Mission analysis of the OirthirSAT nanosatellite to demonstrate in-orbit extraction of shoreline position vectors from multi-spectral imagery

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ABSTRACT

European coastlines are under increasing threat due to rising sea levels because of increasing global temperatures because of climate change. Models used by scientists to analyse and predict coastal erosion require recent and responsive data to improve analyses of how our shorelines will change over the coming decades. A novel use of nanosatellites to perform the image processing and data formatting has been proposed to generate responsive and ready-to-use datasets for use in coastal modelling. The resulting mission proposal won the LaunchUK Nanosat Design Competition run by the UK Space Agency. This paper presents an overview of the OirthirSAT student nanosatellite mission along with the system analysis performed in STK and a summary of the operational modes, as part of an ongoing skills initiative to upskill the next generation of climate scientists and space systems engineers.

1 INTRODUCTION

Open-source datasets from satellite constellations including Landsat and Sentinel [1] are widely used to generate data on coastal change processes including seasonal shoreline change, but there is a significant barrier to entry for early-career researchers due to the overwhelming amount of available data and pre-processing required. It may also be preferable to repeatedly image a single target location at a time to reduce the amount of data downlinked and to enable the use of lower-cost platforms. The increasing capability of nanosatellite components makes CubeSat missions to study coastal dynamism an increasingly attractive option to researchers and, combined with the rapid advancements in deep learning processing techniques, can enable nanosatellite platforms to perform some of the pre-processing in orbit, reducing the size of files required to be transmitted to the ground and improving communications bandwidth. The UK Space Agency identified that there is a growing shortfall in engineers and scientists in the UK with skills that are well-suited to the space sector. As such, the LaunchUK Nanosat Design Competition was organised to provide a student team with funding to design, develop and assembly a nanosatellite for a climate-related mission [2].

In July 2022, OirthirSAT was selected as the winning entry into the competition and has since been working towards its critical design review. The OirthirSAT team is comprised of undergraduate and postgraduate students from the College of Science and Engineering at the University of Glasgow, more specifically from the James Watt School of Engineering and the School of Geography and Earth Sciences. The OirthirSAT nanosatellite will generate an open-source data product for coastal researchers that is responsive and pre-formatted, enabling fast and efficient development of coastal models by minimising the downlink of large image files through the extraction of shorelines vectors in-orbit. Using artificial neural networks, the file size will be reduced and will be converted to a vector file automatically, with the coastline outline and vegetation edges transmitted to the ground station.

The mission aims to monitor the changes in the UK's coastline over a two-year period through the in-orbit extraction of shoreline position vectors from coastal imagery which are an indication of morphological changes. Analysis is performed using GMAT and STK and will be used to generate a CONOPS for the OirthirSAT mission. The included analysis demonstrates that the nanosatellite provides coverage of the UK coastlines, can downlink data to a UK-based ground station and maintains pointing accuracy defined by the system requirements.

2 OIRTHIRSAT MISSION

Seasonal shoreline change is an important indicator of coastline health, especially in the intertidal zone defined between the low and high tides of the coastline. Open-source data from Copernicus or Sentinel and Landsat missions provides a wealth of multi-spectral EO data that can be used to generate shoreline vectors that are used to model how shorelines change over time, a process which will become ever more important in the face of rising sea levels. Annual and seasonal shoreline change are two of the many coastal change processes that can be modelled using a time history of data from coastal locations. Different coastal change process occurs on a varying spatiotemporal scale, with cliff-buff retreat and long-term sediment changes requiring data over tens or hundreds of years but at lower resolutions, and sand grain movement or tidal transport occurring over shorter timescales and at a smaller spatial scale. Vitousek et al. [3] present a complete overview of the use of remote sensing along with other methods of observation to model and predict these processes. In previous work, the OirthirSAT team used this review to identify other coastal change processes that could be observed using a similar nanosatellite mission [4].

Onboard processing for micro and nanosatellites is a growing trend with the recent launch of the Intuition-1 CubeSat from KP Labs [5], [6] presenting a similar use case of performing onboard image processing using deep learning techniques to generate EO datasets. The primary benefit of demonstrating this architecture is that the costly downlink of imagery can be vastly decreased for datasets where the imagery is less critical. In the case of OirthirSAT, the shoreline and vegetation boundaries can be extracted as georeferenced ESRI shape or GeoJSON files without downlinking each image sample.

2.1 MISSION DESIGN

The OirthirSAT mission is comprised of a ground segment incorporating a primary and secondary ground station along with a mission control centre, and the space segment which consists of a 3U nanosatellite. Since the selected imager has an optical train along the spacecraft body Z axis, a tuna can be added to allow the imager lens to protrude through the positive Z face, providing more space internally. This configuration of imager has the disadvantage of taking up a valuable Z face, with the negative Z face taken up by the Endurosat UHF Antenna III. This means that the S-Band Antenna must be mounted on an X or Y face, which is less common and requires pointing along two normal vectors. As the solar arrays deploy to increase the surface area of the positive X face, the S-Band Antenna is placed on the negative X face.

