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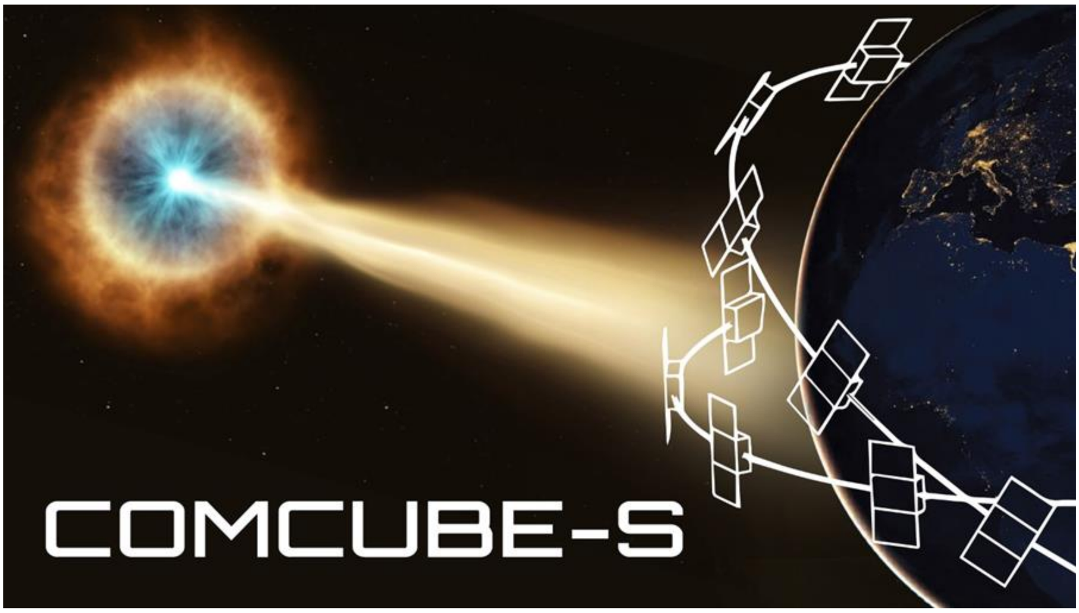

COMCUBE-S

Executive Summary Report

OSIP Study

'Innovative Mission Concepts Enabled by Swarms of CubeSats'

Affiliation(s): University College Dublin Center for Space Research (Prime), AAC Clyde Space (Sub 1), IJCLab (Sub 2)

Activity summary:

COMCUBE-S is a swarm of 27 12U CubeSats each carrying a novel Compton telescope which is used to measure the polarisation of gamma-ray bursts (GRBs) as well as provide low-latency GRB localisations for counterpart discovery in the multi-messenger era of time-domain astronomy. This study explores the concept of operations for such a swarm, the development of its innovative payload and platform and provides simulations of the polarimetric, burst detection, burst localisation, and alert latency performances. The study results demonstrate that the COMCUBE-S concept is a compelling and ground-breaking science case for high energy astrophysics.

