop foundational technologies to enable sustainable operations of Earth observation spacecraft in very low Earth orbits (VLEO) i.e., those below 450 km. SOAR features two payloads: i) a set of steerable fins that can expose different materials to the oncoming atmospheric flow developed by The University of Manchester, and ii) a forward-facing ion and neutral mass spectrometer (INMS) that provides in-situ measurements of the atmospheric density, flow composition, and velocity from the Mullard Space Science Laboratory (MSSL) of University College London. These payloads enable characterisation of the aerodynamic performance of different materials at very low altitudes with the aim to advance understanding of the underlying gas-surface interactions in rarefied flow environments. The satellite will also be used to test novel aerodynamic attitude control methods and perform atmospheric characterisation in the VLEO altitude range. SOAR will perform the first in-orbit test of two novel materials that are expected to have atomic oxygen erosion resistance and drag-reducing properties, providing valuable in-orbit validation data for ongoing ground-based experimentation. Such materials hold the promise for extending operations at lower altitudes with benefits particularly for Earth observation and communications satellites that can correspondingly be reduced in size and cost. The platform for SOAR is largely based on GOMX-3 heritage and the spacecraft was assembled, integrated, and tested by GomSpace A/S. The satellite was launched on the SpX-22 commercial resupply service mission to the International Space Station in on 3rd June 2021 was subsequently deployed into orbit on the 14th June 2021. This paper presents the final preparations of SOAR prior to launch and provides an overview of the planned operations of the spacecraft following deployment into orbit.

Keywords: Orbital Aerodynamics; Drag and Lift Coefficient; Gas-Surface Interactions; Thermospheric Wind; CubeSat.

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
ADCS	Attitude determination and control system
AO	Atomic oxygen
EO	Earth observation
FMF	Free molecular flow
GSI	Gas-surface interaction
INMS	Ion and neutral mass spectrometer
ISS	International space station
ROAR	Rarefied orbital aerodynamics research (facility)
RWA	Reaction wheel assembly
SOAR	Satellite for orbital aerodynamics research
VLEO	Very low earth orbit

1. Introduction

Interest in the use of very low Earth orbits (VLEO), those between approximately 150 km and 450 km in altitude, for commercial satellite operations has been growing due to the numerous benefits to the both application-specific and platform-related factors associated with a reduction in orbital altitude [1]. Notably, for Earth observation and communications systems, the reduced distance to the target can significantly benefit the payload design, either allowing a reduction in mass or an improvement in the mission performance. Further benefits to the general spacecraft platform design include a reduction in the expected radiation dosage and assured post-mission disposal due to the increased atmospheric density and therefore aerodynamic drag leading to orbital decay and eventually deorbit. This same mechanism of rapid natural orbit decay also ensures that any debris is quickly cleared from the VLEO range of altitudes. The probability of collision is therefore reduced, and the risk of debris accumulation will remain low.

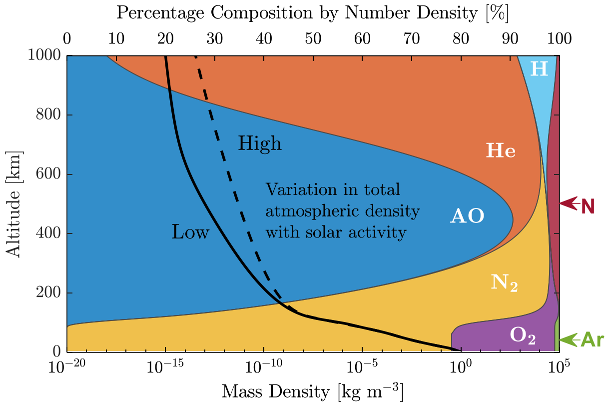

Fig. 1 Atmospheric density and composition with altitude in VLEO [2].

However, despite still being many orders of magnitude lower than at ground-level (see Fig. 1), the increase in atmospheric density at lower orbital altitudes and the associated aerodynamic drag also presents the greatest challenge to sustaining operations in VLEO for a meaningful mission lifetime. Propulsion systems can be used to compensate for this drag and extend mission lifetimes, but the mass of propellant required to do so quickly becomes prohibitively large as altitude is reduced. Thus, unless frequent resupply missions can be launched to replenish on-board storage the satellite must be launched with enough propellant to last the entire mission duration.

Novel atmosphere-breathing electric propulsion (ABEP) concepts aim to solve this problem by collecting the residual gas particles in the atmospheric flow and utilising these as the propellant in an electric thruster. However, whilst such systems are currently being developed [3,4], advances in aerodynamic drag reduction are also needed to support designs that can be integrated onto future flight platforms by reducing requirement such as thrust and power.

