



Solar cUbesats for Linked Imaging Spectropolarimetry

<http://sulis.space>

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Abstract

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Determining the 3D magnetic field of the solar corona is key to answering fundamental questions about the true nature of solar atmospheric heating and solar eruptive events driving space weather at Earth. SULIS will be a flagship UK-led space science mission, which will lead a step-change in our understanding of the key physics of the Sun-Earth environment, through innovative UK-built 11U CubeSat (small-satellite) technology with industrial partnership. SULIS is now listed as 1 or 5 high priority, large-scale, fundable, solar system projects by STFC Science and Executive Board. SULIS consists of 3 pairs of formation flying coronagraphs, with one pair in a High Earth Orbit (HEO), whilst the other two pairs enter 1 AU STEREO-like Earth orbits, ahead-of and behind Earth, over a 5-year mission lifetime. SULIS will answer important questions about the 3D evolutionary properties of the magnetic field of the solar corona, at remarkably high cadence (~1-min), in order to determine the potential geo-effectiveness of Coronal Mass Ejections (CME's) at the earliest opportunity, as well as, tracking of CME's to determine their 3D kinematics. SULIS will compliment operational space weather missions, through exploring the science underpinning space weather sources, in order to establish better forecasting systems in future.

3D Coronal Magnetic Fields

The coronal magnetic field is **one of the most important observables** in the solar atmosphere, yet, **one of the least explored**. It is challenging to measure but **critical for understanding the science underpinning Space Weather**

- **Cononal Mass Ejections:** Space weather sources are solar flares, CMEs, solar energetic particles, and geomagnetic disturbances. Knowing the north-south orientation of magnetic fields in CMEs (simulated in **Figure 1**) is critical for determining the potential geo-effectiveness of a CME upon impact with Earths magnetic field. The magnetic field in the corona dictates the role of MHD instabilities (such as the Kink and the Torus Instabilities) thought to drive prominence eruptions and CMEs.
- **Solar Flares:** Energy released in solar flares s stored in the coronal magnetic field. How much energy depends on how well we can directly measure the coronal magnetic field.
- **Origins of Solar Wind Acceleration & Coronal Heating (waves or reconnection?):** One of the longest-standing problems in solar and astro-physics concerns **a)** how MHD waves in the solar corona dissipate their energy leading to atmospheric heating. **b)** what is the role of magnetic field line braiding and reconnection in coronal loops with regard to atmospheric heating. Both wave-based phenomena and reconnection-based phenomena, across both active regions and quiet Sun, are through to be governed by the coronal magnetic field which we has never been measured across the full-disk. This is now possible with current technology.

Aim of SULIS: Understand the Sun's link to the inner heliosphere and the science underpinning space weather via revolutionary UK-led CubeSat technology. In order to accurately quantify the magnetic energy stored in the corona, **we require high cadence (<1 min.), high resolution (<1 arcsec), magnetically sensitivie (<5 Gauss), continuous, direct measurement and 3D mapping of the coronal magnetic field both on-disk and off-limb.**

- SULIS Key Objectives:
1. Provide the **first direct measurements of the 3D coronal magnetic field** (unique science).
 2. Provide **eclipse-quality imaging of the extended solar corona** (out to 5 solar radii) for deeper understanding of fundamental science underpinning space weather.
 3. **Demonstrate UK-led future technologies** (i.e., laser optical communications).

