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CIRCE: Coordinated Ionospheric Reconstruction Cubesat Experiment

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ABSTRACT

The Coordinated Ionospheric Reconstruction Cubesat Experiment (CIRCE) is a collaborative space mission between the UK Defence Science and Technology Laboratory (Dstl), and the US Naval Research Laboratory (NRL) in developing small satellite ionospheric physics capability. CIRCE will characterise space weather effects on a regional scale in the ionosphere/thermosphere system. Properly characterising the dynamic ionosphere is important for a wide range of both civil and defence applications such as GPS, communications, and sensing technology.

Consisting of two near-identical 6U (2x3U) CubeSat buses, the CIRCE nanosatellites will fly in a lead-follow tandem configuration in co-planar near-polar orbits at 500km altitude. Provided by Blue Canyon Technologies (BCT), the two buses will use differential drag to achieve and maintain an in-track separation of between 250 and 500km, allowing short time-scale dynamics to be observed in-situ. These nanosatellites each carry a complement of 5 individual scientific instruments, contributed from academic, industrial, and government partners across the UK and US.

Scheduled to launch in 2021 via the US Department of Defence Space Test Program, the two CIRCE satellites will provide observations to enable a greater understanding of the driving processes of geophysical phenomena in the ionosphere/thermosphere system, distributed across a wide range of latitudes, and altitudes, as the mission progresses.

INTRODUCTION

The Coordinated Ionospheric Reconstruction Cubesat Experiment (CIRCE) is a collaborative space mission between the UK Defence Science and Technology Laboratory (Dstl) and the US Naval Research Laboratory (NRL) in developing small satellite ionospheric physics capability. The overall aim of this collaboration is to build on our strong existing relationship in this area to address emerging priorities through joint research. Key areas of interest are improved space situational awareness, C4 (command, control, communications & computing), space weather and investigating options for affordable space capabilities. An overview of the CIRCE mission is provided by (1). Here we briefly describe the mission concept, with a main focus on the UK payloads.

The Ionosphere & Relevance of the Space Environment

The Earth's ionosphere occupies a region around 85 km to more than 600 km in altitude. Formed by solar radiation that ionises the neutral species of the atmosphere, this charged plasma interacts with the ambient electric and magnetic fields in the near-Earth environment. Despite being orders of magnitude less dense than the neutral atmosphere around it, the ionosphere exhibits significant interaction with the upper atmosphere. The ionosphere can also transmit, refract and reflect radio waves. The ionised gases comprising the ionosphere have airglow signatures visible throughout the day and night, providing an opportunity for them to be observed and characterised.

While the overall climatology and diurnal variability of this ionised layer of the atmosphere is relatively well understood, the ionosphere exhibits a remarkable dynamic variability in response to space weather events (e.g. the radiation, charged particles, and magnetic fields associated with solar flares and coronal mass ejections), and dynamics driven from the lower atmosphere (waves, tides, circulation, meteorological events). The resulting ionospheric behaviour and structures can dramatically affect the propagation of radio waves, even disrupting them completely. These effects can interfere with technologies such as communications links, geolocation systems and radar.

Thus, characterisation of these short-timescale dynamics of the ionosphere is vital to enable an understanding of the origins of disturbances to systems, discriminating between environmentally-driven effects and technical malfunctions, and enabling space situational awareness. Additionally, understanding the dynamics of this region allows engineers to better protect equipment and personnel from the effects of space weather, and provide a more resilient capability.

CIRCE Mission Objective/Overview

The CIRCE mission objective is to accurately characterise the dynamic ionosphere. The mission is scheduled to launch in 2021, supported by the US DoD Space Test Program, and will be inserted into a circular 500km +/- 10km orbit with a 90º +/- 5º inclination. CIRCE will exploit multiple sensor measurements across a two-satellite constellation to characterise the short-timescale dynamics in the ionosphere. The constellation consists of two near-identical 6U CubeSat buses, provided by Blue Canyon Technologies (BCT). The satellites will be flown in a 3-axis stable configuration, with the 2U x 1U axis facing the ram direction, and the 3U x 1U axis facing the nadir direction. The two spacecraft will use differential drag to achieve and maintain a lead-trail configuration, with an in-track separation of between 250 and 500km, allowing for short timescale dynamics to be observed.

Each of the CIRCE CubeSats will carry a complement of three UK and two US payloads (Figure 1). These instruments have all been contributed from academic, industrial and government partners across the two nations.