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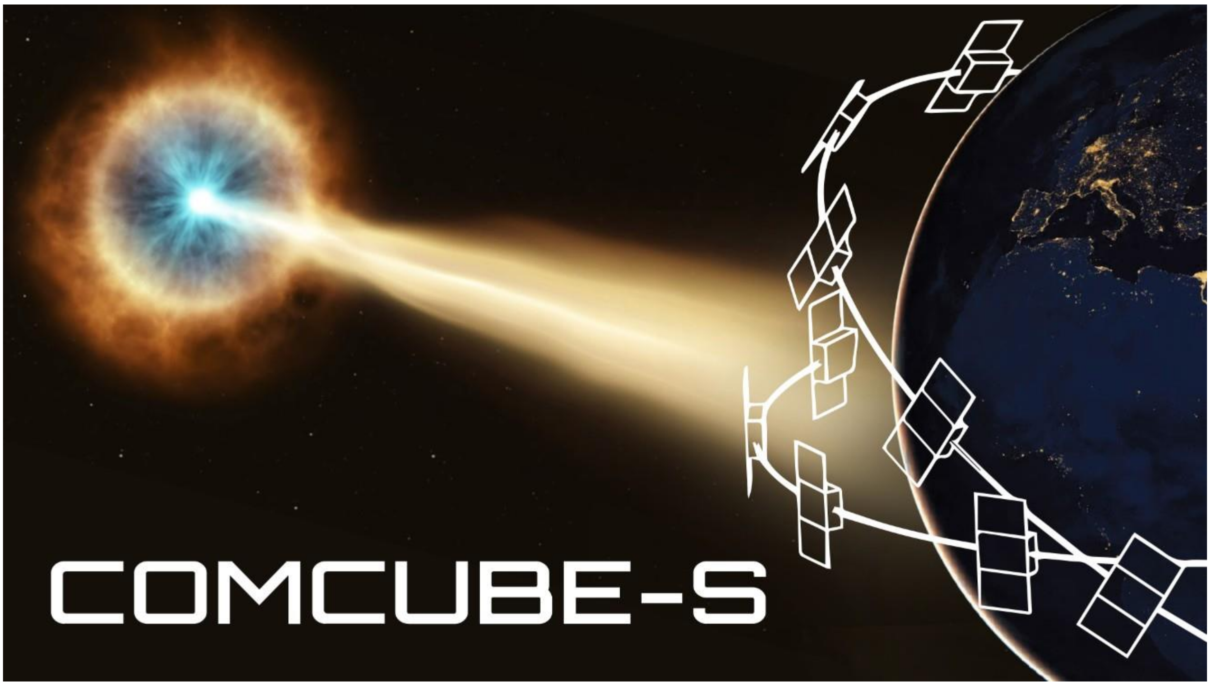

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1 Introduction

1.1 Science Background

Gamma-ray bursts (GRBs) are the brightest, most violent explosions in the Universe, lasting from less than 100 ms to several hundred seconds. Long GRBs (> 2 s in duration) are thought to be emitted when a very massive star collapses. Short GRBs (< 2 s) are understood to be created by the merger of neutron star binaries. The joint detection of a source of gamma-rays (GRB 170817A) and gravitational waves (GW 170817) from the coalescence of a binary neutron star provided a spectacular confirmation of this prediction, opening the exciting new field of multi-messenger astrophysics. In both short and long GRBs, a transient accretion disk is formed around a newly formed black hole or neutron star, and two narrow jets of material are launched at close to the speed of light on either side of the disc.

The detection of the host galaxies and measurements of their redshift using optical spectroscopy showed that GRBs are produced at cosmological distances. The high luminosity of GRB jets makes them detectable in the first galaxies to form in the Universe, up to redshifts of z > 10. There would be considerable interest in being able to determine the absolute magnitude of a GRB from its measured parameters (time scales, peak energy, bulk Lorentz factor, etc.) so that its distance can be estimated from its apparent luminosity. This would give us a new powerful way of studying the structure and evolution of the Universe from **new standard candles**. At present, however, the physics behind the GRB explosion is not sufficiently well known for that. In particular, the dominant radiation mechanism responsible for the GRB prompt emission remains poorly understood.

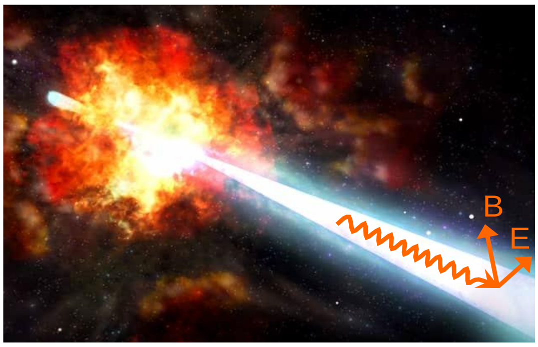

Figure 1: Measuring the preferential orientation of the E-field vector of GRB gamma-rays will add a new dimension to our understanding of astrophysical jets.

Spectral and light-curve information alone has proven insufficient for understanding the plasma composition, the magnetic field origin and structure, as well as the main energy dissipation process in GRB jets. Linear polarisation measurements can add a new dimension to our understanding of ultra-relativistic jets by revealing the magnitude and coherence of magnetic fields carried by the jet, as well as the radiation mechanism and viewing geometry. Thus, accurate polarimetry of a significant sample of GRBs, including time-resolved analyses, can unambiguously distinguish the various models of GRB prompt emission.

Reducing the GRB alert latency together with providing good source localisation is also an essential condition for gaining a better understanding of GRB physics, as it enables rapid electromagnetic follow-up observations, which are key to better understanding the early activity of the GRB central engine and the generation of the prompt emission.