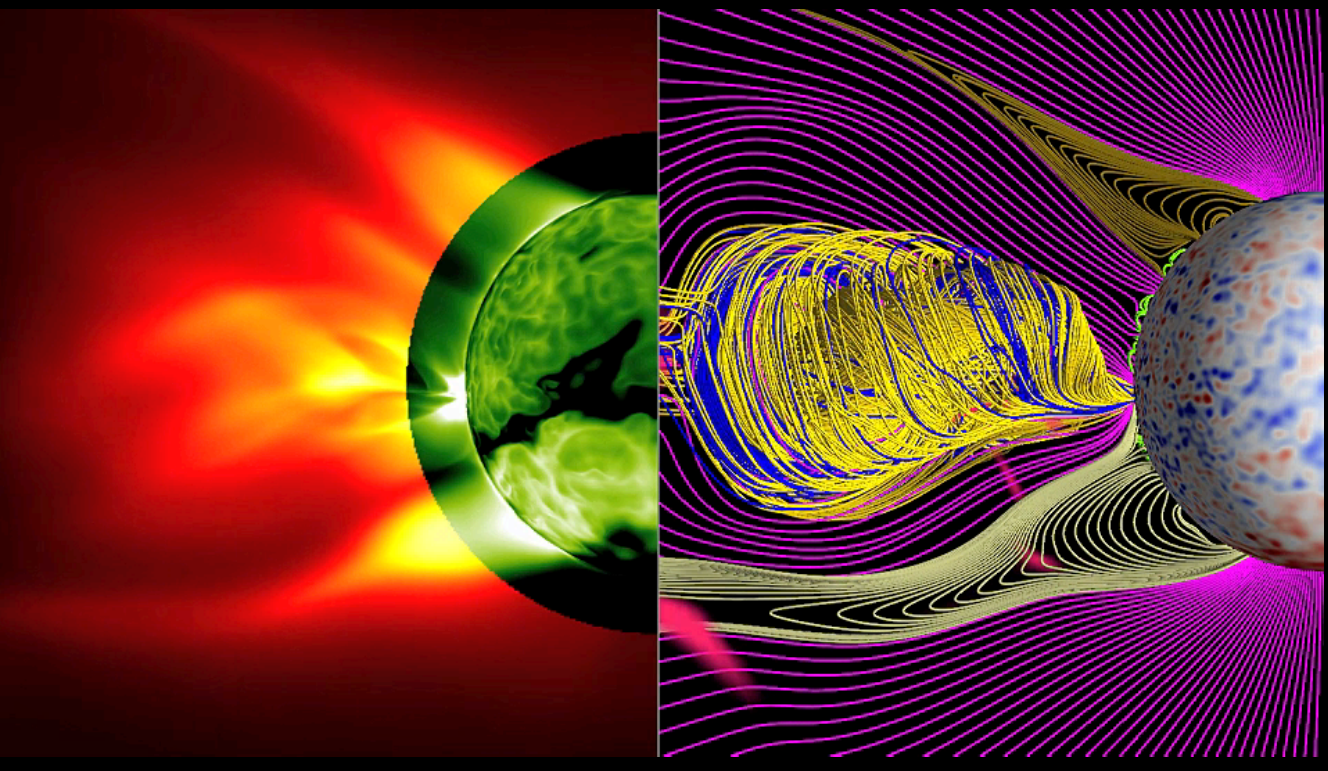


Figure 1: *Left* Simulated EUV images of a CME in the solar corona. *Right* Simultaneous magnetic field line structure in the CME eruption.