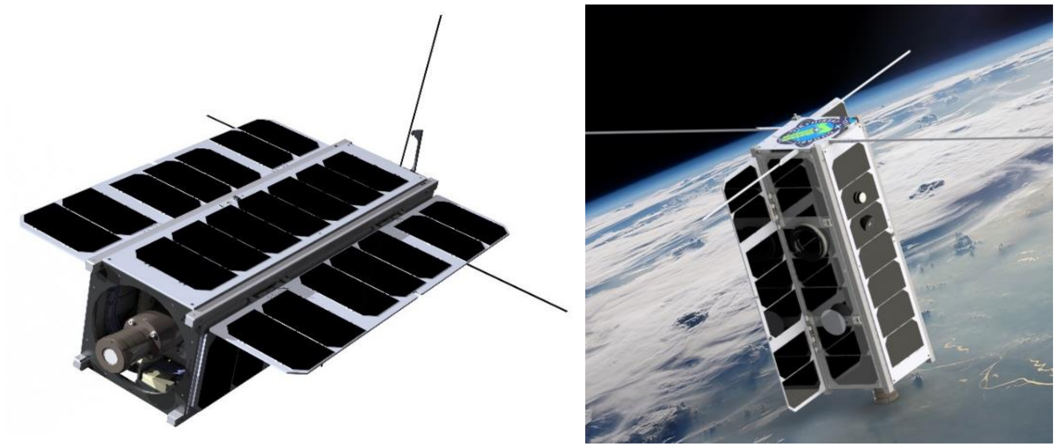

Figure 1. 3D renders of the OirthirSAT nanosatellite presented to the UK Space Agency for the programme CDR.

Ansys Systems Toolkit (STK) is the industry standard software used for the systems analysis of space missions and has been used alongside NASA's General Mission Analysis Tool (GMAT) to design candidate orbits and to perform various analyses required to realise the design of the OirthirSAT nanosatellite.

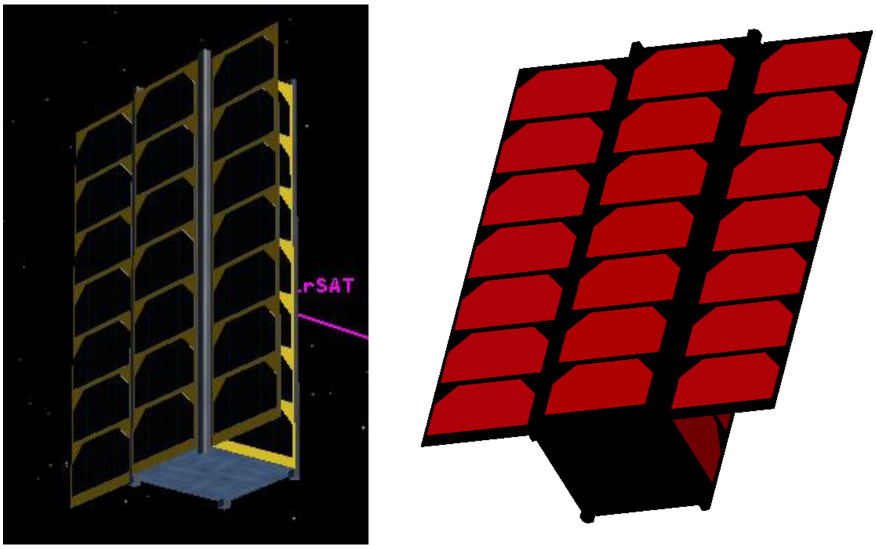

Figure 2. Simplified articulating Blender representation of the OirthirSAT nanosatellite imported into STK for detailed power generation analysis.

A model of the OirthirSAT nanosatellite has been developed in Blender, future versions will be exported from the CAD model, with solar cells defined on each axis and deployable solar arrays built on hinges to allow for deployment events in STK. The resulting model can be seen in Figure 2, as part of a 3D graphics window and in the solar power tool respectively.

2.2 Space Segment System Architecture

Table 1 details the main subsystem components that constitute the OirthirSAT nanosatellite. The decision was made to procure COTS subsystems rather than a fully integrated CubeSat bus to provide more opportunities for students to develop hands-on training with nanosatellite subsystems, an area that is usually restricted to graduate engineers in the space industry. A platform OBC was selected that was compatible with the Bright Ascension GenerationOne framework, a modular model-based software architecture with existing support for a growing number of CubeSat components. The onboard processing, revolving around deep-learning-based image segmentation and pixel classification algorithms including multi-layer perceptron (MLP) [7] and U-Net [8] architectures will be implemented on a secondary payload computer (PDC) which will be comprised of a Zynq-based SoC running a custom RTOS. This decision was made to ensure that the processing software could be updated separately from the flight software with minimal risk.

Table 1. OirthirSAT Nanosatellite platform and payload components.

Functional Component	Manufacturer	Component
Onboard Computer (OBC)	AAC-Clyde Space	KRYTEN-M3-PLUS
Electrical Power System (EPS)	AAC-Clyde Space	STARBUCK-NANO-PLUS PHOTON Deployable Solar Arrays PHOTON Body Solar Arrays OPTIMUS-40 Battery
Attitude Determination and Control System (ADCS)	CubeSpace	CubeADCS Gen2
TT&C Communications (UHF)	Endurosat	UHF Antenna III UHF Transceiver II
Payload Communications (SBAND)	Endurosat	S-Band Antenna S-Band Transmitter II
Payload Imager (MSI)	Simera Sense	MultiScape50
Payload Data Computer (PDC)	Steel Electronique	NINANO
3U Structure (STR)	AAC-Clyde Space	ZAPHOD-3U

Separate two-way telemetry, tracking and control (TT&C) UHF and S-band data downlink communications systems are included as while the objective of the mission is to demonstrate the extraction and compression of key data from imagery, images will still need to be downlinked for system validation. Since the publishing of previous preliminary design information in [9] and [10], the larger OPTIMUS-40Whr battery has been selected to replace the equivalent 30Whr model to provide additional power margin for the nanosatellite. Figure 3 presents the system architecture with the primary communication protocols defined. Secondary backup UART channels are not depicted but are present where additional pins are available on the PC104 connector.

