Experimental Results from the Satellite for Orbital Aerodynamics Research (SOAR) Mission

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Abstract

The Satellite for Orbital Aerodynamics Research (SOAR) is a 3U CubeSat that has been designed to investigate the aerodynamic performance of different materials and perform demonstrations of aerodynamic attitude control manoeuvres in very low Earth orbit (VLEO). SOAR was deployed from the ISS on 14th June 2021 into a naturally decaying orbit and deorbited on 14th March 2022. This paper provides an overview of the operations performed during the mission and presents preliminary experimental results obtained from this spacecraft.

SOAR was designed and launched within the frame of DISCOVERER, a Horizon 2020 project that aimed to support the development of a new class of commercially viable spacecraft operating in VLEO, i.e., orbits below 450 km in altitude. Operating in these lower altitude orbits has several benefits to the design of spacecraft, particularly for Earth observation and communications applications. However, development of spacecraft that can operate sustainably at these altitudes requires advancement in foundational technologies, for example atmosphere-breathing electric propulsion (ABEP) and novel aerodynamic materials.

The primary aim of SOAR was to characterise the aerodynamic performance of different materials at very low altitudes and accomplished this task using a set of steerable fins that exposed different materials to the oncoming flow and an ion and neutral mass spectrometer (INMS) to provide in-situ measurements of atmospheric properties. SOAR was also designed to perform novel aerodynamic attitude control manoeuvres and measurements of thermospheric winds.

Two of the materials carried to orbit were selected for their atomic oxygen erosion resistance and potential improvement in aerodynamic performance. The identification of such materials would allow for a reduction in the drag experienced in VLEO, the design of atmospheric intakes with greater efficiency used for ABEP, and implementation of enhanced aerodynamic attitude and orbit control. Ongoing ground-based experimentation seeks to further characterise the properties of such materials and to deepen our understanding of the physical interaction mechanisms that occur in the rarefied flow environment of VLEO.

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

Nomenclature

Acronyms/Abbreviations

ABEP	Atmosphere-Breathing Electric Propulsion
ADCS	Attitude Determination and Control System
AO	Atomic Oxygen
EO	Earth Observation
GSI	Gas-Surface Interaction
INMS	Ion and Neutral Mass Spectrometer
ISS	International Space Station
SAA	South Atlantic Anomaly
SEU	Single Event Upset
SOAR	Satellite for Orbital Aerodynamics Research
SSP	Sub-Solar Point
TLE	Two Line Element
TTFF	Time to First Fix
VLEO	Very Low Earth Orbit

1. Introduction

Very low Earth orbit (VLEO), below an altitude of approximately 450 km, is an orbit regime characterised by significant aerodynamic effects due to the increase in atmospheric density that influences the design of satellites intended to operate at these altitudes.

Benefits to operating satellites at these lower altitudes in LEO have been recognized [1], particularly with application to Earth observation [2] and communications missions [3], [4]. However, significant obstacles to the commercial adoption of this orbital regime for such missions remain, principally related to the enhanced atmospheric and aerodynamic environment at lower orbital altitude.

As the atmospheric density increases as orbital altitude is lowered, an orbiting spacecraft will experience a greater number of interactions with the residual atmospheric particles at lower altitude, increasing the magnitude of the aerodynamic forces experienced. In VLEO, for typical spacecraft size, mass, and geometric configuration, these forces result in significant drag acceleration and orbital decay with critical impact on the useful orbital lifetime before re-entry. Increased aerodynamic torques may also result in spacecraft stability and control issues at VLEO altitudes.

As shown in Fig. 1 [5], the predominant gas species in VLEO is highly reactive atomic oxygen (AO). In combination with the high orbital energy, AO can cause significant erosion of materials on the external surfaces of spacecraft.

A proposed solution to the challenge of reduced natural orbital lifetime in VLEO is drag compensation using propulsion. Development of atmosphere-breathing electric propulsion (ABEP) technology is also underway to address the issue of significant propellant requirement for drag compensation methods [6]–[8].