The main science goal of COMCUBE-S is to **gain a breakthrough understanding of the fundamental physical mechanism and extreme physical conditions that give rise to the prompt emission of GRBs, and in so doing also allow them to be used as standard candles for cosmology**. The COMCUBE-S CubeSat swarm will outperform conventional gamma-ray missions for both gamma-ray polarimetry and always providing full sky coverage with low-latency alert notifications and quick source localisation.

1.2 Compton Polarimetry

The required polarimetric measurements of GRBs can be ascertained using a Compton telescope which works based on the principle of Compton scattering. As shown in Figure 2, a Compton telescope works by Compton scattering a high-energy photon in one detector (typically called D1) before fully absorbing the scattered photon in a second detector (D2). Both detectors measure the interaction point and energy deposited. This gives the trajectory of the photon post-scatter as well as the angle through which the photon has scattered, constraining the photon source to an annulus. The ambiguity of the source position is resolved when several photons from the same source are detected.

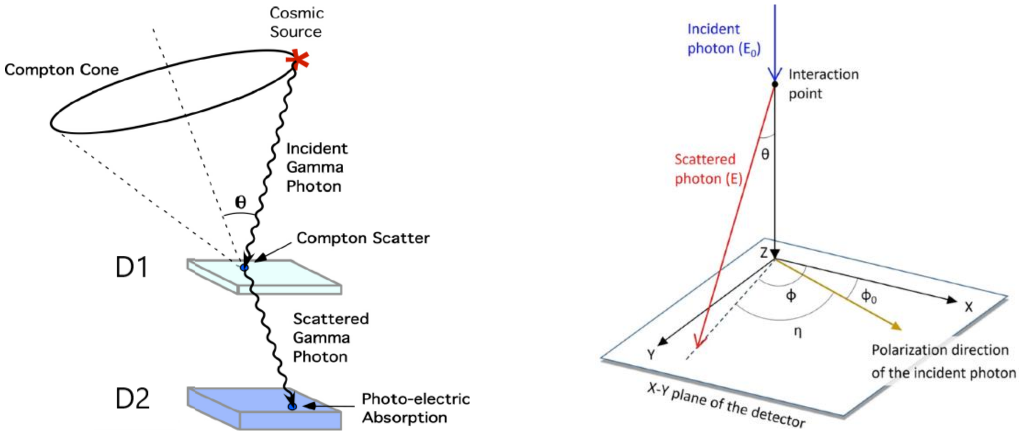

Figure 2: Left – Compton telescope detection principle. Photons are Compton scattered in the D1 layer before being fully absorbed in the D2 layer. Right – Principle of linear polarisation measurements using Compton scattering: polarised photons tend to scatter perpendicularly to the incident polarisation direction.

With the source position determined, the azimuthal scattering angle of each photon can also be determined. Given a distribution of Compton events as a function of azimuthal scattering angle, the gamma-ray polarisation can be measured as polarised photons tended to scatter perpendicularly to the incident polarisation direction.

1.3 Science Goals

The Science Traceability Matrix in Table 1 Table 1: Science Traceability Matrix for defining the payload and mission functional requirements. provides a summary of the scientific objectives and measurement requirements, and lists the resulting payload and mission functional requirements. The COMCUBE-S mission concept fully meets these requirements.

Table 1: Science Traceability Matrix for defining the payload and mission functional requirements.

Main Science Goal	**Detailed Science Objectives**	**Scientific Measurement Requirements**	**Payload and Mission Functional Requirements**
Improve our understanding of astrophysical jets so that GRBs can be used as standard candles in cosmology	• Determine the jet composition (matter or B-field dominated) • Determine the jet magnetic field structure (turbulent or ordered) • Determine the jet energy dissipation process (internal shocks or reconnection) • Determine the prompt emission mechanism(s) (synchrotron, inverse Compton) • Determine the jet physical parameters (bulk Lorentz factor, opening angle, amplified B-field, fraction of accelerated electrons...)	• Measure the prompt emission spectrum and light curve of more than 600 GRBs • Measure time-integrated polarisation of more than 60 GRBs with an MDP < 30% • Measure time-resolved polarisation of more than 12 GRBs • Enable rapid follow-up observations for multi-wavelength and multi-messenger astrophysics	• Field of view: 4π • Alert latency: 10 - 30 s after trigger • Absolute time accuracy: 10 µs • Energy range: ✓ 60 - 500 keV for polarimetry ✓ 30 keV - 10 MeV for spectroscopy • Localisation accuracy: ✓ < 5° for GRB polarimetry ✓ < 2° for 120 GRBs per year for rapid follow-up observations • Polarisation sensitivity: MDP < 30% for long GRBs with $F > 10^{-5}$ erg cm^{-2} • Mission duration: 2 years of the full constellation after commissioning