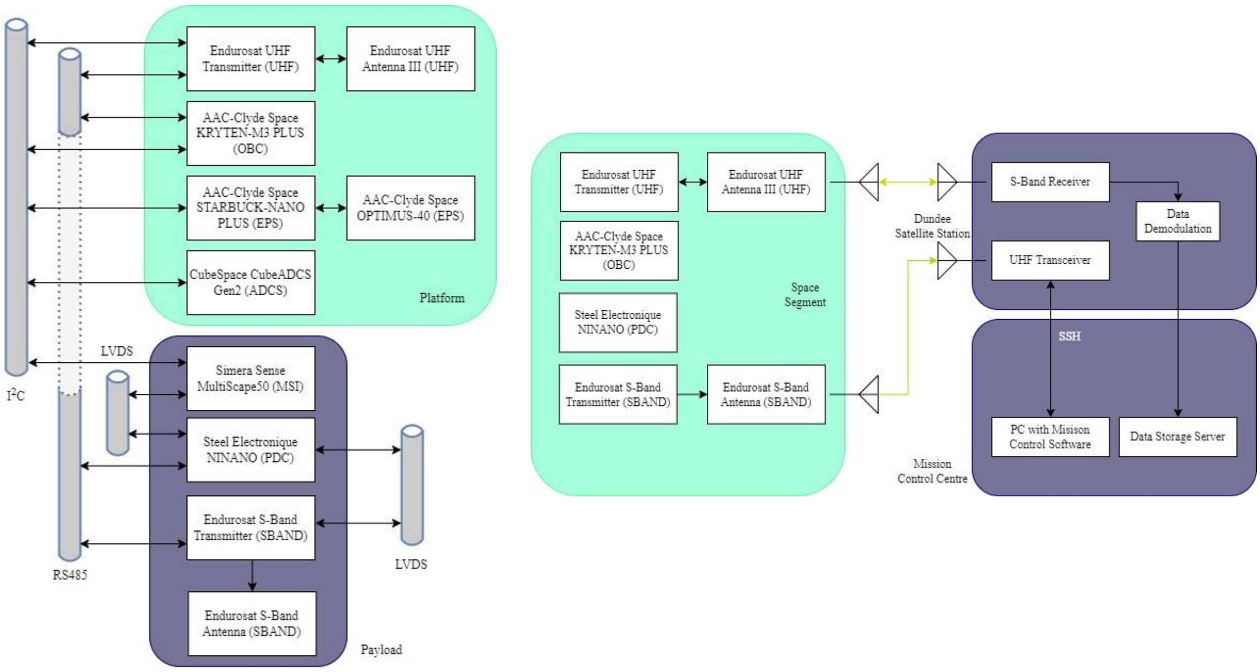

Figure 3. Systems and Communication Architecture for the OirthirSAT nanosatellite and ground segment.

2.3 Ground Support and Mission Control

The mission control center will be hosted in the James Watt School of Engineering at the University of Glasgow which will enable students to learn about how nanosatellites are operated. The primary ground station has been selected as Dundee Satellite Station. While this is not optimal given the primary target area for imaging is the UK, the proximity to the university enables knowledge sharing which is a key development outcome. As a result, a second ground station will be selected in the southern hemisphere, most likely in South Africa or South America to provide an additional data downlink option for formatted payload data.

2.4 Nanosatellite Operating Modes

The definition of spacecraft operating modes is critical for the development of the onboard flight software and is used to refine duty cycles and schedule tasks including data downlink, imaging sun pointing. The operational phases during the deployment of the nanosatellite, as defined in the concept of operations (CONOPS) are shown in Figure 4.

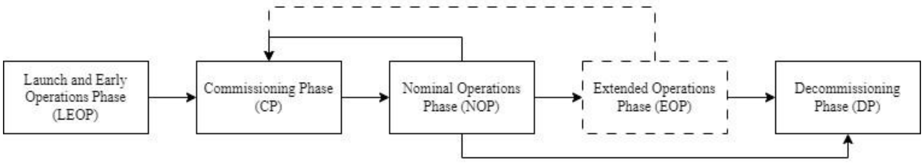

Figure 4. Operational phases during the deployment phase of the OirthirSAT programme.

LEOP refers to the initial power-on of subsystems and deployment of solar arrays and UHF antenna for the space segment, while the ground station attempts to track and begin two-way communications. The commissioning phase (CP) runs through a set of tests to ensure that all subsystems are operating as expected and may be repeated following software updates. This section presents a brief overview of the modes defined for the OirthirSAT nanosatellite platform for the nominal (NOP) and extended operation phases (EOP). These phases refer to mission segments where the nanosatellite will capture data, process it onboard and downlink it to the ground station. A top-level state diagram of the modes defined in the NOP is presented in Figure 5.