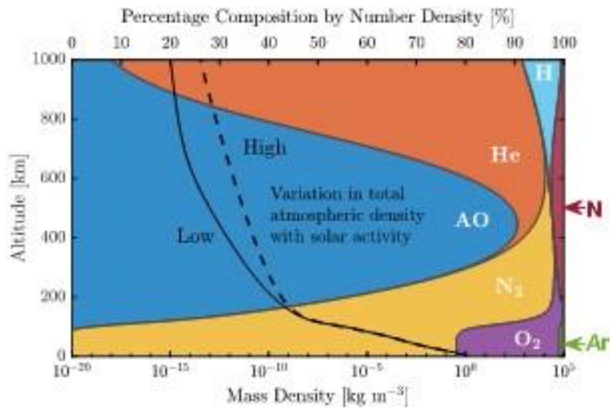

Fig. 1. Atmospheric density and composition with altitude in VLEO.

The identification or development of new materials is also key to sustaining satellite operations in VLEO. Materials that can reduce the drag experienced in orbit (together with judicious design of the external spacecraft geometry) and that are resistant to erosion by AO are of key importance to enabling the use of this orbital regime.

2. Materials for Aerodynamics in VLEO

Due to the highly rarefied nature of the VLEO atmosphere, the aerodynamic forces generated are driven by the gas-surface interactions (GSIs) between the oncoming particles and the spacecraft surfaces.

Data from prior missions in VLEO indicates that the oncoming particles are adsorbed to the spacecraft surfaces, transferring much of their incoming energy, and are subsequently reemitted diffusely and in thermal equilibrium with the surface [9]. This behaviour is described for example by the Diffuse Reemission Incomplete Accommodation (DRIA) GSI model with an

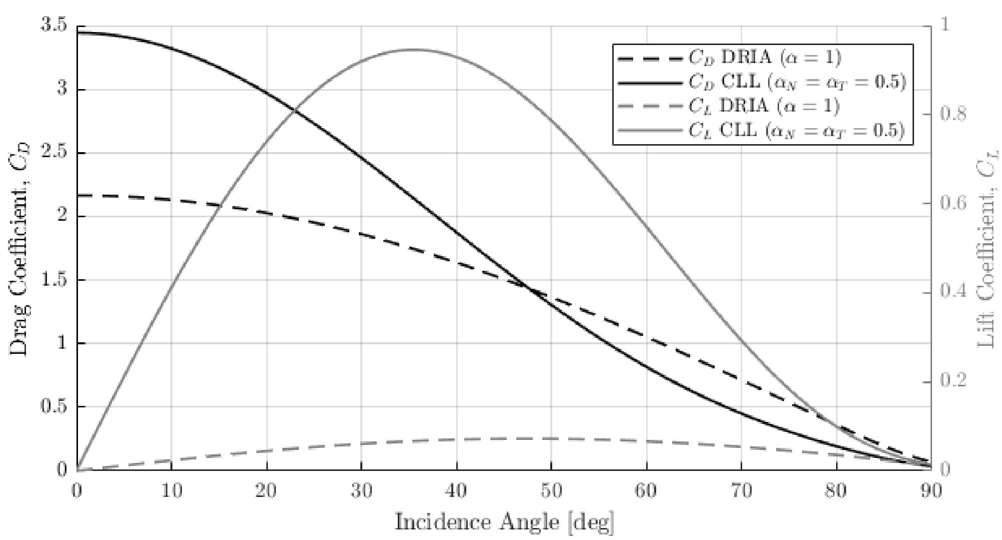

Fig. 2. Drag and lift force coefficient for a single-sided flat-plate of reference area 1 m^2 with incidence angle from normal to the flow for different GSI models and accommodation coefficients.

