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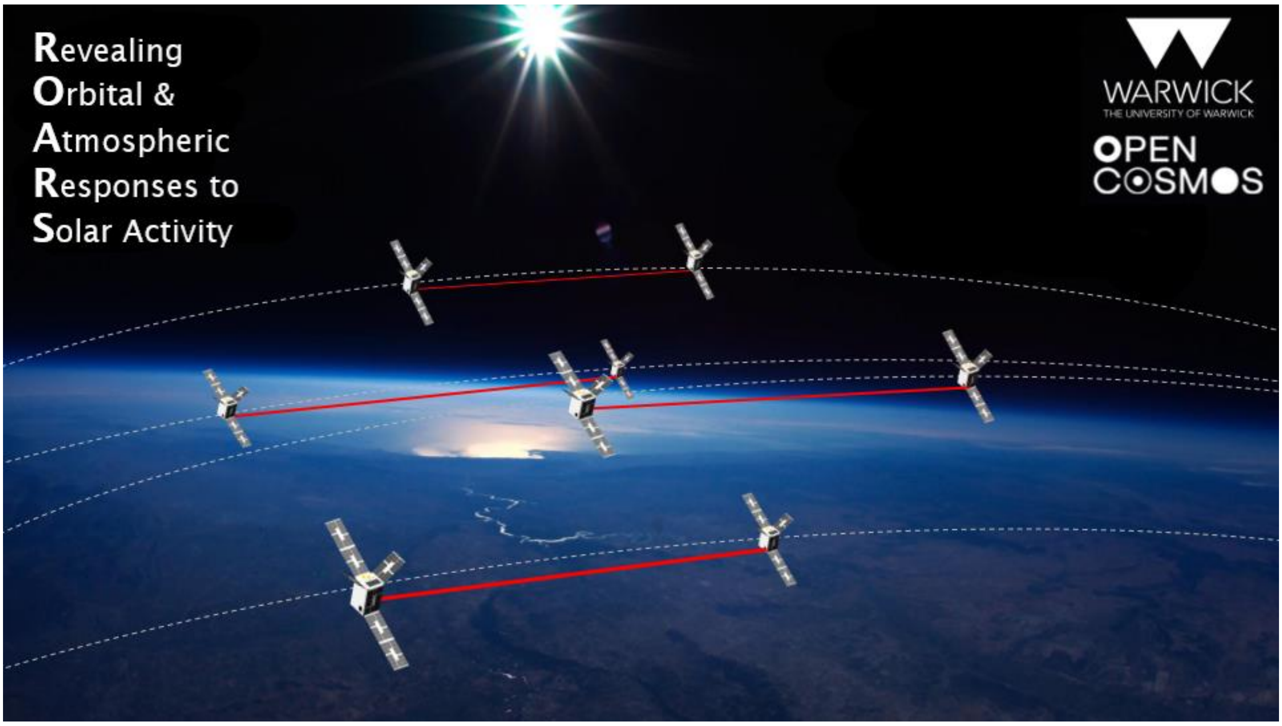

ROARS: Revealing Orbital and Atmospheric Responses to Solar Activity

Executive Summary
Pre-phase A system study

Innovative Mission Concepts Enabled by Swarms of CubeSats

Affiliation(s): University of Warwick, OpenCosmos, University of Birmingham, University of Northumbria, University of Bath, University College London, University of Stuttgart

Activity summary:
The ROARS (Revealing Orbital and Atmospheric Responses to Solar activity) swarm will provide a disruptive step-change to knowledge of our upper atmosphere with direct impacts to fundamental science, space weather forecasting and satellite conjunctions warnings. This report describes a pre-phase A feasibility study into the mission concept. This study formulates the scientific requirements, investigates the payloads and outlines the developmental pathways to meet the requirements. The analysis includes design of the spacecraft and full mission, including launch, orbital insertion and formation maintenance, to provide the envisaged distributed set of scientific measurements of magnetosphere-ionosphere-thermosphere interactions and associated effects on satellite orbits.