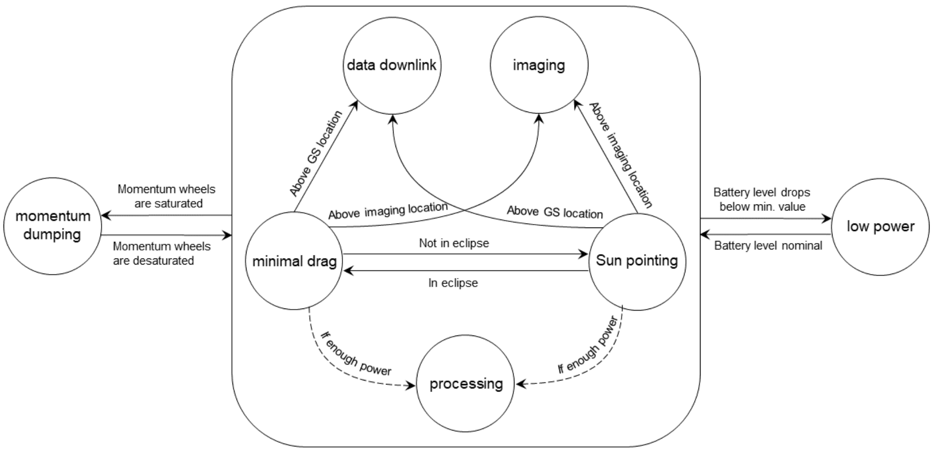

Figure 5. NOP and EOP state diagram for the OirthirSAT nanosatellite.

Primitive state machines for each of the modes used in the NOP are presented in Figure 6 below.

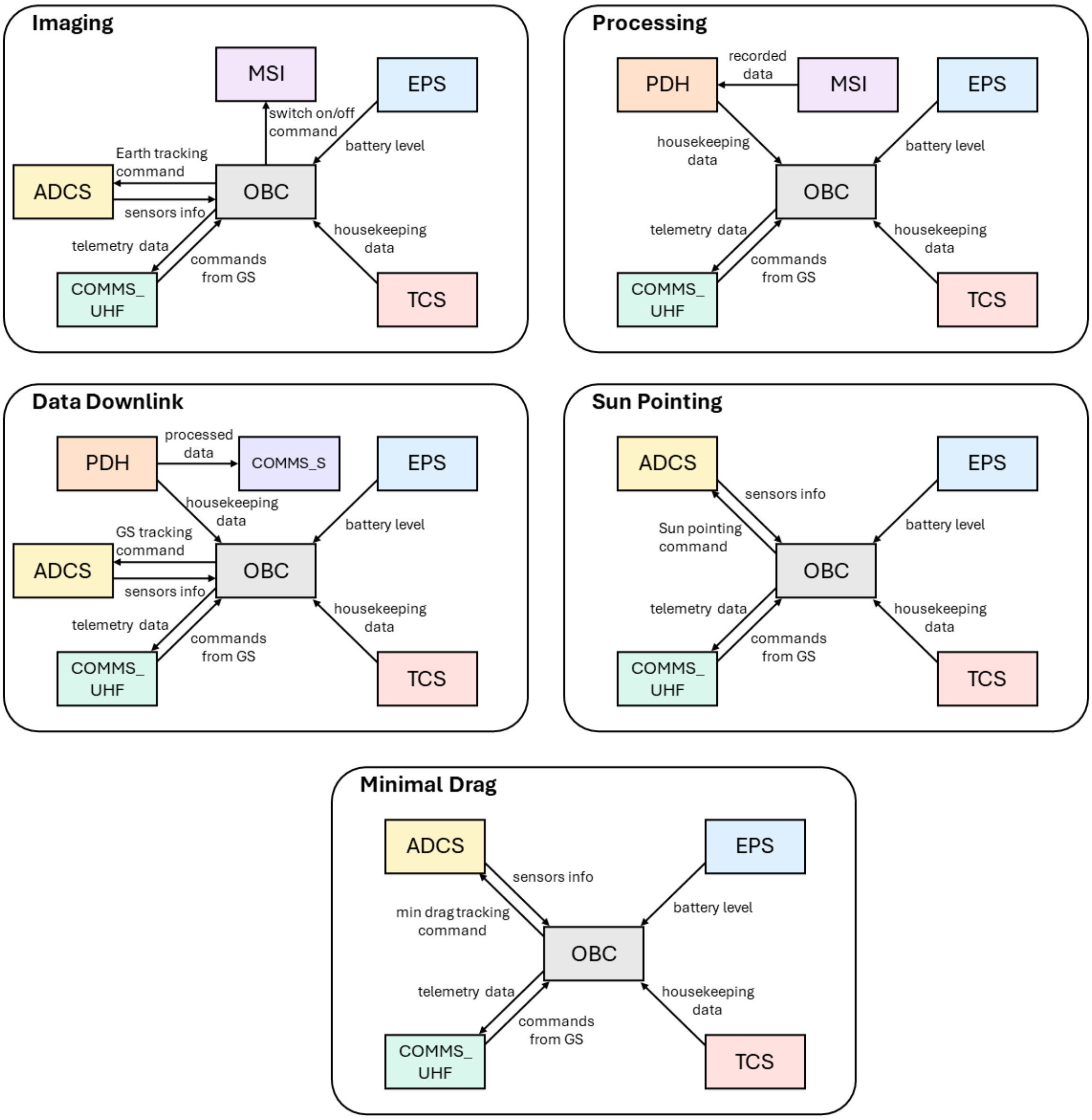

Figure 6. Primary nanosatellite operating modes depicted as illustrative state machines.