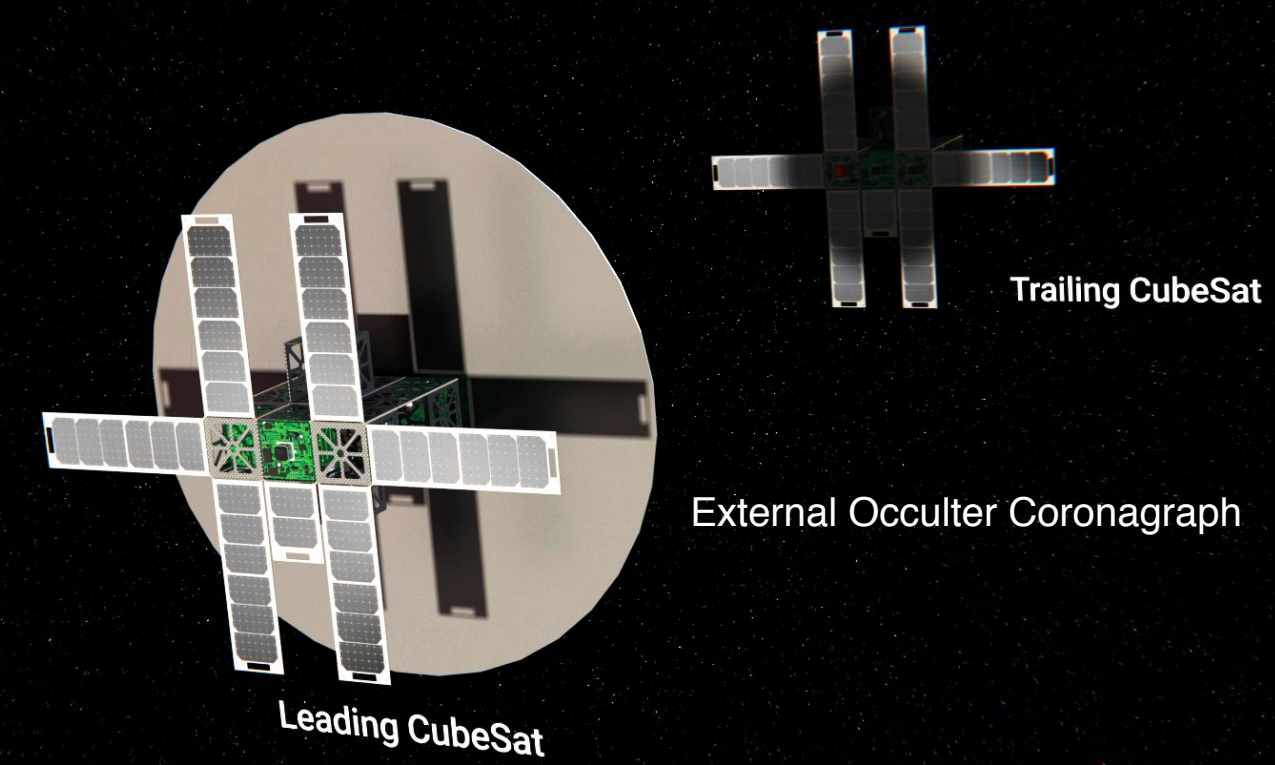
Formation Flying Coronagraph

SULIS will build-on and demonstrate the strength and legacy of UK space leadership