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Executive Summary

Objectives: The accumulation of space debris, and congestion of near-Earth orbits, represent an outstanding challenge to the safe use of our space environment. Over 27,000 pieces of orbital debris are actively tracked by the Space Surveillance Network, while over 170 million smaller pieces that cannot be tracked, also pose catastrophic collision risks. Satellite drag from the Earth's upper atmosphere is a primary perturbative force on near-Earth orbiting satellites, and its accurate characterisation is essential to predicting and preventing further collisions and the run-away proliferation of space debris. Atmospheric drag in Low Earth Orbit (LEO) is highly sensitive to solar activity and the solar wind-magnetosphere interaction. Magnetospheric current systems close through the ionosphere and associated ion-neutral collisions, i.e. Joule heating, can drastically modulate the spatially- and temporally-varying outer extent of the atmosphere. Unlike the many isolated in-situ measurements carried out by space missions so far, distributed neutral, plasma and magnetic field observations by a swarm of CubeSats across LEO, in tandem with precise tracking of their orbital dynamics, offer the global view necessary to disentangle the influence of the coupled magnetosphere-ionosphere-thermosphere system on satellite orbits. This novel mission architecture will obtain the first coordinated measurements in LEO across a range of altitudes, latitudes and longitudes to understand the evolution of field-aligned and ionospheric currents, Joule heating and the response of the neutral atmosphere. Coordinated orbit- and ground-based space surveillance and tracking campaigns (GNSS, laser, optical) will simultaneously relate the CubeSats' orbital dynamics to the in-situ measurements, whilst laser inter-satellite-links will provide extended in-orbit tracking of orbital perturbations and resolve meso- and micro-scale atmospheric drag dynamics.

This ROARS mission to LEO is enabled by rapid developments in low-cost technology miniaturisation and represents an unprecedented opportunity to observe and predict the forces of satellite drag. The science strategy is to obtain a coordinated, distributed set of space- and ground-based measurements using a swarm of CubeSats, to characterise the influence of the inter-connected magnetosphere-ionosphere-thermosphere (M-I-T) system on satellite decay levels across LEO altitudes. This cross-cutting endeavour builds upon magnetospheric formation flying measurement concepts, to constrain how solar activity modulates upper atmospheric dynamics, and utilises an extensive satellite tracking ground segment that spans radar, laser ranging and optical systems and connects knowledge and technologies across disciplines. Two overarching themes drive this multi-point mission architecture, which is designed to facilitate model validation and data assimilation:

[1] Obtain coordinated measurements of upper-atmospheric variability across multiple LEO altitudes to resolve the 3D+time structural dynamics that affect satellite drag (measure the environmental inputs)

[2] Obtain and develop the best-ever space- and ground-based measurements of the CubeSats' orbital elements to quantify orbital perturbations arising from solar activity (measure the technological effects)

Mission: The swarm consists of eight 16 U spacecraft. The swarm will be launched into a polar orbit near 500 km and an orbital transfer vehicle will establish their formation. Two satellites will have apogees over the north pole of 500 km and perigees of 350 km over the south pole. Two further satellites will observe across the same altitudes but possess an opposing argument of perigee, i.e. perigee over the north pole and apogee over the south pole. Two further satellites will populate a circular orbit near 425 km with the same orbital period as the eccentric orbits and two further satellites will also orbit at 425 km with a small separation in local time to the first two. This swarm configuration achieves two main aims. Firstly, the common orbital periods will result in the first radial alignments in the auroral regions, allowing three dimensional sampling of the upper thermosphere and ionosphere along connected magnetic field lines. Secondly, each point in the swarm will contribute to forming a large number of tetrahedra over the poles to provide unprecedented curlometer magnetometer capabilities for measuring field aligned currents. Within each orbit, two satellites will be distributed with along-track separations of 100 to 1000 km to sample associated spatio-temporal variabilities and allow intersatellite distance ranging measurements for in-orbit tracking of drag variability and orbital perturbations. The swarm will maintain the relative formation whilst naturally decaying in altitude to sample lower and lower regions of the atmosphere down to below 300 km.

Payloads: The eight satellites will each carry a comprehensive set of payloads for measuring the neutral and charged upper atmosphere and interaction with the magnetosphere. These instruments have all been recently miniaturised with many gaining, or set to gain, flight heritage in the coming years. Each spacecraft will carry dual intercalibrated neutral particles instruments to measure the neutral densities responsible for atmospheric drag as well as the along-track, cross-track and vertical winds responsible for transport and atmospheric variability. Plasma payloads will similarly measure the ion densities and drifts with a Langmuir probe for high

cadence local electron densities and wave activity. The tetrahedral magnetic field measurements will provide curlometer measurements of field-aligned-currents and disturbances propagating along magnetic field lines. GNSS signal sampling will allow the determination of total electron content at, and in-between, each point in the swarm. The leading and trailing satellites in each orbit will contain inter-satellite communications for bidirectional ranging measurements to continuously measure changes in their relative distances and thus their orbital evolution due to atmospheric drag variabilities. Passive retroreflectors will be fitted to the nadir face of each spacecraft to enable precise satellite tracking from ground satellite laser ranging stations.