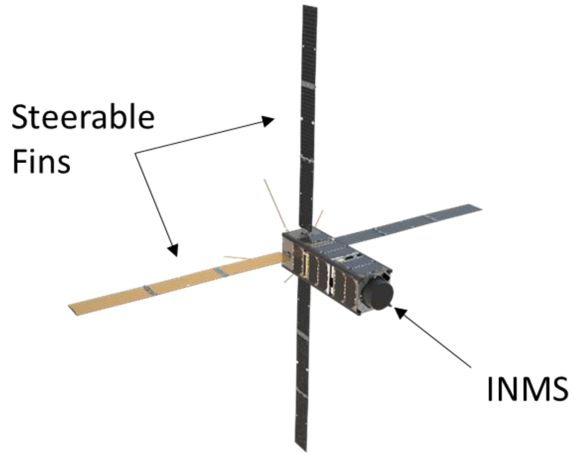

Fig. 3. The Satellite for Orbital Aerodynamics Research (SOAR)

energy accommodation coefficient $\alpha = 1$. As a result, the drag experienced by a spacecraft is high and is largely dependent on the projected or cross-sectional area to the oncoming flow rather than the detailed geometry.

However, materials that have reduced thermal (or energy) accommodation and demonstrate some quality of specular-reflection behaviour can provide greater control of the aerodynamic forces generated. Such behaviour can be described for example by the Cercignani-Lampis-Lord (CLL) GSI model for accommodation coefficients $\alpha_N, \alpha_T < 1$.

As shown in Fig. 2, at shallow angles to the flow, such materials would have the potential to minimise the momentum exchange, reducing the experienced drag. Conversely, as the surface is orientated normal towards the oncoming flow, the drag would be significantly increased. Using the relative surface angle, lift forces of useful magnitude could also be generated and used for aerodynamic control purposes.

The abundance of AO present in VLEO is considered a key contributing factor to the GSI behaviour observed for traditional materials. In addition to causing surface erosion affecting GSI quality, AO has also been shown to adsorb to the spacecraft surface, stimulating diffuse and thermal re-emission behaviour [10].

Thus, materials for aerodynamics in VLEO need to be resistant to or tolerant of the detrimental effects of AO. Efforts to the identify or develop such materials is ongoing [11]–[13].

Development of facilities to characterise and test AO resistance [14], [15] and more specifically the aerodynamic behaviour of different materials in rarefied orbital flows is also being progressed [16]. However, to ensure the validity of these ground-based experiments and determine how well they can reproduce the effects experienced in the true VLEO environment, on-orbit testing is also required.

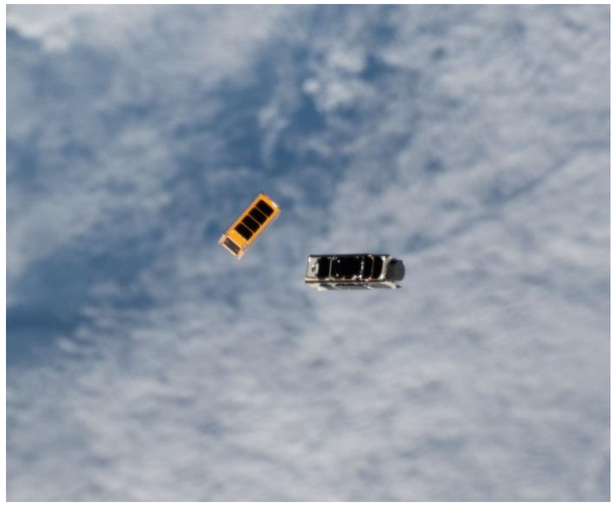

Fig. 4. SOAR (right) and RamSat (left) after deployment from the ISS [photo credit: NASA]

3. The Satellite for Orbital Aerodynamics Research

SOAR, the Satellite for Orbital Aerodynamics Research, was designed to investigate the aerodynamic performance of different materials in VLEO. The satellite was also developed to perform additional experiments to measure the in-situ atmospheric composition and density, the velocity of thermospheric winds, and to demonstrate aerodynamic attitude control manoeuvres.

SOAR was a 3U CubeSat that was equipped with a set of four steerable fins (coated with different materials) and a ram-facing ion and neutral mass spectrometer (INMS).

Using the two payloads and orbit/attitude sensors, the satellite was designed to orientate the materials on the steerable fins individually at varying angles to the oncoming flow. The resulting change over time in observed orbit trajectory or attitude behaviour could subsequently be analysed and the aerodynamic coefficients (lift and drag) inferred [17], [18].