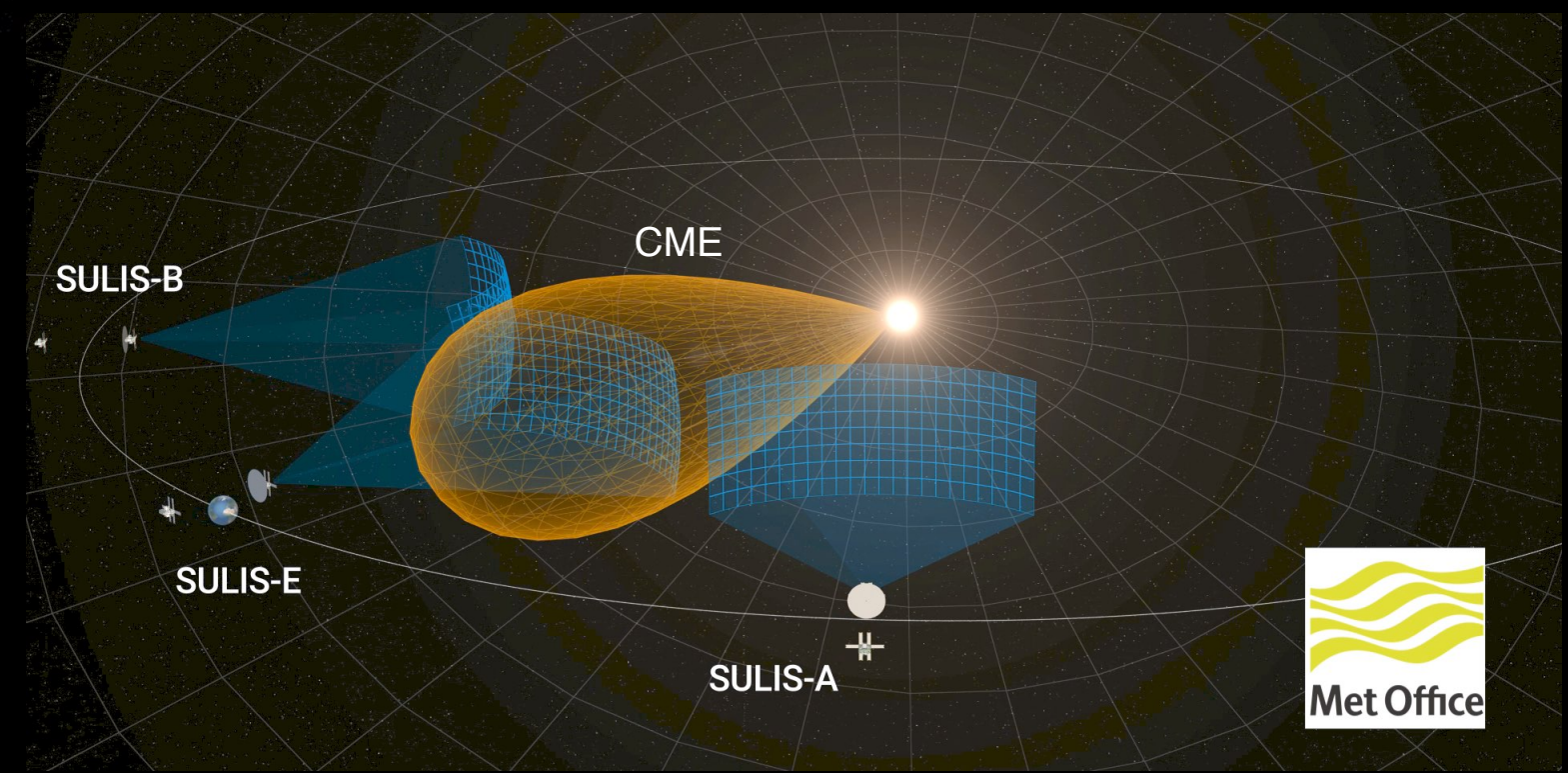
SULIS CubeSat construction will be managed by industrial partners SSTL. SSTL delivers complete mission solutions for remote sensing, science, exploration, navigation and telecommunications. The ground station segment for mission operations will be supported by STFC-RAL Space in collaboration with SSTL.

To properly determine the magnetic field of the solar corona, single-viewpoint Coronal Emission Line Spectropolarimetry (CELS) is not enough. **We require multiple-viewpoint CELS** with a large separation angle for disambiguation of the plane-of-sky coronal magnetic field vectors. Utilising the collective power of space-based stereoscopy (depicted in **Figure 2 Bottom**), employing CELS from instruments housed in pairs of CubeSat's (depicted in **Figure 2 Top**) makes up SULIS (combining 3 pairs: **SULIS-Ahead**, **SULIS-Behind** and **SULIS-Earth**) will enable reconstruction of the 3D coronal magnetic field in real-time.

Clusters of small ~15 cm telescopes (suitable for 11U CubeSat's) operating collectively can achieve the same magnetic field sensitivity as a large ~1 m telescope, but at a **significant cost saving**. The technological innovations of SULIS will advance the power efficiency, communications and control for CubeSat's and small-satellite constellations in general.



Bottom: The 3D magnetic field and kinematic properties of a CME from the Sun can be tracked through the combination of synchronous observations from 3 pairs of CubeSat's flying in formation, along the Earth orbit. Each CubeSat pair is referred to as SULIS-A, SULIS-B and SULIS-E. The UK Met Office is a key stakeholder in the SULIS mission concept.