2 Mission Concept

COMCUBE-S is a constellation of 12U CubeSats that detect GRBs and measure their spectral, temporal and polarisation properties. They also determine GRB positions on the sky and provide fast notifications for follow-up observation by other facilities. The primary payload on each CubeSat (Figure 3) is a Compton telescope which includes 8 double-sided silicon strip detectors (DSSDs) arranged in two layers (D1), 16 scintillator detectors (D2A) underneath the DSSDs and 8 scintillator detectors (D2B) on the sides of the instrument. It detects single-interaction events (gamma rays fully absorbed in one detector) in an energy range of 30 keV – 2 MeV, which are used to detect GRBs, measure their spectra and temporal profiles, and double-interaction events (Compton scattered gamma rays) in an energy range of 100 keV – 2 MeV, which are used for polarisation measurements and imaging. The secondary payload is a bismuth germanate (BGO) spectrometer which extends spectral measurements up to 10 MeV. The satellites operate in zenith-pointing mode to provide maximum Compton effective area for sources not occulted by Earth.

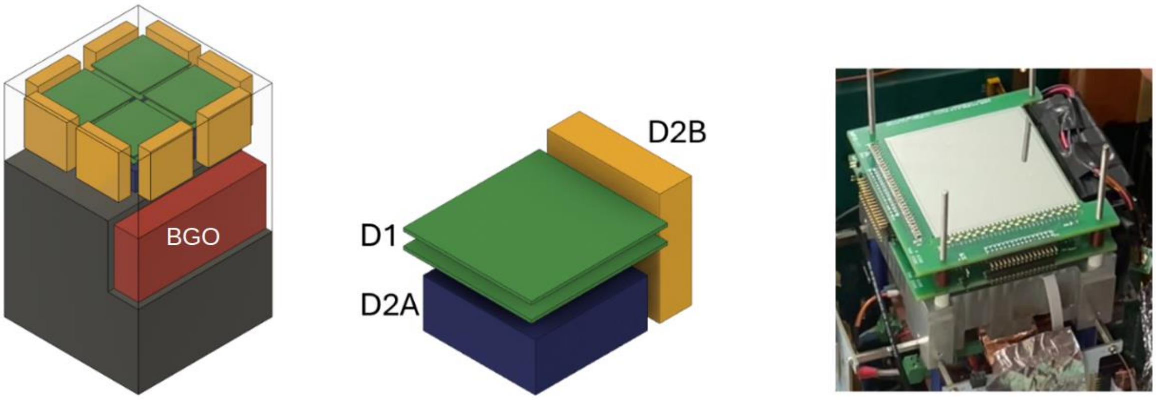

Figure 3: Left – Schematic image of a COMCUBE-S 12U CubeSat with a Compton telescope on top and a BGO spectrometer in the middle. Centre – One quarter of the Compton telescope showing a block of four D2A detectors under two DSSD layers. Right – photograph of a one-quarter prototype which was recently flown on a high-altitude balloon.

The Compton telescope on board each satellite has a large field of view that spans the entire sky. By simultaneously observing the same GRB, all satellites work together as a single distributed telescope with a large effective area. The satellites will perform gamma-ray background observations continuously, which will be stored onboard as time-tagged single-photon event data, regularly downlinked to the ground using an S-band link to two ground stations and sent to the science operations centre. A third ground station will be used for spacecraft and orbit maintenance by the mission operations centre. This is illustrated in Figure 4.

The satellites will also autonomously exchange observation information in real time, expecting a high intensity gamma-ray burst against the recent background rates. The satellites will continuously share their observed gamma count rates to detect a simultaneous increase on multiple satellites, which allows detecting fainter GRBs than ever. Once a potential GRB detection is established, all satellites are notified, and the operations enter into a trigger alert period autonomously. The satellites form a data link chain and rapidly relay their selected observation data to a master satellite, which is *ad hoc* selected being in the most favourable position above a ground station. The appointed master satellite will downlink the data of all satellites to the ground using an S-band link.

