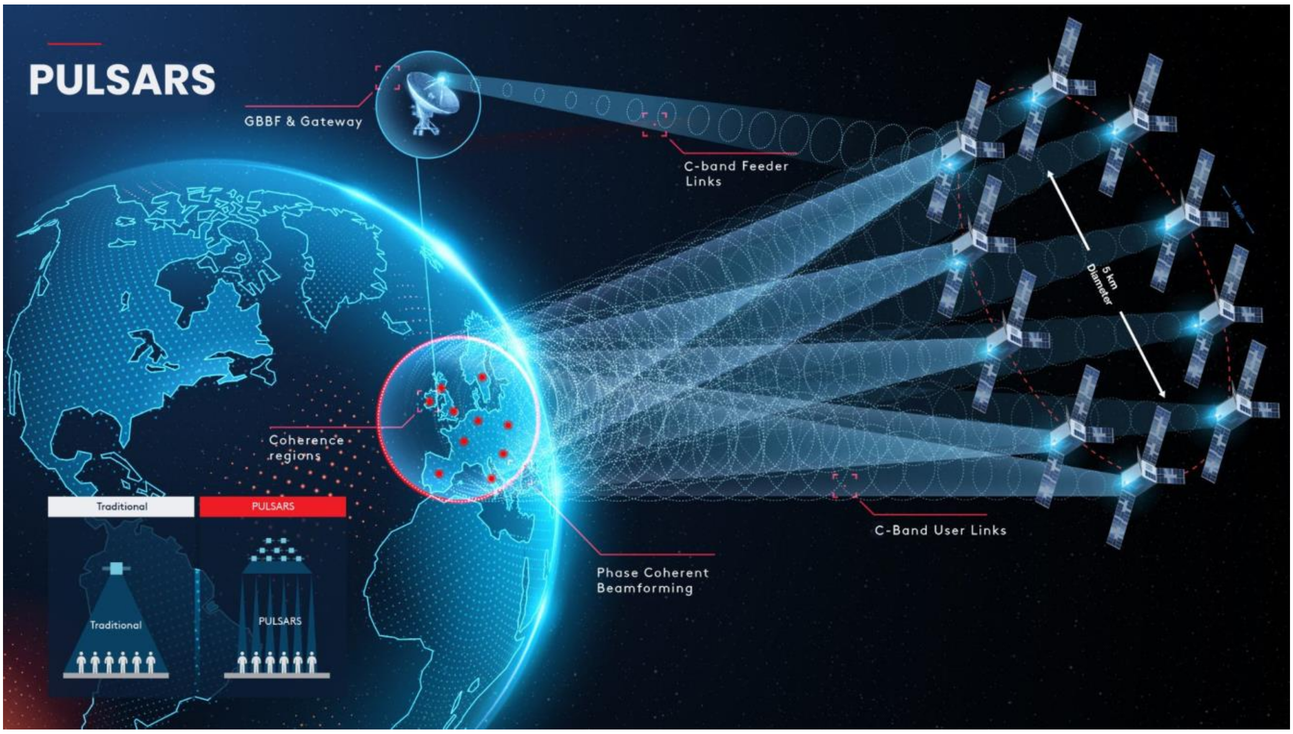
→ PREPARATION



PULSARS swarm (Precision Ubiquitous Low-cost Synthetic Aperture Regional Satellites)

Executive Summary

<u>SysNova Systematic Study</u>

Innovative Mission Concepts Enabled by Swarms of CubeSats

Affiliation(s): Satellite Applications Catapult, Open Cosmos

Activity summary:
In this project, a feasibility study for the PULSARS geostationary CubeSat system has been carried out. This involves the definition of a public protection and disaster relief use case using the satellite C-band, evaluation of a 16U CubeSat platform, and investigation into the spacecraft and ground segment technology required for coherent beamforming using a swarm of 20 independent spacecrafts. PULSARS mission design and system architecture are proposed, as well as a programme of technology development, enabling the spacecraft to operate for a minimum of three years. Remaining technological and regulatory challenges have been identified to validate the system concept further.

→ THE EUROPEAN SPACE AGENCY

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Table of Contents

1. Introduction 3
   1.1. Background and Context 3
   1.2. Objectives and Scope 4
2. Key Findings 5
   2.1. Mission Feasibility Study 5
   2.2. System Concept Definition 6
   2.3. Key Technology 7
3. Conclusion 8
   3.1. Project Summary 8
   3.2. Recommendations 8

1. Introduction

1.1. Background and Context

PULSARS is a novel geostationary satellite communications system, formed of a swarm CubeSats operating in close proximity, and intended to serve a public protection and disaster recovery (PPDR) use case. The system's altitude of approximately 36,000km means that it is able to serve a wide geographic area, and the 10km diameter of the formation enables tight user beams to be formed, in the order of a few hundred metres in diameter.