In the free-molecular flow (FMF) environment of VLEO, the aerodynamic drag experienced by spacecraft is principally determined by the direct interactions between the gas particles in the oncoming flow and the external surfaces (collisions between the particles in the gas itself are rare on the length-scale of a typical spacecraft). For most conventional spacecraft materials these gas-surface interactions (GSIs) have been shown to have diffuse re-emission characteristics with high accommodation (i.e. the particles transfer almost all their energy and momentum to the surface) [5,6]. As a result, significant drag forces are generated, proportional to the spacecraft cross-sectional area to the flow.

Materials that can specularly or quasi-specularly reflect the oncoming gas particles with reduced levels of accommodation would be able to support a reduction in the experienced drag force when oriented at shallow angles to the oncoming flow. These materials would also be able to provide lift forces of greater magnitude with application to aerodynamic control.

As shown in Fig. 1, LEO altitudes between 150 km and 800 km are also characterised by a high relative prevalence of atomic oxygen (AO), a reactive species of gas formed by the interaction of UV with oxygen molecules at these altitudes. The additional velocity of objects orbiting at these altitudes (~7700 ms^{-1}) means that the collision energy of AO with the spacecraft surfaces is very high and that most materials will experience some form of physical or chemical degradation.

The surface contamination and erosion by AO affects the GSIs on the external surfaces of spacecraft and their associated aerodynamic performance. Candidate materials for enhanced aerodynamic performance must therefore be resistant to the effects of AO to ensure long-term operation in the VLEO environment.

Candidate materials with these desired properties (AO resistance, quasi-specular reflections, and low accommodation) are being developed at the University of Manchester. These materials will be tested in the forthcoming Rarefied Orbital Aerodynamics Research (ROAR) facility [7–9], an experimental facility that combines an ultra-high vacuum environment with a beam of hyperthermal AO (with appropriate flux and energy) to simulate the oncoming gas flow present in VLEO. The facility also contains moving sensors to measure the mass and energy of the particles within the oncoming beam of AO and those re-emitted and reflected from the surface of the material samples, allowing observation, characterisation, and mapping of the GSIs and associated scattering behaviour.

2. The Satellite for Orbital Aerodynamics Research

To validate the results that will be generated with ROAR, in-situ data from the true VLEO environment is required. The Satellite for Orbital Aerodynamics Research (SOAR) has been developed to provide this information by performing in-orbit characterisation of the aerodynamic performance of different materials. SOAR will also perform experiments to characterise the atmosphere and demonstrate orbit and attitude control manoeuvres.

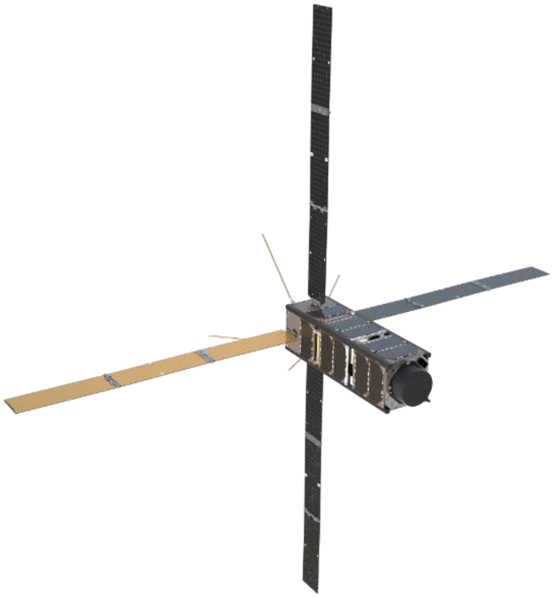

Fig. 2 The Satellite for Orbital Aerodynamics Research (SOAR)

SOAR (see Fig. 2) is a 3U CubeSat that has a set of four steerable fins that can expose different materials to the oncoming flow at varying angles of incidence. The spacecraft also has an ion and neutral mass spectrometer (INMS) that nominally faces towards the direction of the oncoming flow and can measure the atmospheric density, composition, and velocity. A capable attitude determination and control system (ADCS) is also included on the platform consisting of a state-of-the-art IMU, fine sun sensors, magnetometers, a reaction wheel assembly (RWA), and magnetorquers. A GPS receiver is also included to provide precise orbit position and velocity data. An exploded view of the platform is provided in Fig. 3.