Massively-multiplexed Spectropolarimetry

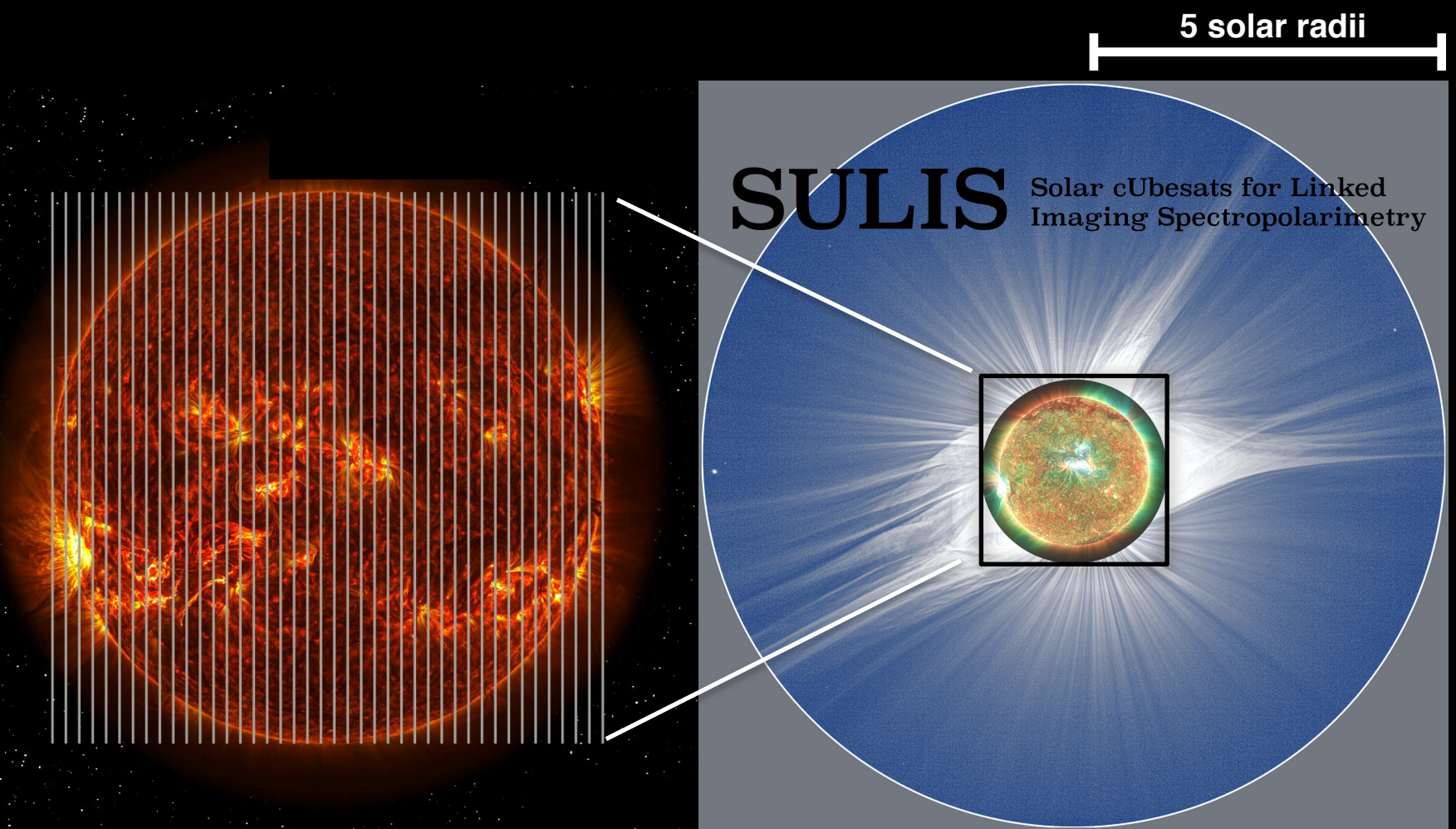
The unique combination of trailing and leading CubeSat's in each satellite pair (SULIS-A, SULIS-B and SULIS-E) results in **a)** ultra-low scattered light through the application of an external occulter for maximising polarimetric sensitivity and **b)** the opportunity to observe **3D magnetic fields off-limb and on-disk simultaneously & stereoscopically for the first time**

Trailing CubeSat Instrumentation (Coronagraphic Hyperspectral Imager): A coronagraphic high-resolution multichannel spectrometer together with a state-of-the-art broadband hyperspectral imager for observing the off-disk extended corona. An accompanying novel hyperspectral imager is included, which is linked to the development of the PanCam instrument on ExoMars (e.g. ST/G003114/1). The emission line spectra will infer electron temperatures, ion densities, bulk flow speeds and non-thermal heating, and link these to the spectropolarimeter magnetic field measurements. To provide context and high-resolution imagery, the spectrometer entrance slit is mirrored producing 'slitjaw' images. This system rapidly scans the visible range across the extended corona providing a spectral profile for the corona's broadband continuum.