The system makes use of ground-based beamforming (GBBF), wherein time delays are applied to individual satellite signals based on the slightly varied path lengths through each satellite to the user, meaning that most of the complexity is situated at the ground station, enabling relatively simple satellites to be used.

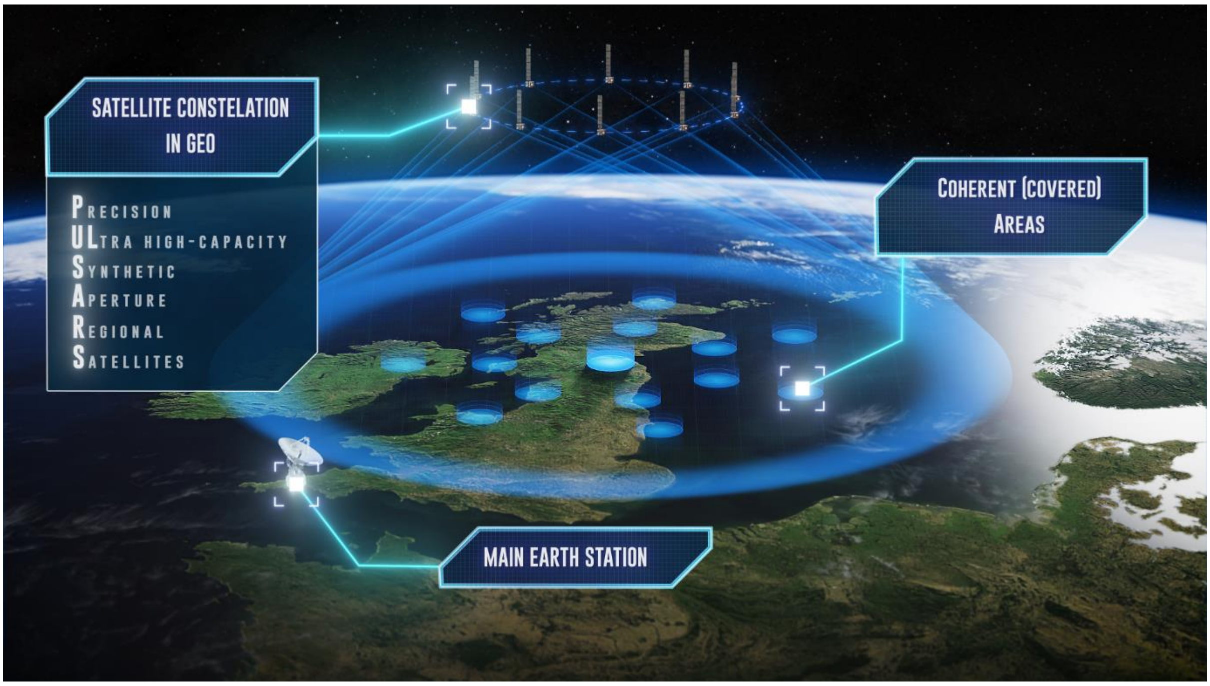

Figure 1: Artistic redemption of PULSARS system design

The 20 16U-CubeSats envisioned for use in the PULSARS system possess fully transparent payloads, meaning that no processing or correction of signals is carried out onboard, and that they simply forward the signal to users after frequency conversion.