When the fins are all oriented either parallel to or perpendicular to the oncoming flow, the minimum and maximum drag configurations respectively, natural restoring torques will be generated and the satellite has an aerostable configuration. However, due to the lack of damping in the VLEO environment, the satellite will still oscillate about the equilibrium position, i.e. the direction of the oncoming flow.

SOAR can perform the aerodynamic performance characterisation of four different materials. These experiments can be performed by exposing the same material to the oncoming flow simultaneously on two opposing steerable fins. When a pair of opposing steerable fins are counter-rotated the interactions of the surfaces exposed to the flow will cause the spacecraft to nominally experience a torque in the roll axis. Contrastingly, when a pair of steerable fins are co-rotated the spacecraft will experience a torque in pitch or yaw.

In either case, the ADCS can be used to stabilise the satellite and point the satellite towards the oncoming flow direction to ensure the accuracy of the INMS measurements. However, due to the atmospheric co-rotation (in inclined orbits) and the thermospheric winds that are highly variable and poorly modelled, the ADCS cannot know the true direction of the oncoming flow. The LVLH (local-vertical local-horizontal) coordinate system is therefore used as a reference but is not expected to deviate significantly from the direction of the oncoming flow. Any misalignment of the spacecraft with respect to the flow will however reduce the measurement accuracy of the INMS and affect the aerodynamic interactions with the steerable fin surfaces.

The drag coefficient associated with exposure of different materials at varying angles of incidence can be measured when a pair of steerable fins are either co-rotated or counter-rotated. In each case, the RWA will be used to stabilise the satellite in all three axes. After a given period in the chosen configuration, the drag coefficient can be determined from the position and velocity data by performing an orbit determination process. With appropriate models for the other external forces that act on the satellite, a free-parameter fitting process can be used to return the best-fit drag coefficient.

Comparatively, to determine the lift coefficient a pair of steerable fins will be counter-rotated and the satellite will be left uncontrolled in the roll-axis (i.e. the RWA will perform pitch-yaw control only). A process of attitude determination can subsequently be used to perform the free-parameter fitting of the lift coefficient.

In each case, a trade-off between the duration of the experimental period, the attitude control requirements, and the uncertainty associated with the estimated aerodynamic coefficients arises. Critically, if the attitude control actuators become saturated, the experiment will be terminated as the satellite motion will become uncontrolled. If the experimental period is too short, the variation in orbital trajectory or attitude motion may not be notable in the collected data and the aerodynamic coefficient fitting will be poor. The variation in magnitude of the aerodynamic forces and torques with altitude therefore has a significant effect on the experimental uncertainty. In general, uncertainty for the drag coefficient is lowest at approximately 300 km in