SOAR was launched on the SpaceX CRS-22 resupply mission to the ISS on 03 June 2021 and deployed on 14 June 2021 into an orbit with apogee and perigee of 421 km and 415 km respectively (Fig. 4). SOAR was initially allocated to NORAD ID 48850 but was later reallocated to 48851 after the separation between SOAR and RamSat became large enough for the spacecraft to be distinguished by their different communication frequencies.

The first contact with the satellite was made shortly after deployment and the initial subsystem checkout and commissioning activities were initiated. These operations were successfully completed on 25 August 2021. Subsequent operations focused on the calibration of the ADCS (external magnetometer and 3 axis control tuning) and payload commissioning.

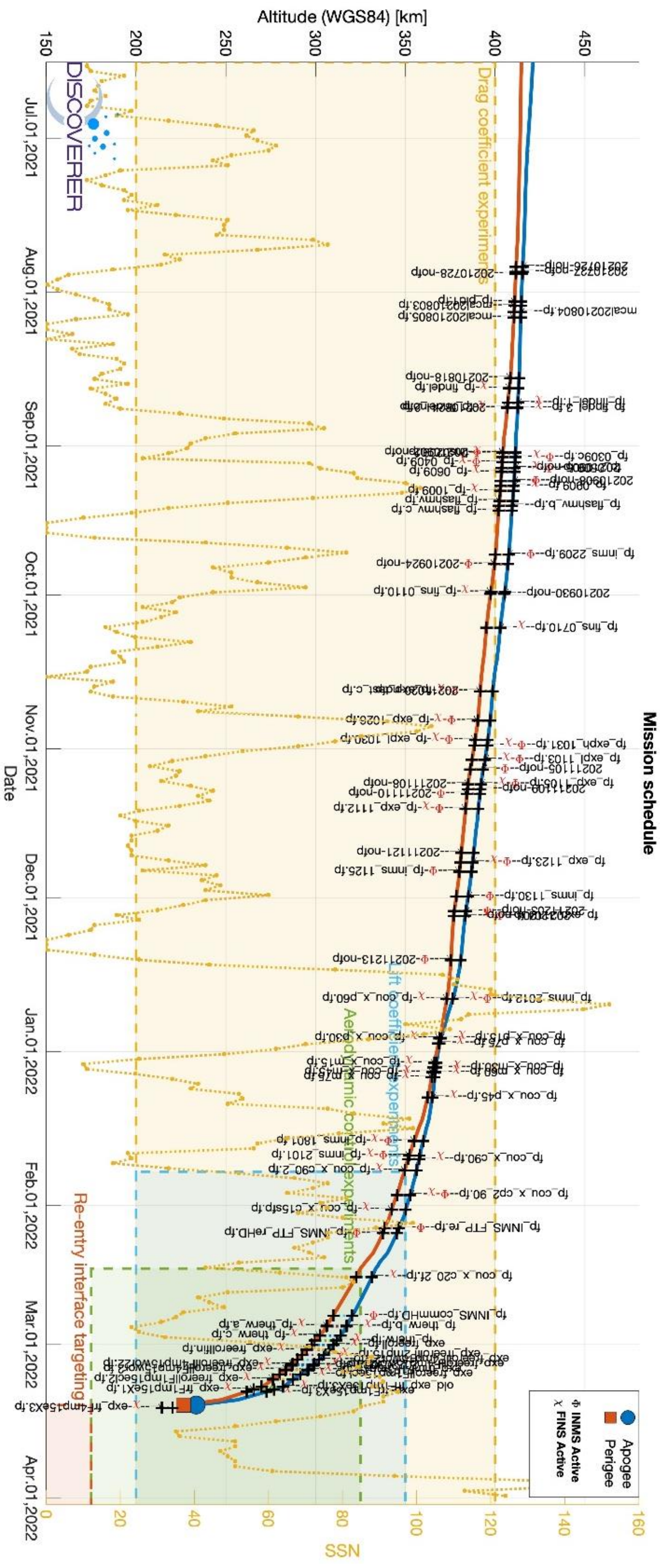

Fig. 5. Summary of SOAR experimental operations (labelled) with orbital apogee/perigee altitude and observed sunspot number (SSN).