The downlinked data is then processed immediately by a high computing power science data centre to determine the sky coordinates of the source and other relevant parameters for immediate observation follow-up by ground telescopes and other facilities. With every localization, the science data centre sends an alert to its partnering follow-up ground observation facilities within the GCN or a similar collaboration.

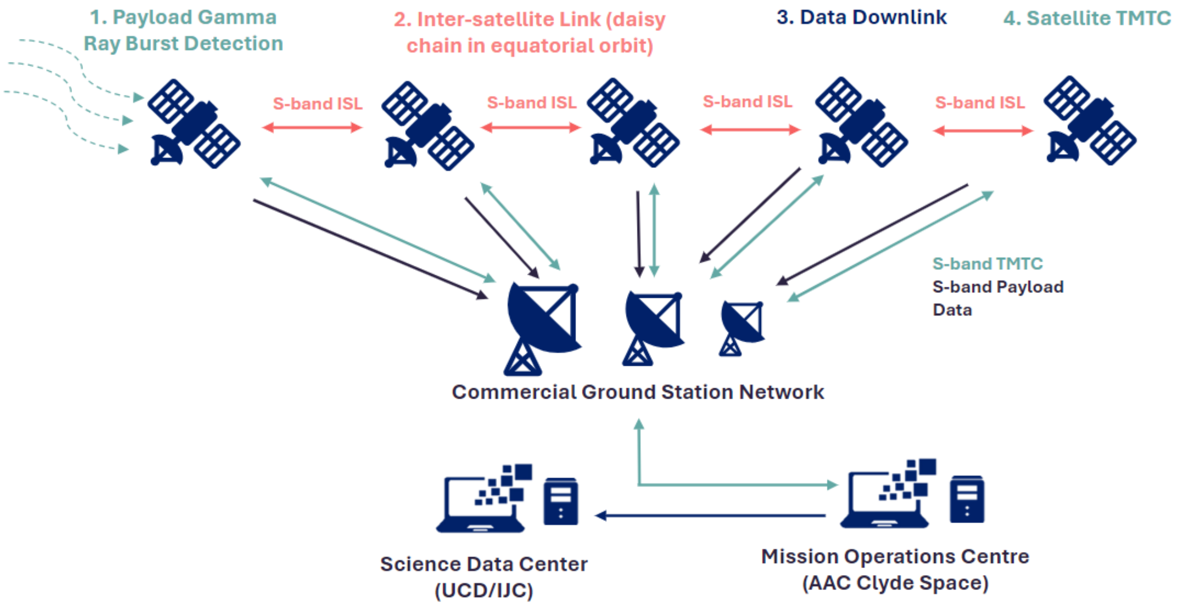

Figure 4: Representation of the concept of operations of the COMCUBE-S swarm.

The GRB localisation is first obtained from the detector count rates on all satellites which are sensitive to the source position. Localisation using Compton imaging and the pseudo-range multilateration method based on time delay measurements will be used to increase the reliability and accuracy of the results.

A great advantage of a distributed, intelligent CubeSat swarm gamma-ray observatory as opposed to a single large satellite mission is that the swarm is replenishable and scalable, has graceful degradation, and new swarm members with improved performance or new instruments can be added for continuous, maintained learning and improvement, with a significantly lower development and maintenance cost.

3 Payload

Each COMCUBE-S spacecraft carries a Compton telescope built using novel detector materials and components. This instrument is optimised for Compton polarimetry by extending the D2 absorption detector layer by introducing a ring of additional detectors around the perimeter of the D1 scattering layer. This geometry gives a more effective polarimeter by enhancing the efficiency of the detector for Compton events where the incoming photon is scattered close to 90°.

The D1 scattering layer in the COMCUBE-S Compton telescope is made of novel double-sided silicon strip detectors (DSSDs). Single-sided silicon strip detectors have extensive heritage in space missions, but with DSSDs, segmenting both the anode and cathode into orthogonal strips gives full positional information from a single photon interaction event, unlocking the ability for silicon detectors to be used in Compton telescopes.

The COMCUBE collaboration have been working toward the goal of designing, building, and launching a Compton telescope on a CubeSat platform by performing extensive simulations and building prototype detectors. Having achieved the milestone of demonstrating a prototype detector on a high-altitude balloon flight, this work has reached a level of maturity where a CubeSat version is within reach. This study has seen the development and expansion of that prototype to a full-scale CubeSat design.