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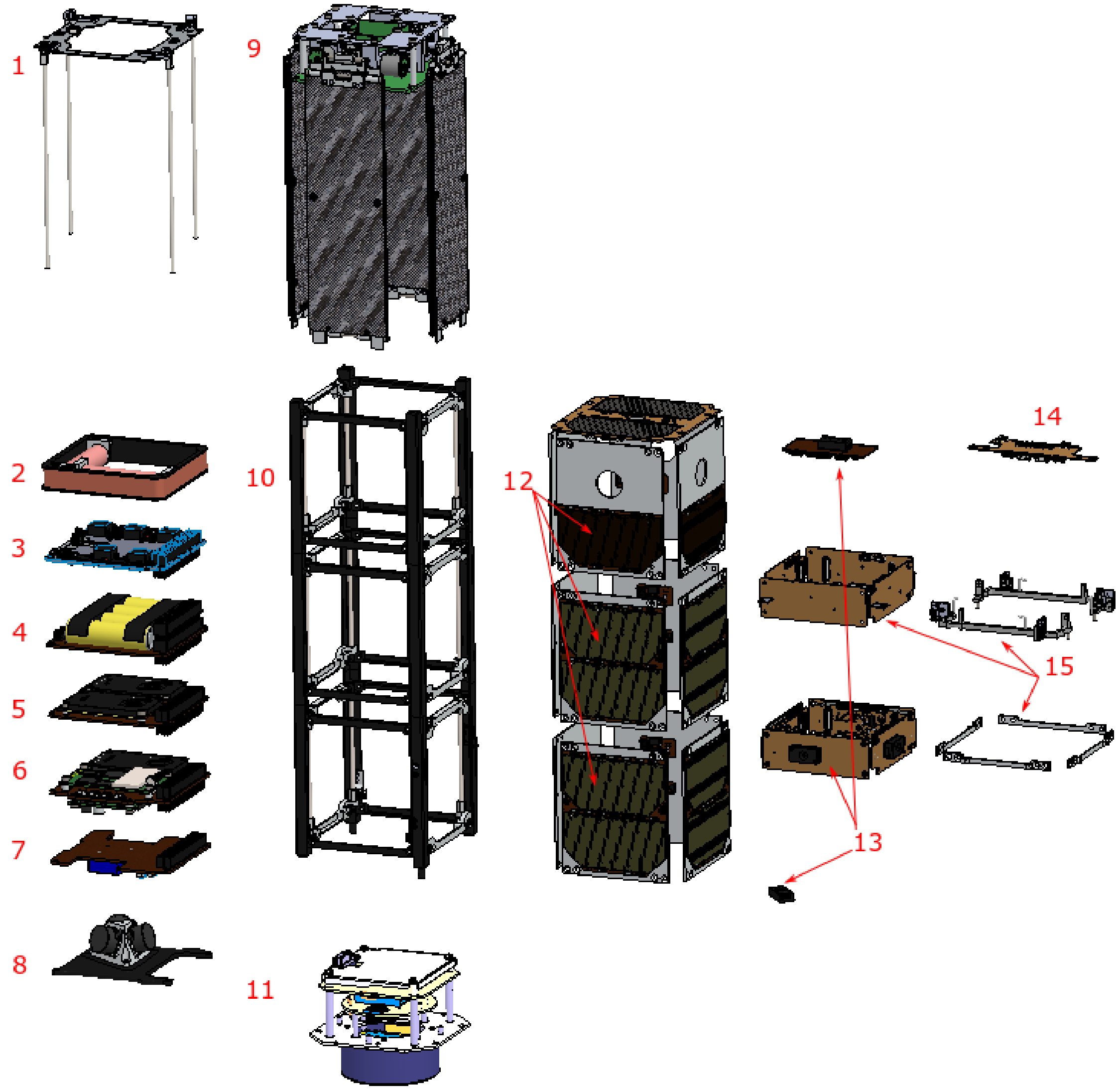
altitude, whilst the performance for the lift coefficient experiments will increase with reducing altitude [10].

SOAR will test four different materials in the VLEO environment. Gold and borosilicate glass coatings have been selected for their known AO erosion resistance and characterised difference in AO recombination cross-section, a possible indicator of specular reflection performance. Two further novel materials have been selected for their potentially improved GSI properties, aerodynamic performance, and AO resistance.



1 NanoCom ANT430
2 NanoTorque GST600
3 NanoPower P31U
4 NanoPower BP4
5 NanoMind A3200 (OBC) + NanoCom AX100
6 NanoMind A3200 (ADCS) + Astrofein WDE
 + Novatel 719 GPS
7 NanoUtil Breakout + NanoSense M315
 + Epson G370 IMU
8 Astrofein RW-1
9 Aerodynamics Payload (Steerable Fins)
10 ISIS 3U Structure
11 Atmospheric Characterisation Payload (INMS)
12 Solar Arrays
13 NanoUtil GomSpace Sensor Bus Interstages
14 NanoUtil Flight Preparation Panel
15 Launch Stow and Release System

Fig. 3 Exploded view of SOAR showing subsystems and components.

5. Current Status

The Satellite for Orbital Aerodynamics was assembled at GomSpace HQ in Aalborg, Denmark. The aerodynamics payload (steerable fins) was provided by The University of Manchester, and the atmospheric characterisation payload (INMS) by the Mullard Space Science Laboratory (MSSL), University College London.

SOAR was launched on the SpaceX CRS-22 resupply mission to the ISS on 3rd June 2021 and subsequently deployed into orbit on the 14th June 2021 (see Fig. 5).

The lifetime of SOAR from its initial insertion orbit has been estimated to be between approximately 6 months to 18 months depending on the predominant configuration selected for the satellite (e.g. minimum or maximum drag during idle operations) and the progression of the solar cycle and associated atmospheric density. An outline of the mission operations based on the satellite altitude is presented in Fig. 6.