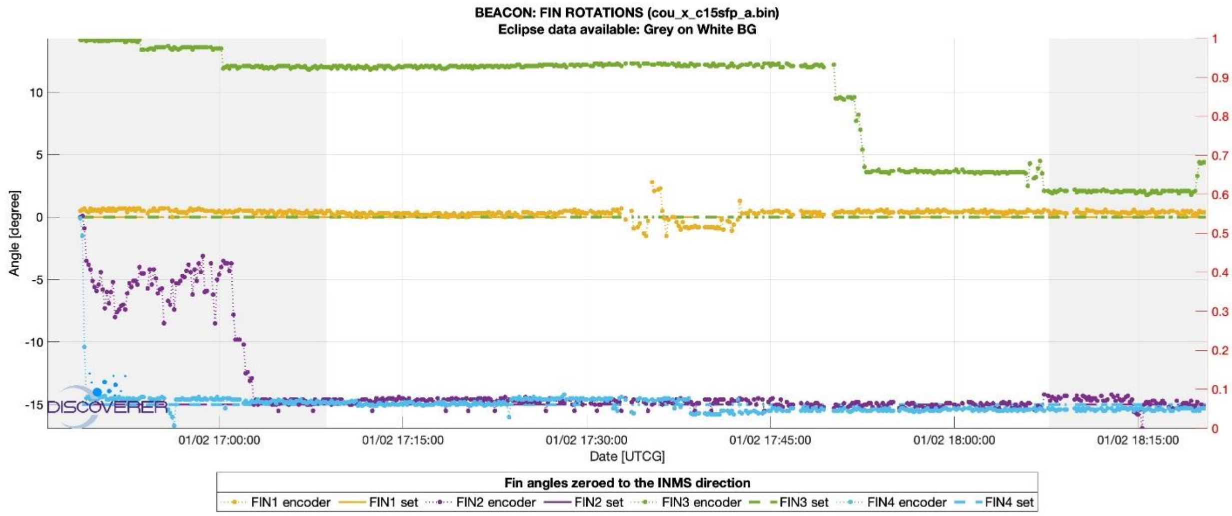

Fig. 6. Mechanical issue with steerable fins illustrated for FIN2 (+Y) and FIN3 (-X).

The first experimental operations were started on 20 October 2021 focusing on the characterisation of the drag coefficient of the materials on the steerable fins using counter-rotated configurations. However, due to issues encountered whilst performing the INMS commissioning (see Section 4.1), this payload was not used during these operations. Experiments to determine the thermospheric wind vector were conducted between 23 February 2021 and 28 February 2022. From 01 March 2022, the operations focused on the lift coefficient determination using different configurations of the ADCS (change in RW mapping and magnetorquers disabled).

Due to the challenges of tracking the satellite at lower altitude, limitations of the link-budget, and issues with the steerable fins, the aerodynamic attitude control and re-entry interface targeting manoeuvres could not be tested.

The final TLE for SOAR was published on 13 March 2022 (epoch at 13 05:08:13) with an apogee and perigee altitude of 233.6 km and 226.5 km respectively. The final beacon communications received by the mission team were on 13 March 2022 at 23:46:00. The satellite was considered by USSAPCECOM to have decayed from orbit on 14 March 2022, 9 calendar months after deployment from the ISS.

A summary of the experimental operations performed by SOAR over the mission lifetime is given in Fig. 5.

4. Issues, Challenges, and Lessons Learned

4.1 INMS Flight Performance

The initial commissioning of the INMS was completed successfully and the response packets generated by the instrument were verified to have data consistent with the ground testing of the instrument. The current draw of the instrument was also consistent with the scripts run.