Some modes including momentum dumping and low-power mode are kept separate to indicate a higher priority level, as the nanosatellite will transition to these modes from any other mode if the CubeADCS Gen 2 reaction wheels begin to approach saturation, or the battery levels are projected to decrease to below 30% margin.

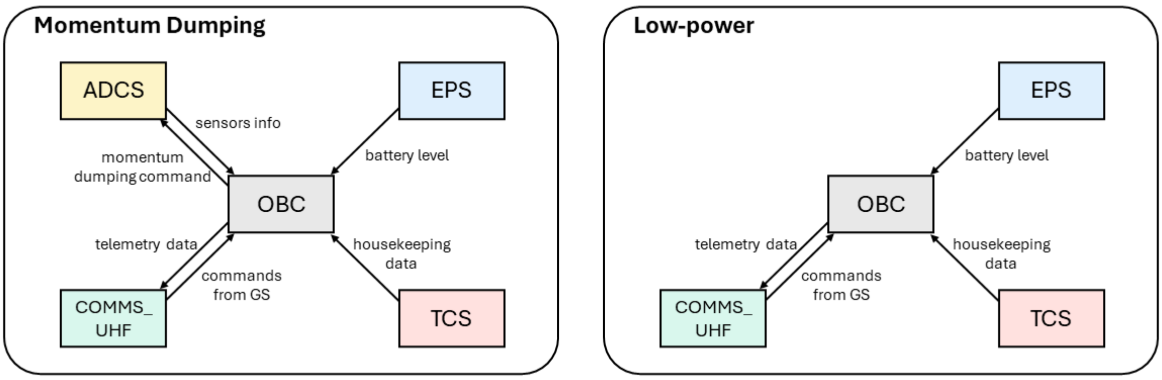

Figure 7. Illustrative state machines depicting momentum dumping and low-power modes.

Two final modes that are not present during NOP and EOP are initial deployment which will only be present in the LEOP phase and the de-orbit or maximum-drag mode which is defined as an emergency mode for decommissioning.

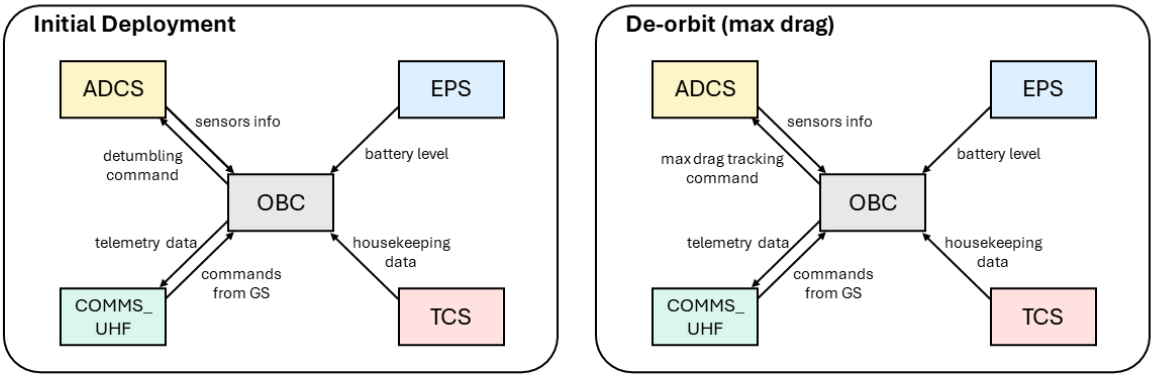

Figure 8. Illustrative state machines depicting the initial deployment (LEOP) and de-orbit modes.

3 ORBIT ANALYSIS

We provide a brief analysis of key characteristics of the candidate orbit along with justifications for the selection. The orbit is analysed using STK and GMAT with reference files available for other student teams to use as educational resources for comparable mission designs.

3.1 Imaging Requirements

To provide a comparable resolution of data to Landsat-5, a popular choice of EO imagery, while covering the UK coastlines, a Ground Sampling Distance (GSD) of 30m/pixel (±25%) was defined. This is classed as moderate resolution and aligns to the GSD's of a number of CubeSat compatible multi-spectral imagers. Further analysis of available COTS imagers can be found in [1]. Some of the key requirements with respect to the mission are presented in Table 2.

Table 2. Imaging and data processing requirements for the OirthirSAT Nanosatellite.

Requirement ID	Requirement Description
NANO-UNIT-021	Shoreline position and vegetation edge data shall be provided to the public for download in vector formats of georeferenced ESRI Shapefiles and GeoJSON files.
NANO-UNIT-019	OirthirSAT should produce at least two winter seasons of shoreline position and vegetation edge data.
NANO-UNIT-018	OirthirSAT shall classify pixels containing cloud density over a specified threshold, generating a binary cloud mask that will be subtracted from the overall processed image in accordance with the processing flow.
NANO-UNIT-015	OirthirSAT shall capture imagery of the Earth at a ground cell resolution of 30 m ±25%.
NANO-UNIT-012	OirthirSAT shall utilise multispectral instrumentation to image the Earth in four (4) spectral bands: Blue (410 to 490 nm), Green (490 to 540 nm), Red (650 to 700nm) and Near Infrared (750 to 900 nm).
NANO-UNIT-020	OirthirSAT shall undertake processing that extracts shoreline positions and vegetation edges from the captured data.