Ground Segment: The in-orbit measurement architecture will be supported by an extensive ground segment. The orbits will pass enable extended conjunctions with EISCAT_3D incoherent scatter radar facility, enabling measurements of plasma density, electron and ion temperature, and ion drift velocity with high spatial resolution at regions lower down in the atmosphere where the field aligned currents close and the satellite cannot sample. The satellites orbits and their evolution will be tracked using the International Laser Ranging Service (ILRS) along with customised data from a Satellite Laser Ranging station in Graz, Austria, and a proposed station in the Antarctic (UKSA). Ground Optical Tracking telescopes, particularly those at the Roque de los Muchachos Observatory, La Palma, as well as nodes of the Numerica network at multiple longitudes, will provide angles-only measurements for orbit determination, offering near-continuous coverage of the satellites during passes and contributing to anomaly diagnosis through brightness monitoring.

Spacecraft: The spacecraft will be standardised 16 U CubeSat architectures with system configurations and magnetic cleanliness heritage from the ESA NanoMagSat spacecraft design. They will be three axis stabilised via reaction wheels with one 4 U face pointing to the ram and an 8 U face to the nadir. Triple deployable solar panels will provide average generated power of 60 W. The satellites each have a wet mass of 30 kg. A 1 m deployable boom will host the magnetometer. The data will be retrieved using direct to earth X-band downlink. Each satellite will have electric propulsion capabilities for maintaining the swarm formation and then also altitude during the final mission phases. Each spacecraft will have an identical payload configuration with the exception of the inter-satellite laser ranging system which will be located on the leading and trailing face of the trailing and leading spacecraft, respectively, of each pair in each orbit. The spacecraft coefficient of drag and surface properties (colour, weathering) will be precisely determined prior to launch to support orbit determination and tracking.

Community & Stakeholders: ROARS is the product of a large consortium now spanning over 30 institutions across 10 countries in Europe, North America, Africa and Asia. This broad support will be focussed into dedicated working groups to coordinate the various elements of the mission. The mission is fundamentally interdisciplinary spanning numerous space physics and space weather fields (magnetospheric, ionospheric, thermospheric) as well as the space surveillance and tracking and space domain awareness communities. A Science Working Team will form an umbrella organisation for an Observational and Data Analysis working group, a Ground-Based Observations working group, Satellite Tracking working group, and Modelling and Data Assimilation working group. These will engage the wider associated communities and citizen scientists through public outreach. The direct relevance of the mission to space weather forecasting and conjunction warnings for satellite operators has already formed strong connections with industrial stakeholders with the UK MET Office, AXA XL, Atrium Space Insurance and Airbus all formally expressing strong support for the mission and interest in accessing the outcomes. The mission is highly synergistic with further planned missions in this area such as the NASA’s Geospace Dynamics Constellation (GDC) and Electrojet Zeeman Imaging Explorer (EZIE), and there is overlap in the science teams of these missions.

Impact: The ROARS mission has the potential to provide unparallel observations of the upper atmosphere where a dearth of such observations and missions exist, and enable a new era of upper atmospheric science and interdisciplinary investigations between the space weather and space surveillance and tracking domains. Through the ROARS mission and beyond, this will lead to an associated generation of students, young scientists and scientific careers and increased societal knowledge. Notably, this mission can also be used as a pathfinder for future operational space weather forecasting services. Terrestrial weather forecasts rely upon tens of thousands to hundreds of thousands of grounds stations providing consistent data streams to drive and correct global circulation models. Current space weather models rely on few direct measurements with much being made of the indirect inversion of satellites orbital changes to infer along-track densities across hours to days. Direct measurements can provide a ground truth for space weather forecasts of the upper atmosphere with this mission able to probe the benefits and drawbacks to forecasts and conjunctions warnings, from observing key points in the system. The identified payloads, their technological development and implementation within ROARS, thus have the ability to play a foundational role in developing a new space weather infrastructure spanning our geospace environment.