Leading CubeSat Instrumentation (Massively-multiplexed Spectropolarimeter & Magnetometer): Bespoke 99-slit, massively-multiplexed coronal spectropolarimeter for uniquely measuring magnetic field vectors in the corona of the inner solar atmosphere. Prof Lin (PI of the DL-NIRSP instrument on DKIST) has secured \$2 million of NSF funding (2018) to develop a TRL-4 prototype designed to fit into 11U CubeSat's. The disk-imaging near-IR spectropolarimeter will be uniquely hosted on the sunward occulting CubeSat of each pair. Diffraction-grating spectrographs simultaneously observe several visible and near-IR spectral lines over multiple slits across the solar disk, as depicted in **Figure 3**. Inversion of the *Fe XIII* 1.075μm and *He I* 1.083μm spectra yield the magnetic field vectors through normal and saturated Hanle and Zeeman Effects.

Figure 3: *Left* SDO/AIA synoptic observation of the solar disk from EUV channels with a grid of slit spectrometers overlaid. The **Leading CubeSat's** massively multiplexed design enables rapid mastering of the full-disk (1 min cadence) for polarimetric magnetic field inversions of the near-IR spectral lines.

Right Anticipated simultaneous coronagraphic observations by the occulted **Trailing CubeSat** instrumentation observes the corona out to 5 solar radii enabling tracking and kinematic analysis of CME eruptions in 2D or 3D (stereoscopically)