These requirements were developed for the System Requirements Review (SRR) and refined for the Preliminary Design Review (PDR) held with the UK Space Agency in 2022.

3.2 Orbit Definition

The LaunchUK Nanosat Design Competition provided some key requirements for the team entries, one of which being the requirement for a sun-synchronous orbit (SSO). To ensure that the mission was able to image the eastern and western coasts of the UK mainland, a trade-study was performed, with orbit definition iterated on until a suitable selection was found. Due to the uncertain nature of the launch provider and date, several options remain open to the mission with a single orbit selected as the preferred option. The 7D106R orbit was selected as the primary orbit, with the xDxxxR notation referring to the revisit time in days and number of revolutions between revisit times.

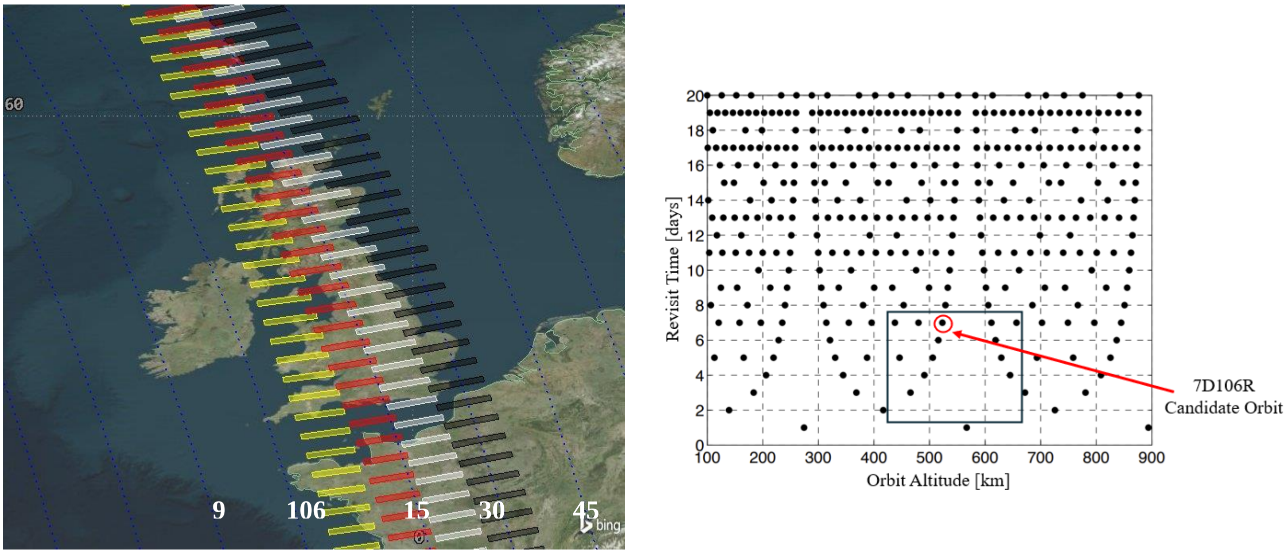

Figure 9. 7D106R candidate orbit identified on a plot of sun-synchronous orbits, adapted from [11]. Valid configuration space denoted by the box, which is bounded by requirements on revisit time, GSD, and minimum and maximum mission lifetime. Available imaging passes are shown in STK along with the pass number.

Table 3. Off-nadir pointing angles required to image the UK using the ground traces highlighted in Figure 9.

Orbit Number	**15**	**30**	**45**	**106**
Swath	Red	White	Black	Yellow
Off-Nadir Pointing Angle	5°	15°	22.5°	-15°

Note that these ground tracks are calculated at the initial orbit altitude of 523.3km as the swaths will decrease in width as the orbit decays. In addition to the four orbits that can be used to image the UK, pass 91 could additionally be used to image certain areas currently not covered, predominantly the southwest but given that the primary areas of interest are covered this is reserved.

3.3 Ground Station Contact Time

For the 7D106R candidate orbit and under ideal observation from the ground station, a total of 57 access periods are possible. These are produced by the STK Access tool and the satellite orbits are depicted in Figure 10 below.