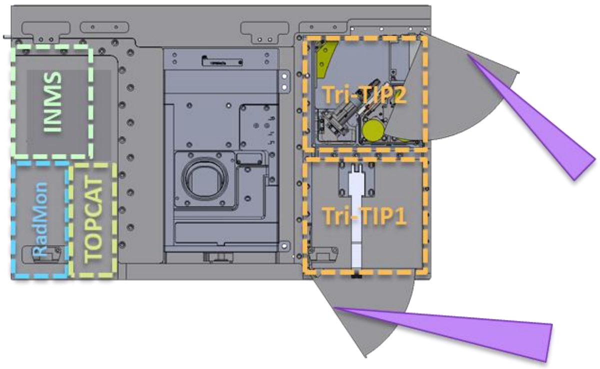

Figure 1: Schematic of the CIRCE spacecraft, showing the positions of the UK payloads (left) and US payloads (right) within the lead spacecraft bus. (From Nicholas et al., 2019).

UK PAYLOADS: IRIS SUITE

From the UK, Dstl is contributing the In-situ and Remote Ionospheric Sensing (IRIS) suite (2). With one installed on each spacecraft, the IRIS suite comprises three distinct and highly capable scientific payloads in a compact ~2U volume (Figure 2).

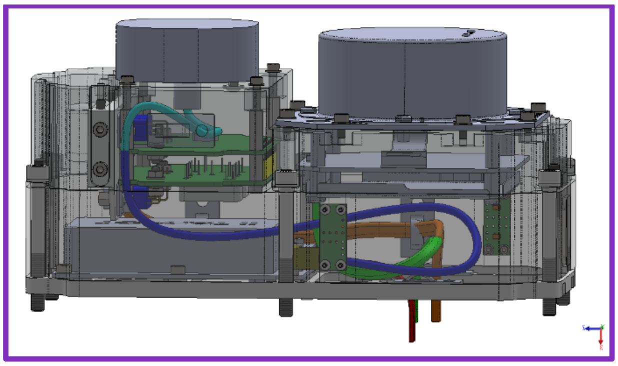

Figure 2: IRIS Suite CAD Model, comprising INMS (top right), the TOPCAT GPS antenna top left), RadMon (centre left), and the TOPCAT GPS receiver (bottom left)

The three payloads showcase the capabilities of UK academia/industry:

1. University College London's Mullard Space Science Laboratory (UCL/MSSL) contribute the Ion and Neutral Mass Spectrometer (INMS).

2. Surrey Satellite Technology Ltd (SSTL)/University of Surrey contribute the RadMon radiation monitoring payload.

3. University of Bath contribute the TOPside ionosphere Computer Assisted Tomography (TOPCAT II), a tri-band GPS receiver that measures signal propagation delay to map the ionosphere.

The IRIS payloads are designed to make in-situ ionospheric particle and radiation measurements, combined with remote sensing of GPS signals to derive the electron density of the ionosphere and plasmasphere. Two IRIS suites are provided for CIRCE, occupying the front 2x1U of the lead satellite, and the rear 2x1U of the trailing satellite. With each spacecraft passing through the same region of the ionosphere with a short time delay, CIRCE will be able to observe environmental changes over far shorter timescales than the typical satellite revisit rate of one orbital period.

The datasets derived from the IRIS payloads are anticipated to:

- Improve our understanding of the variability of properties such as atmospheric drag and the chemistry of the thermosphere, and measure the impact of space weather and other effects on the upper atmosphere;

- Assist in the design and planning of future space missions by highlighting areas of low Earth orbit (LEO) with particularly increased radiation, and helping to shape orbital and shielding requirements for future satellites;

- Validate the Multi-Instrument Data Analysis System (MIDAS (3)) tomography algorithm for characterising the topside ionosphere and plasmasphere, measuring the differential phase of received GPS signals to infer total electron content (TEC) of the atmosphere between the receiver and GPS satellite, and thus deriving the electron density of the region.

In addition to providing substantial scientific interest independently, the sensors comprising the IRIS suite were specifically selected to enrich the scientific output of the US Tri-TIP payloads, providing contextual environmental data alongside the UV photometry measurements of electron density.

It is noteworthy that the IRIS suite was developed, from concept to final flight model delivery (Figure 3), in just one year.