However, during further commissioning activities (from 2021-10-31) to increase the voltage of the instrument to measure faster moving particles, it was identified that the science data packets contained particle counts and energies much lower than would be expected for the tests being performed. Subsequent testing focused on verifying the current draw of the instrument and correlating the data received with the platform (and therefore instrument) pointing with respect with the oncoming flow direction.

During further instrument testing, the high-voltage monitor on the instrument started to measure 4095V (12-bit high) rather than the ~1400V previously reported. The corresponding science packets also contained zero readings rather than background particle counts as previously observed. Following this only zero-count data packets were returned by the instrument and it was considered to have suffered an irrecoverable on-orbit failure.

The location of the spacecraft during execution of these scripts was close to both the South Atlantic Anomaly (SAA) and simultaneously the Sub-Solar Point (SSP). The likelihood of a Single Event Upset (SEU) was therefore high, however given the limited diagnostic information available from the instrument via the OBC, this cannot be definitively confirmed.

4.2 Steerable Fin Performance

Following successful commissioning operations and initial testing, performance issues with the rotation of the steerable fins was observed, initially in the +Y face and to a lesser extent the -X face. Some slowness in rotating to the desired positions was observed from the encoder reported position, suggesting a sticking behaviour in the drive mechanism.

Further operations prioritised the use of the +X & -Y fins, to avoid any immediate deterioration of the problem

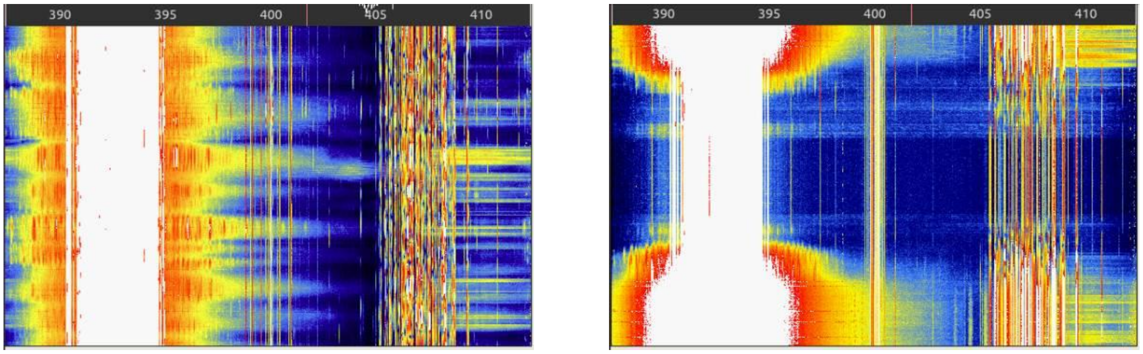

Fig. 7 UNIMAN ground station survey using an external SDR connected to the antenna. Sweeps of 0 to 360 deg in azimuth (left) and 0 to 180 deg elevation (right) performed.

in the +Y & -X fins whilst further investigations could be performed. However, evidence of similar performance issues arose in these fins, and was observed to generally increase over the mission lifetime.

Initially, these problems did not significantly affect the experiments to determine the drag coefficient as the desired rotations could still be completed. However, as the performance degraded, the required time to even perform small rotations became prohibitive to the planning of experimental operations.

These performance issues also excluded the testing of the active aerodynamic attitude control method as the desired fin rotations could not be performed and the intensive use of the payload may have further exacerbated the mechanical issues.

Attempts were made to correlate the mechanical issue with eclipse periods under the hypothesis that thermal expansion and contraction may be partly responsible for the sticking behaviour. However, as the issue escalated, a definitive cause could not be identified. The mechanical design, manufacturing and assembly tolerances, vibrational loading during launch, and thermal cycling on orbit may have all contributed to the problem.

4.3 Flash Memory Issue

An issue writing to the primary file system on the satellite OBC was encountered on 08 September 2021. The satellite was equipped with two separate memory modules for redundancy. It was therefore possible to backup the files stored on *flash0* to *flash1* and attempt a reformat of the memory to resolve the issue.

Whilst time-consuming, this process was necessary as the time required to re-upload large files (e.g. aerodynamic attitude controller and associated databases) via the TT&C link would have been prohibitive prior to the end of the mission.