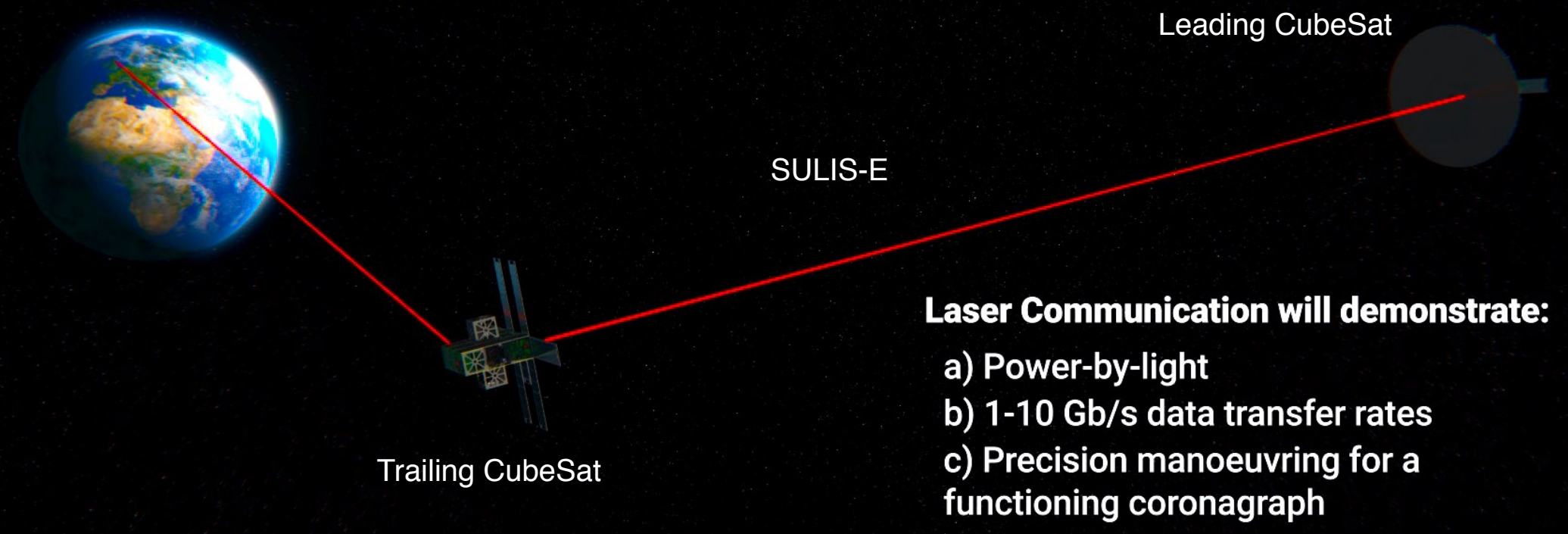


Novel Laser Optical Communications

SULIS offers bespoke UK technology demonstration with a wide range of applications, benefitting society and industry across many sectors

Next-generation Power-by-light Optical Wireless Communications (OWC) technology will be demonstrated in space for the first time. The demand for high-speed internet services has driven emergent technologies capable of delivering ultra-high data rates to end users. SULIS will demonstrate optical power transmission (offering mark-up data transfer rates compared with X-band antenna transmission) characteristic of *Power-by-Light* systems, an elegant method for powering PV solar cells across large distances, using laser light (aka **Li-Fi**). Li-Fi can also achieve very precise alignment of formation-flying *smart* CubeSat's, important for maintaining a precise satellite alignment for a functioning coronagraph. SULIS will demonstrate autonomous CubeSat clusters which self-consistently control proximity satellite manoeuvres. This is of substantial interest within the international spaceflight community, e.g., the AAREST mission highlights the need for enabling technology for assembly of future large space telescopes.

Li-Fi is the future of communications technology (Northumbria University): Li-Fi communication will rapidly redistribute the data between CubeSat pairs (i.e. SULIS-A & B), before transmission to SULIS-E at ~100 Mbps each. In 2001, a 50 Mbps link was successfully established between the ARTEMIS geostationary satellite and the SPOT-4 satellite. SULIS-E will also redistribute data and provide a downlink transfer at ~600 Mbps, as depicted in **Figure 4**. In 2013, NASA's lunar laser communication demonstration achieved an impressive downlink rate of 622 Mbps. The application of high-speed data transfer using light is highly advantageous for SULIS given that Li-Fi significantly reduces the payload mass. Li-Fi technology is a novel solution for **1)** limited CubeSat bandwidth (Li-Fi offers expansive bandwidth) **2)** connectivity (Li-Fi is highly energy efficient in monochromatic laser light) and **3)** range (Li-Fi can transfer ethernet internet speeds).



- Laser Communication will demonstrate:**
- a) Power-by-light
 - b) 1-10 Gb/s data transfer rates
 - c) Precision manoeuvring for a functioning coronagraph

Future

- SULIS **compliments operational space weather missions** (e.g ESAs potential L5 mission, NASA's L1 follow-on to DISCOVER and the ASPIICS/PROBA-3) paving the way for future space weather instruments. All partner organisations have established **public outreach programmes** and will **promote SULIS and raise public awareness of space weather hazards**.
- **SULIS is ambitious**, yet risk is mitigated through the initial launch of SULIS-E, followed by SULIS-A & B, 1-2 years later. Limiting the initial mission to one pair will first test the feasibility of the formation-flying coronagraph.
- **SULIS provides an exciting opportunity** to strengthen the collaborative relationship between STFC and the UK space industry. The UK's growing space sector is a core part of the UK government *Industrial Strategy*.

Project Partners

- Gary Lay, Business Line Director, SSTL
- Prof Richard Harrison, Chief Scientist, STFC RAL Space
- Dr Jackie Davies, Helio. Team Leader, STFC RAL Space
- Phillip Steen, Head of Technology, Andor Technology Ltd
- Mark Gibbs, Head of Space Weather, UK Met Office
- Prof Shadia Habbal, IfA, University of Hawaii (USA)
- Prof A Ding, Technische Universitaet Berlin (Germany)
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