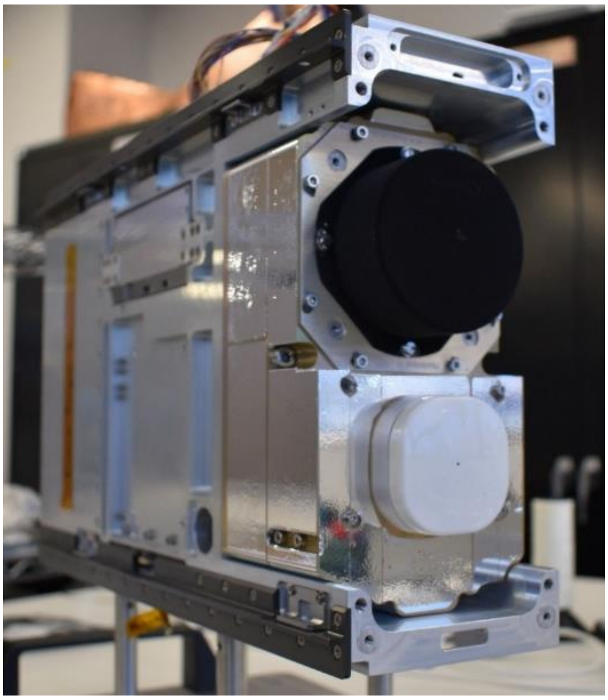

Figure 3: The IRIS Suite Flight Model undergoing integration with one of the CIRCE Buses (courtesy BCT)

INMS

Developed by University College London's Mullard Space Science Laboratory, the Ion and Neutral Mass Spectrometer (INMS) is a cylindrical electrostatic particle analyser, utilising innovative technology to miniaturise the sensor to smaller than 1U in size (Figure

4). The sensor is capable of measuring the density of various ionised and neutral particles in the environment the spacecraft passes through, but is optimised to measure O, O_2, NO and N_2 ion and neutral particle concentrations in the thermosphere (4).

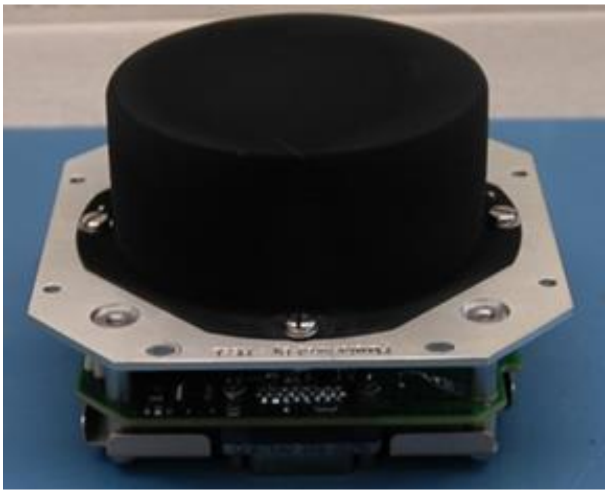

Figure 4: The Ion and Neutral Mass Spectrometer (courtesy UCL/MSSL)

The key sensor components, shown schematically in Figure 5, consist of a collimator/ion filter, an ioniser and a charged particle spectrometer. Charged particles entering the aperture can be rejected in the ion filter region by applying voltages to its electrodes. The ionizer consists of an electron source, an energy selector and a beam steerer and provides a beam of up to 50 eV electrons that is steered into the charge exchange region. The spectrometer consists of a cylindrical geometry electrostatic analyser and a Channel Electron Multiplier (CEM) detector.

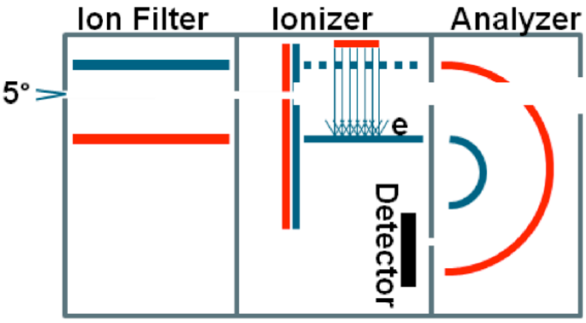

Figure 5: Schematic of INMS Internal Components (courtesy UCL/MSSL)

When voltages are applied to the ion filter and the ionizer is turned on, ions are rejected in the filter whereas the neutral particles are ionized by the electron beam, and subsequently energy analysed in the analyser. On the other hand, when both are turned off, neutral particles pass through a gap in the analyser whereas the ions get energy analysed in the analyser. At any instant in time, the INMS operates either in ion or in neutral particle detection mode, with the capability to acquire full distributions at as low as 16 ms per mass species. In most applications, the instrument is typically operated alternatively in ion and neutral particle detection mode with the mode configurable via a UART interface as desired.