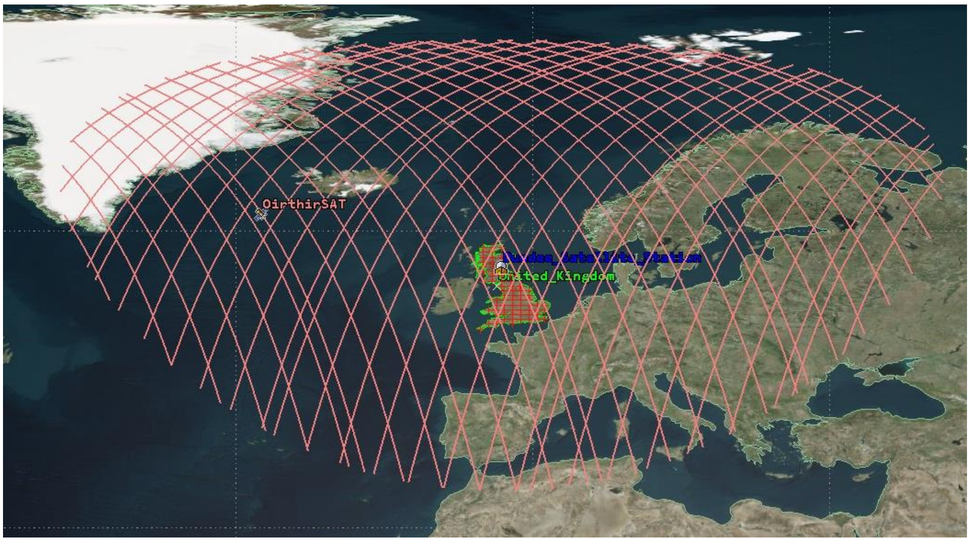

Figure 10. 7D106R orbit segments with visibility to the nanosatellite from Dundee Satellite Station using a sensor with a 5° FoV but with access to perfect positional information and full hemispherical FoR, generated in STK.

These access passes range from a minimum duration of 109.5s to a maximum of 718.3s with a mean of 546.7s. In reality, this figure will be lower due to limitations in the FoR of the ground station, with azimuth and elevation angles reduced due to obscuring geographic features.

4 DE-ORBIT ANALYSIS

For an effective analysis of seasonal shoreline change, a minimum of two winter's worth of data would be required. Given the uncertainty surrounding the launch provider for the mission, this results in a minimum data-gathering phase of two years. This could be extended to an EOP if desired. This is captured by NANO-UNIT-006 of the OirthirSAT requirements that will be made available. NASA, ESA and other space agencies dictate that spacecraft in LEO must deorbit or be placed within graveyard orbits within 25 years of the end of their mission. Due to the orbit altitude, nanosatellite size and lack of onboard propulsion, the OirthirSAT nanosatellite will deorbit without assistance, therefore a maximum orbit lifetime of less than 25 years is required. Despite a maximum drag mode being defined in the concept of operations, the de-orbit analysis is performed with the assumption of a tumbling nanosatellite and therefore an average of the CubeSat faces is used as an approximation. Reference [12] provides a slightly dated but comprehensive review of CubeSats launched between 2003 and 2011 along with their maximum, minimum and average CSA that was used to inform the deorbit simulation.

Table 4. OirthirSAT Nanosatellite de-orbit analysis parameters and estimates using MATLAB, GMAT and STK.

Atmospheric Model	JacchiaRoberts
Drag Model	Spherical
Gravity Model	JGM2
Point Masses	Sun, Moon
GMAT Deorbit Estimate	3.8 years
STK Lifetime Estimate	4.9 years
MATLAB Simulation	5.5 years

There is some variance in estimate which is to be expected with simulations spanning several years, however the minimum estimate exceeds the minimum requirement for a NOP of 2 years while the maximum estimate is well within the 25-year de-orbit time and only just exceeds the FCC's proposed 5-year rule that is under discussion [13].

4.1 Effect of decreasing altitude on Swath and GSD

The orbital decay will result in a loss of altitude throughout the first two years of the mission, leading to a reduction in swath and Ground Sampling Distance (GSD) over the course of the mission. Figure 11 shows the reduction in swath and GSD as a result of the decreasing orbit SMA using the Simera Sense MultiScape50 imager during the NOP. A more detailed analysis on swath and GSD for COTS nanosatellite imagers can be found in [4].

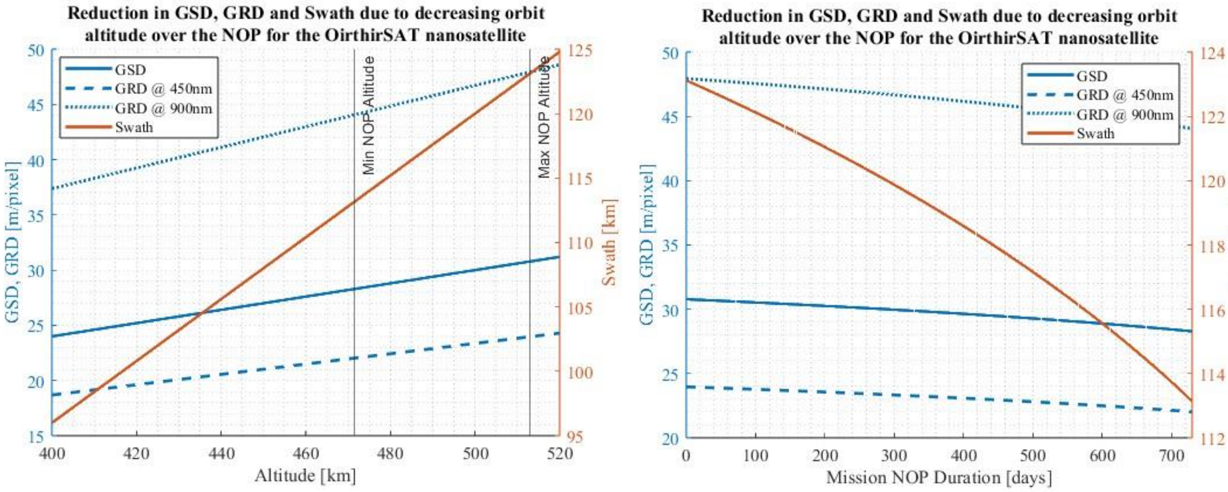

Figure 12. Reduction in GSD, GRD and Swath of the Simera Sense MultiScape50 imager during the NOP due to decay in orbital altitude.