Transitioning to operations using only the *flash1* memory was also not desirable as this would have removed the redundancy of having two memory modules that could be used to store critical files and would have also halved the effective on-board memory.

The issue was resolved following the backup operations by reformatting the memory module on 22 September 2021.

4.4 Ground Segment Performance

A ground station based at The University of Manchester was intended to provide dedicated ground support for the SOAR mission. The location selected was the roof of the Schuster building following a survey of alternative locations, principally based on site accessibility, availability of power and network services, physical security, and to avoid interference with radioastronomy (excluding Jodrell Bank).

The installation and commissioning of the ground station was however significantly disrupted and delayed by the COVID-19 pandemic. During the initial commissioning of the ground station, significant noise issues were noted on both the primary and secondary radios. Subsequent survey of the radio spectrum using an SDR indicated significant interference from the adjacent 390-395 MHz spectrum, raising the noise floor considerably in the vicinity of the SOAR downlink frequency (401.732 MHz). This noise was found to be relatively independent in azimuth at the ground station location and localised in elevation towards the horizon (Fig. 7).

In practice, the presence of this noise significantly increased the elevation angle at which downlink packets from the satellite could be reliably received (typically above 25deg), reducing the number of and usable duration of any given passes with line of sight. As a result of frequent packet loss, particularly at lower elevations, the effective rate of data downlink was significantly affected, slowing down the commanding and operations of the spacecraft.

To maximise the ability to downlink data from the satellite and perform more frequent operations, alternative ground segment solutions were investigated.

And the Leaf Space "Leaf Line" service was selected. The contracted service provided access from high performance ground stations in Europe with an effective capacity of 21 minutes per day (approximately 3 passes of 7 minutes each). This additional capacity, in combination with the improved link quality from the commercial ground station service, enabled operations towards the end of the mission to be performed much more quickly than would have been possible with only the ground station in Manchester and occasional support from the GomSpace ground station in Aalborg.

4.5 Ground Station Tracking at Low Altitude

Towards the end of the mission, at lower altitudes, the ground station tracking performance of the satellite was found to degrade significantly, critically affecting the uplink and downlink capability.

Ground segment tracking of the satellite was performed using SGP4 propagation of the latest available TLE. However, it was noted that these TLEs were quickly becoming stale and that the pass of the satellite did not occur as predicted (offset in time resulting in errors in azimuth and elevation). Manual correction of the tracking was attempted while the satellite was in view of the ground station, principally based on the observed doppler shift of the signal. However, this corrective action was time consuming, and improvements could not generally be capitalised on due to the short duration of the pass.

Eventually, the errors in TLE-based tracking resulted in frequent gaps in communication when the satellite was not visible from the ground station during the expected pass, i.e., it was leading or trailing the ground station tracking a large angle.

The increased rate at which the TLEs for the satellite were observed to be of use for effective tracking was attributed principally to the atmospheric and aerodynamic variations during the mission. The latter period of the SOAR mission was characterised by significant variability in the sunspot number (see Fig. 5) and therefore atmospheric density. The use of the steerable fins on fins on the satellite to perform the desired experiments also results in variation of the aerodynamic coefficients and reference area. In the SGP4 model and TLE, these factors are only captured within the static fitted B* term.

For orbit prediction in the lower altitudes of VLEO, TLE based methods may therefore become quickly out of date and inaccurate and not capable enough to provided suitable pass prediction for ground station tracking purposes. Availability of regular GPS position data from the satellite would have been helpful in providing more frequent tracking information on the satellite, allowing access times and passes to be modelled and predicted independently of the available TLEs (though problems of force model selection and appropriate provision of dependent parameters still exist).

4.6 ADCS/OBC Reboots

During the mission a number of ADCS and OBC reboots were experienced. These reboots resulted in forced changes to the ACDS modes of the spacecraft (return to BDOT pointing mode), and interruption or cancellation of any queued autopilot operations. The cause of the initial ADCS reboots was principally due to the magnetometer calibration and was resolved during the commissioning phase of the mission. OBC updates continued frequently during the mission and were largely attributable to CSP WDT triggered reboots.