The INMS sensor installed on the lead CIRCE spacecraft will permanently face the ram direction to collect incoming atmospheric particles, while the trailing spacecraft will periodically rotate to alternate the ram facing section of the spacecraft, allowing the second INMS sensor to collect data from the dayside while the US Tri-TIP sensors are not operating.

The sensor technology has proven flight heritage, having successfully flown on the TechDemoSat 2014 and QB50 missions.

TOPCAT II

Designed and built by the University of Bath, the TOPside ionosphere Computer Assisted Tomography (TOPCAT II) payload is a triple-frequency GPS receiver.

As previously discussed, the variable density of the ionosphere can interfere with the propagation of radio signals passing through it. TOPCAT II derives the total electron content (TEC) of the propagation medium from the differential phase of the received signals. The calculated TEC allows for four-dimensional mapping of the ionosphere (5).

The TOPCAT II payload (Figure 6) consists of a GPS receiver, payload controller board, and a triple frequency antenna. TOPCAT also has previous flight heritage: the TOPCAT I payload was the output of a PhD project and demonstration of the use of commercial-off-the-shelf (COTS) components as a cost effective way to construct an upper-atmosphere scientific payload, which flew on the CubeSat UKube-1, in 2014 (6). The TOPCAT II payload is an updated model of this design, an entirely new electronic design due to a new GPS receiver, and an upgrade from duel to triple-frequency capabilities.

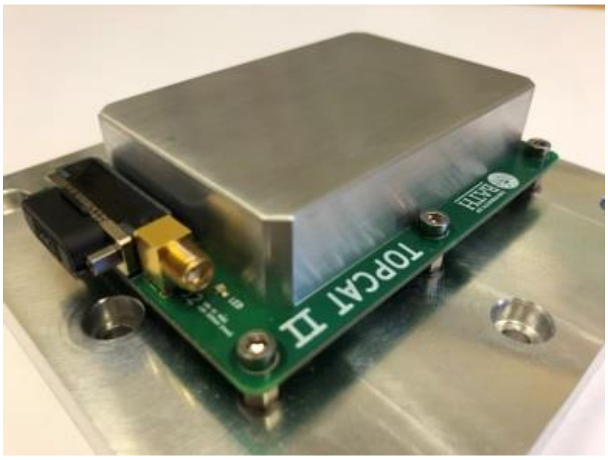

Figure 6: TOPCAT II Receiver Engineering Model

Ionospheric (TEC) tomography is a well-established method of imaging the ionosphere, first demonstrated with LEO satellites of the US Navy Ionosphere Monitoring System (NIMS) and the Russian CICADIA satellites (7).

RadMon

RadMon 3.0 is the latest in a series of mature radiation monitoring payloads from Surrey Satellite Technology Ltd (SSTL). To date, six spacecraft have flown with SSTL developed radiation monitors, in a wide range of orbital regimes. In addition to a veritable spaceflight heritage for the technology, the monitors have provided a near continuous dataset of geomagnetic radiation environment readings since 1992 (8).

The RadMon 3.0 provided for IRIS (Figure 7) is a real-time, low SWAP instrument which provides data on the radiation experienced by the CIRCE spacecraft, and specifically by IRIS. The design has been updated for this mission, a reduction from four printed circuit boards to only two - further reducing the payload's already small volume and mass - required fundamental alterations to the design.