As a result of the changing GSD over the nominal phase of the mission, the image processing algorithms will need to be validated for imagery at GSD's ranging from 30m/pixel at the start of NOP and down to approximately 26m/pixel at the end of NOP or start of EOP. More detailed descriptions of the processing stages can be found in [9] and [10]. Two sample images of the coastline close to Carlisle from Landsat-9 have been generated and downscaled to the GSD that OirthirSAT will operate with.

Figure 13. Landsat-9 images of Carlisle, UK, down sampled to 30m/pixel and 26m/pixel GSD respectively to demonstrate the marginal increase in resolution that would result from a decreasing altitude. Note that the image locations are normalised to enable a comparison of the GSD.

4.2 Solar Array Power Generation

AAC-Clyde Space PHOTON body-mounted and deployable solar arrays have been selected for the OirthirSAT nanosatellite with single, 3U deployable panels folding out from the positive and negative Y faces of the spacecraft along the spacecraft body Z axis, with the panels aligned with the positive X face, that is, facing the direction of motion of the nanosat. This configuration was chosen to enable the use of a deployable UHF antenna and multispectral imager positioned on the negative and positive Z faces respectively. The solar cells used in these arrays are stated to have an efficiency of 30.7%, with each 3U face, constituting 7 cells, generating a maximum of 9W. Since the nanosatellite model built in Blender is an approximation and the sizing of the solar cells is not fully accurate, the STK solar panel efficiency was adjusted until the maximum power generation, occurring when the nanosatellite X+ face is normal to the sun vector, reached 27W. In future the CAD model will be imported into STK to provide an exact representation of the solar cells. Figure 13 shows the power generated per set of solar cells along with the totals of the body and deployable arrays and the maximum and minimum total power generated.

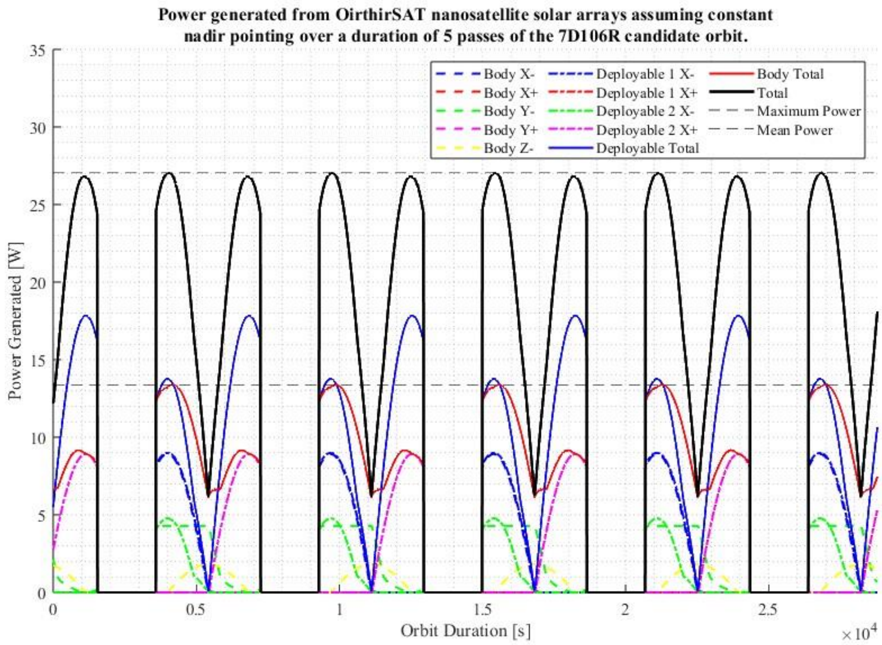

Figure 14. Solar power generated by the OirthirSAT nanosatellite as simulated by STK, under the assumption of constant nadir pointing, over a duration of 5 passes of the 7D106R candidate orbit.

Five passes are plotted with a total duration of 8 hours, since as the candidate orbit is a SSO, the beta angle will remain constant. This simulation used a fixed nadir pointing control mode which is unrealistic but given the distribution of solar cells across all but one face, and the lack of a dedicated sun-pointing mode as described in Figure 6, the simplification can still be useful at this stage in the design process.

5 CONCLUSIONS

This paper has presented a mission overview and brief analysis of the OirthirSAT student nanosatellite programme along with the primary operating modes that the nanosatellite segment will operate with. The Ansys STK scenario and GMAT script is available on the OirthirSAT website for use by other student teams in an effort to share skills that team members have developed over the course of the programme. The OirthirSAT team have completed their CDR and are progressing through to project phase D from ECSS-M-ST-10C with procurement, assembly, integration and testing of the nanosatellite engineering and flight models. In future, the OirthirSAT team will further refine the spacecraft operating modes to derive duty cycles to be integrated into the STK scenario. This will inform the development of the flight software in the Bright Ascension FSDK IDE which will be deployed to the OBC during the integration phase. The team plan for launch of the OirthirSAT nanosatellite, at the earliest, in Q4 2025 but more likely in the first half of 2026.

6 ACKNOWLEDGEMENTS

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