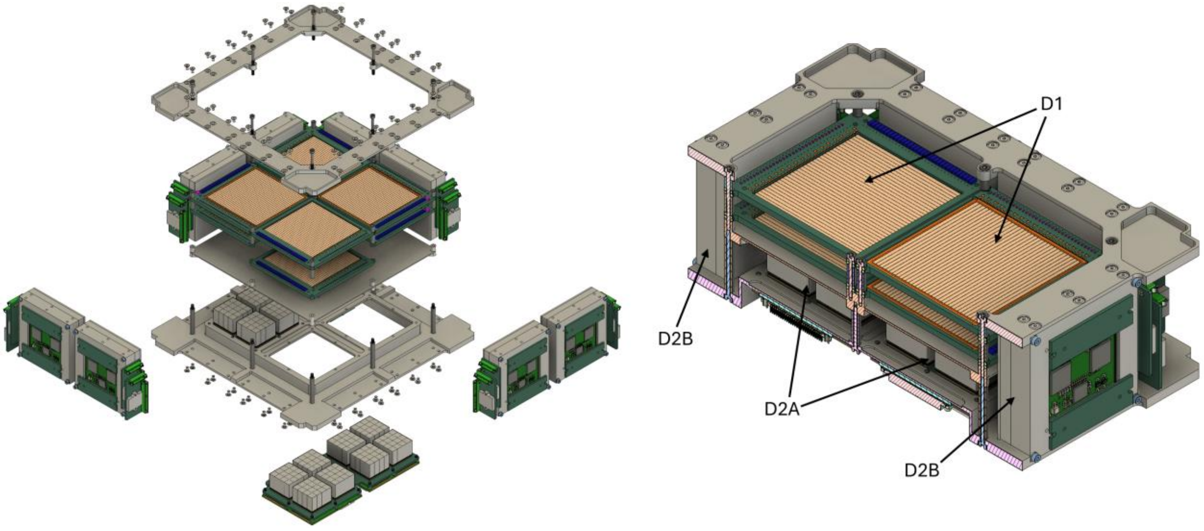

Figure 5: Left – Partially exploded isometric view of the COMCUBE-S Compton Telescope Unit. Right – Cut-away cross-section of the COMCUBE-S CTU showing the various constituent detectors.

The primary payload component, the Compton Telescope Unit (CTU) is shown in (Figure 5). It features:

- a D1 scattering layer comprising eight 64×64 mm^2 DSSDs in a 2×2×2 layout,
- a D2A bottom absorption layer with sixteen 25×25×15 mm^3 segmented gadolinium aluminium gallium garnet scintillators coupled to SiPM arrays for readout,
- and a D2B side absorption layer with eight 50×50×5 mm^3 cerium bromide scintillators coupled to SiPMs for readout.

Each spacecraft also carries a 50×50×150 mm^3 bismuth germanate scintillator as a high energy spectrometer.

4 Spacecraft

The initial baselined solution to meet the mission and payload requirements was AAC Clyde Space’s EPIC 8U form factor spacecraft however the subsequent study concluded that AAC Clyde Space’s EPIC 12U spacecraft is required to accommodate the payload as well as the necessary swarming enabling technologies such as ISL and propulsion.

The baselined platform is being developed as part of the xSPANCION program funded through the European Space Agency (ESA)'s ARTES Pioneer Partnership Projects. The COMCUBE-S 12U spacecraft is shown in Figure 6 and detailed Table 2.