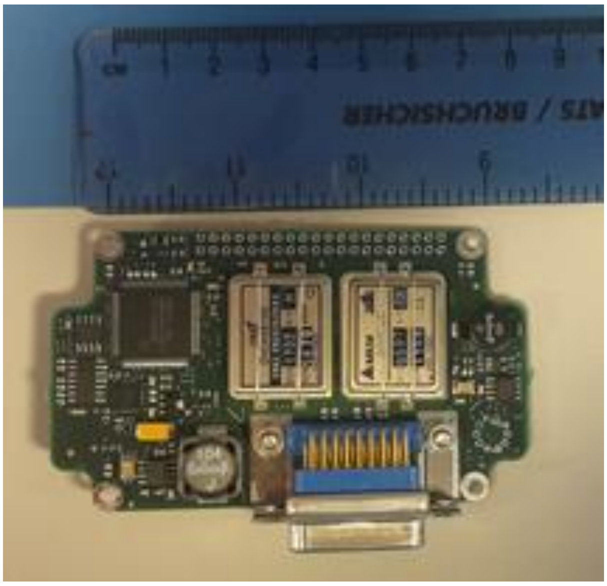

Figure 7: RadMon 3.0 Engineering Model

RadMon will utilise three RadFET solid state dosimeters to measure the total ionising radiation dose experienced by CIRCE: one internal to the payload and two mounted externally within the IRIS suite. Dose rate monitoring is carried out by an ultraviolet (UV) photodiode, and proton and heavy ion fluxes are measured by a large area PIN diode detector.

With two identical RadMon payloads in the same orbit, datasets from both spacecraft can be used for cross-calibration, in addition to providing a useful comparison for identifying spacecraft system upsets and anomalies. Datasets from RadMon are expected to benefit the development of orbital radiation models, in addition to demonstrating increases in particle flux and radiation following space weather events, providing monitoring of the impact of such events.

US PAYLOADS: TRI-TIP

The F-region of the ionosphere, occupying altitudes from ~150 to 500 km, emits several discrete wavelengths of far ultraviolet (FUV) light. Observing these emissions from space based sensors is ideal, as Earth's lower atmosphere completely absorbs FUV wavelengths, so preventing any background light from the surface interfering with observations. These FUV emissions are known as "nightglow", and are often used to observe and characterise the ionosphere (9).

First developed by the NRL for the Constellation Observing system for Meteorology, Ionosphere and Climate (COSMIC) mission (10) (11), the Tiny

Ionospheric Photometer (TIP) is a highly compact remote sensing instrument, designed to observe this FUV nightglow and thus measure the density and physical structures of the ionosphere (11).

Payload Layout & Viewing Geometry

Tri-TIP is a 1U CubeSat compatible instrument, featuring three TIP sensors and a hinged deployable mirror assembly (Figure 8).

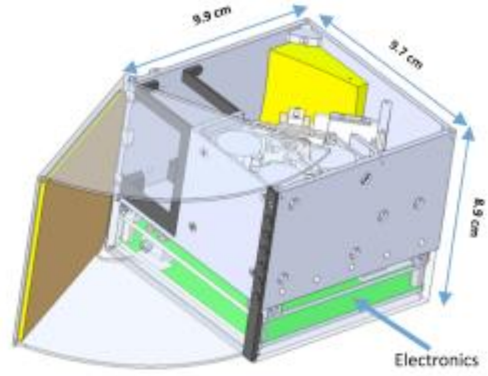

Figure 8: Isometric view of the Tri-TIP instrument, with the hinged mirror assembly deployed. (From Nicholas et al., 2019).

NRL are providing four Tri-TIP instruments for CIRCE, two sensors installed on each spacecraft. On each spacecraft, the two sensors are arranged to have different lines of sight onto the ionosphere below. The in-track separation of the two spacecraft of 250-500 km was chosen to optimise the viewing geometry of the four Tri-TIP sensors, allowing for multi-point sampling of the ionosphere. The Tri-TIP observations will take place on the night-side portion of the orbit, when the nightglow of the ionosphere is most visible. While not operating, the trail spacecraft will flip 180º in the yaw axis to align the second IRIS INMS instrument with the ram direction. See (1) for further details on Tri-TIP for CIRCE.

SUMMARY

Understanding the dynamics of the ionosphere is vital to the operation of various ground-based technologies, as well as spacefaring interests. The CIRCE mission will provide a hugely beneficial insight into these dynamics. CIRCE highlights the considerable capability that can be achieved by scientific CubeSat missions, challenging traditionally-perceived constraints of CubeSat platforms. The development of the IRIS payload in just one year demonstrates the agility of the UK space industry, and showcases the capability of UK academia to swiftly enable high impact space science. There is significant scientific benefit to be derived from the synergistic payloads comprising the CIRCE mission, especially when considering the temporal aspect of the measurements made possible by the dual satellite bus constellation architecture.

ACKNOWLEDGEMENTS

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