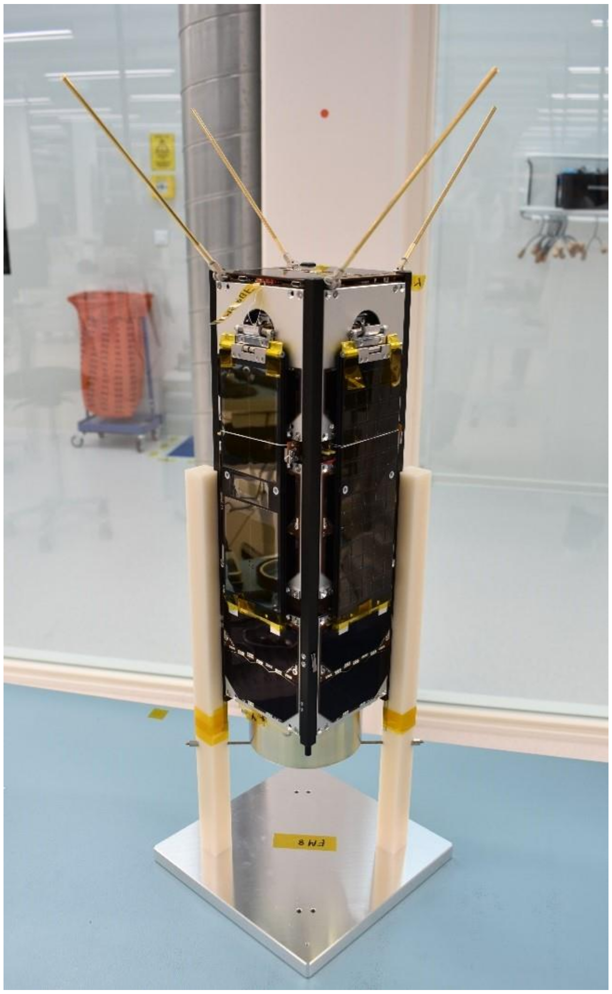


Fig. 4 Fully integrated flight model of SOAR.

Fig. 5 SOAR (right) immediately post-deployment from the ISS on 14th June 2021 [image credit: NASA].

6. Concluding Remarks

The Satellite for Orbital Aerodynamics Research has been designed to perform the characterisation of the aerodynamic coefficients of different materials in the VLEO environment. These experiments will validate and support the investigation of GSIs in rarefied flows in ongoing experimentation in a new ground-based facility that simulates the flow conditions in low altitude orbits.

SOAR has been developed by The University of Manchester, GomSpace, and the Mullard Space Science Laboratory as part of DISCOVERER, a project that is focused on the development of fundamental technologies that will enable the sustained operation of spacecraft in VLEO, principally for EO applications.

The satellite was launched in mid-2021 to the ISS and deployed into VLEO shortly thereafter. After initial commissioning activities…

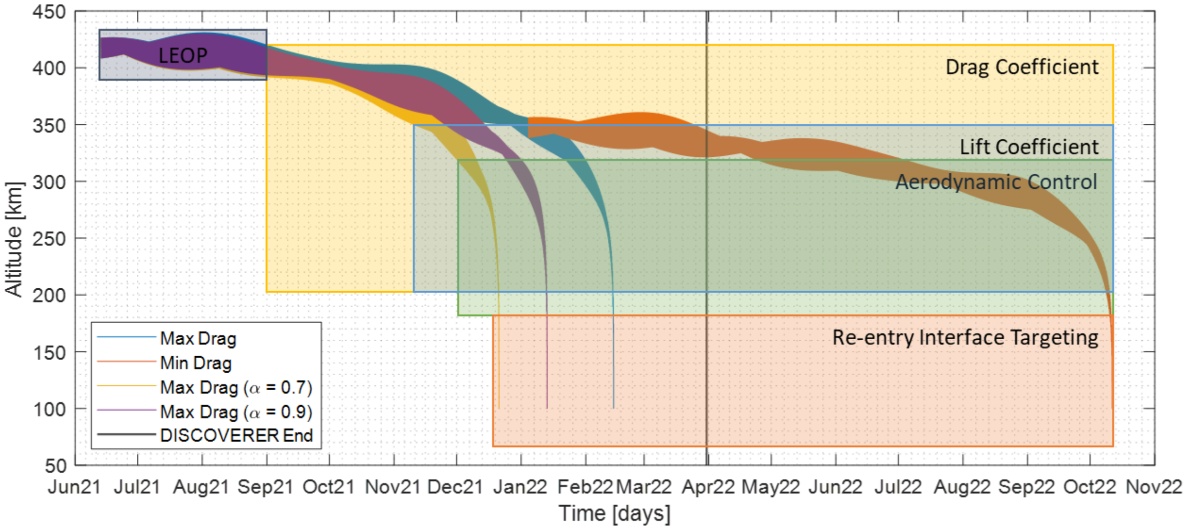


Fig. 6 Summary mission timeline for SOAR.

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