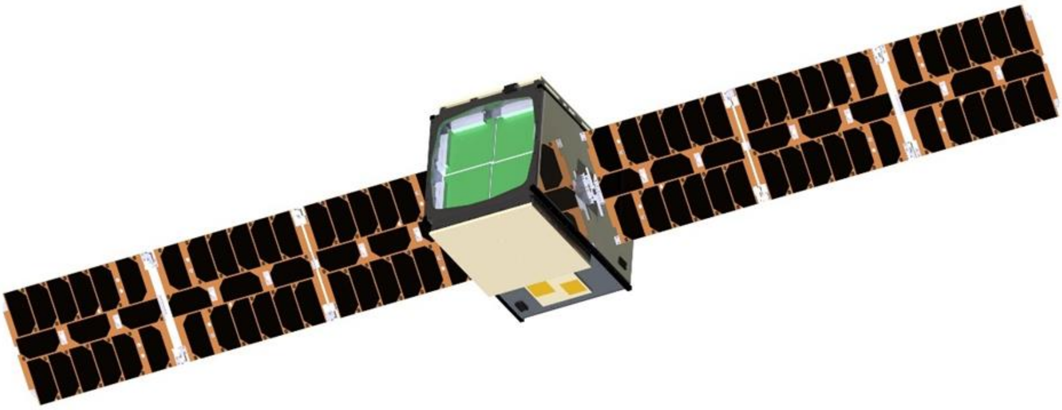

Figure 6: Illustration of design concept for the COMCUBE-S 12U Spacecraft.

Table 2: COMCUBE-S 12U Specification

Parameter	Value
Platform Form	12U
Power Generation	Deployable articulated solar arrays*, 48 W minimum OAP in 500 km equatorial orbit
TMTC/Payload Data Link	S-band
ISL Data Link	S-band
Payload	Compton Telescope Unit, Bismuth Germanate Scintillator Spectrometer
Propulsion	Electric (metal plasma thruster)
*Figure 6 shows the GOMSPACE 3-panel NanoPower TSP	

5 Expected Results

Over the mission lifetime, **COMCUBE-S will detect over 60 GRBs with an excellent sensitivity to polarisation, enabling the main models of GRB prompt emission to be**

distinguished. Breakthrough data on the distribution of energy between matter and magnetic fields within GRB jets and the contribution of photospheric radiation will be obtained from measurements of the variation of the polarisation properties during the GRB prompt emission. These measurements will provide a unique way of studying the geometric structure of ultra-relativistic jets. **COMCUBE-S will be able to perform detailed time-resolved polarisation measurements for more than 8 GRBs per year.**

The swarm architecture of COMCUBE-S enables all-sky coverage and rapid bursts alerts with accurate source localisation. These alerts will make it possible to identify in several GRBs the reverse shock cogenerated in the ultra-relativistic jet as it collides with surrounding material. Together with the unprecedented polarisation capability of the swarm mission, **it will provide the most complete view of the GRB prompt phase ever obtained**.

The coming decade will see the simultaneous operation of cutting-edge observatories, operating at all wavelengths and messengers. The timely and accurate burst notifications which COMCUBE-S will send to the GCN network will **enable the best use to be made of these observatories for the study of GRB afterglows, promising major discoveries from coordinated multi-wavelength campaigns.**

In addition to providing alerts which enable cutting edge GRB science, **COMCUBE-S will allow for rapid follow-up observations of other high-energy sources**, including active galactic nuclei, microquasars, soft gamma-ray repeaters, cataclysmic variables, and X-ray binaries. Additionally, polarimetric observations of sources such as flaring blazars, pulsars, and solar flares by COMCUBE-S, coupled with observations at other facilities, will shed a new light on these sources.

6 Summary & Outlook

The results from this study demonstrate a compelling and ground-breaking science case for high energy astrophysics that can be realised within the programmatic constraints by a swarm of 27 12U spacecraft. The mission will provide breakthrough measurements of GRB polarisation in a large sample, that will undoubtedly lead to a new physical understanding of the sources and environments of GRBs, allowing them to be used as standard candles for cosmology.

The scientific vision encompasses both a standalone capability for GRB temporal, spectral and polarisation measurements of a large sample of events, as well as acting a rapid relay of information to enable ground and space-based follow-up observations to track the early and late-time multi-wavelength afterglows.

COMCUBE-S will play a key role in the emerging field of multi-messenger astrophysics as well. Many of the current fleet of high energy astrophysics missions are at, or near the end, of their operational lifetimes, further reinforcing the need for a GRB mission operating later this decade in concert with gravitational wave and neutrino observatories. Furthermore, COMCUBE-S will be capable of detecting other types of high-energy transient sources, both galactic and extra-galactic, and will therefore have a significant impact more broadly in the field of time domain astronomy.

COMCUBE-S swarm will be a pioneer in building the capability to systematically produce fast alert notifications by implementing new aspects of inter-satellite links and computing. The payload concept is highly innovative by virtue of its high level of integration and compactness compared to traditional Compton Telescopes. The key technology elements have significant heritage already and the team is deeply expert in their use and application in high altitude balloon and space instruments.