4.7 GPS Performance

For the GPS receiver on SOAR a cold start was effectively initiated each time the device is enables and the receiver first needs to search for and identify the available GPS satellite signals. Due to the high relative velocity of the satellites (high doppler shifts of up to ±80kHz can be experienced) and rapidly changing visibility of the GPS satellites, this process is more complex than for ground-based receivers. Following the initial signal acquisition, a new GPS almanac needs to be downloaded (requiring 12.5 minutes) and precise ephemeris data from each GPS satellite in view (30 seconds) is also required before a first fix can be obtained. This process can be further affected by disorientation of the receiving antenna, for example due to a tumbling or rotating attitude. Typical TTFF for small satellites in LEO may take up to 25 minutes.

During the mission SOAR mission, it was found that the "time to first fix" of the GPS receiver was longer than anticipated and variable in duration.

Due to the power constraints of the platform and the power consumption of the GPS receiver, it was not possible to leave this device enabled during idle and routine operations between experiments. A warm-up phase prior to the commencement of the desired experiments was therefore needed. However, as the required duration of this period was not known a-priori, an estimate was used. At the beginning of the mission, the expected GPS warm-up time of 30 mins was exceeded. More conservative estimates of up to 60 minutes was later therefore adopted despite having implications on the power consumption and possible duration of the experimental operations.

The presence of the steerable fins on SOAR may have been a contributing factor to the extended TTFF experienced as they may have provided some obstruction of GPS satellites.

In addition to assisting the challenge of tracking the satellite at low altitudes (discussed in Section 4.6), continuous GPS data during the mission would have been a valuable data set for long term aerodynamic analysis of the satellite, providing a higher accuracy than available from TLE tracking data. Furthermore, availability of the raw data from the GPS receiver (individual satellite code and carrier phase information) would have enabled further post-mission processing and refinement of the satellite position information.

6. Preliminary Experimental Analysis

As a result of the issues experienced during the mission, the number of experiments performed were fewer and volume of data obtained during the lifetime of SOAR was less than desired. With missing elements of the anticipated mission data, the analysis has also become more complicated. However, alternative approaches to the experimental analysis that are not dependent on the availability of the in-situ atmospheric measurements from the INMS are being developed and implemented.

To analyse the performance the materials deployed on the steerable fins, modelled density values are being combined with a free-parameter fitting method for the aerodynamic coefficients and the individual steerable fin surface accommodation coefficients. Whilst the lack of in-situ density data means that absolute values for these parameters may not be determined with confidence, this approach will seek to correlate the aerodynamic performance of the different materials and surface incidences to the oncoming flow in a relative manner.

This approach is just starting to yield success and to reveal very promising results. However, they need further assessment, refinement, and peer review before being made public

Further anticipated results from associated DISCOVERER experiments performed for the same materials on MISSE (Materials International Space Station Experiment) and through the ROAR (Rarefied Orbital Aerodynamics Research) facility will also be used to support the findings from the analysis of the SOAR mission data and will the subject of future journal papers.

7. Conclusions

The Satellite for Orbital Aerodynamics Research (SOAR) was successfully launched and deployed into orbit in June 2021 and operated over a 9-month natural lifetime before deorbiting in March 2022.

Whilst a number of issues were encountered during the mission and many lessons learned by the project team; to have designed, developed, and delivered such an ambitious CubeSat to orbit and to have successfully performed experiments in VLEO on novel materials is undoubtedly a success. This case is only further strengthened when the context and complexities of the COVID-19 pandemic during the preparations of this spacecraft are considered.

Analysis of the data from the mission, specifically pertaining to the characterisation of the aerodynamic performance of the materials in the VLEO environment is ongoing, though has been made more difficult by the unfortunate loss of expected data from the atmospheric characterisation payload. However, with some change in approach, the early results are promising and when further developed will be the subject of further publication in concert with other experimental results from associated work conducted within the DISCOVERER project.

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