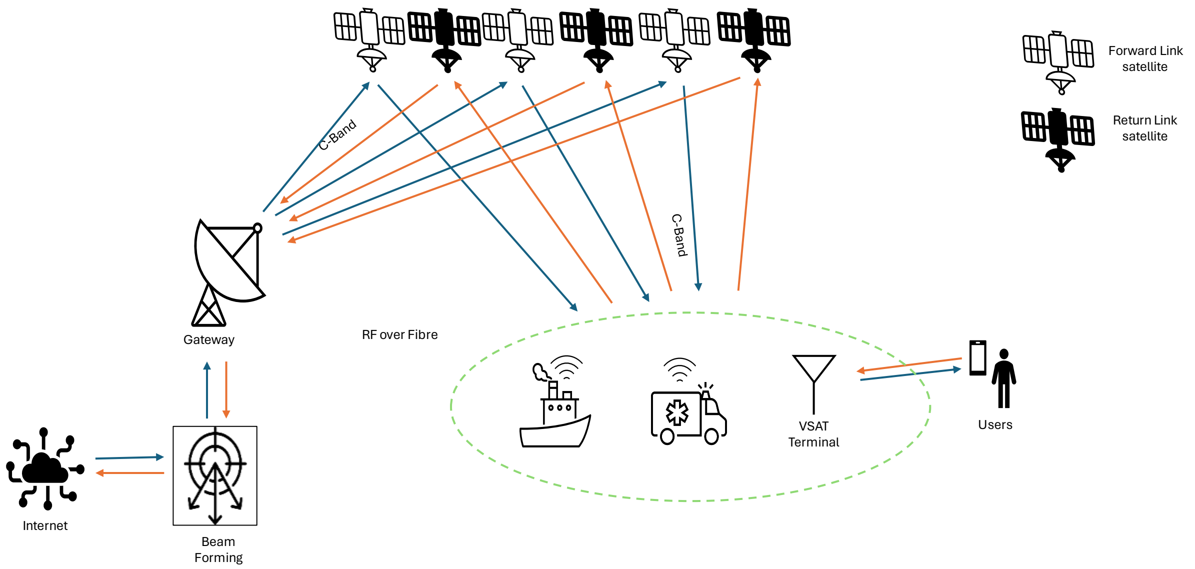

Figure 2: Overview of PULSARS system architecture.

Due to the limited mass, volume and power available in a 16U-CubeSat, the satellite swarm is split into two groups of 10 spacecraft each, serving the forward and return links respectively. For the sake of simplicity and economies of scale, the hardware onboard these two groups of satellites are identical, and only differ in the specific up- and downlink frequencies they operate.

The development of this system was carried out by a partnership between Satellite Applications Catapult and Open Cosmos. These two organisations have leveraged their expertise in satellite communications technology and space mission planning to develop this novel satellite concept, for deployment by 2029.

The PPDR use case was selected due to the need for secure, resilient communications in scenarios where terrestrial infrastructure may not be functional. This will help emergency services to coordinate response efforts and ensure that they are able to maintain communication within a small geographic region.

Moving forward, it will be possible to scale up the satellite swarm with additional, potentially larger satellites to increase the capabilities of the system further, with more satellites able to deliver higher aggregate power, increasing the signal strength at the user, or enabling more users to be served simultaneously.

1.2. Objectives and Scope

The high-level objective of this project is to demonstrate the technical feasibility of the proposed satellite swarm system, within a total projected mission budget of €100M. This involved an analysis of the CubeSat platform including the volume available for hardware components, the power that can be generated, thermal management of the spacecraft, and an investigation into the GEO radiation environment, which is much harsher than that in low Earth orbit (LEO). In tandem with this analysis, the possible communications payloads were also assessed, with a focus on simplicity in order to reduce the cost of the spacecraft, enabling more to be built and to locate the majority of system complexity at the ground site.

In terms of the in-depth technical exploration carried out, the key technology of GBBF was derisked by investigating the processing requirements at the ground station, and the timing stability requirements on the entire system chain.

Larger systematic and programmatic elements of the system were also investigated, including a proposal for the mission lifecycle through development, demonstration, launch, deployment, operation and end of life. This was bounded by the requirements set out in the OSIP CubeSat Swarm campaign definition for cost and deployment timeline, so the readiness of identified key technologies was crucial to the meeting of these constraints.

This outlined the scope of the work to be carried out, and guided the technical analysis summarised in the following sections.

2. Key Findings

2.1. Mission Feasibility Study

The initial requirements set for the satellite swarm system involved a restriction to 16U, 32kg satellites. This was determined to be a minimum viable size of the individual spacecraft due to the equipment required for communications and power generation and handling, and the additional radiation shielding required for the GEO environment. It was due to these constraints that the forward and return link of the communications service were split into separate satellites, with each link using 10 of the 20 total spacecrafts in the swarm. A proposed satellite form factor with a stowed volume of 20cm × 20cm × 40cm, and deployable antennas and solar arrays is seen in Figure 3.

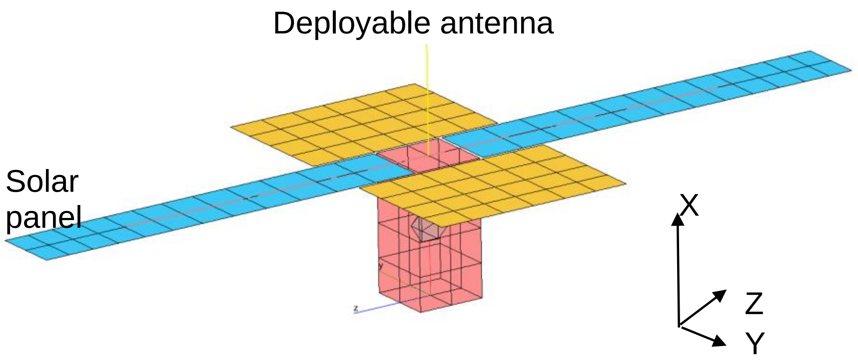

Figure 3: Proposed satellite form factor.

It was also specified that it would be possible for the satellites to be deployed from an available commercial deployer, meaning that the standard 16U configuration shown above was selected, though alternatives were considered. Further analysis will be required to identify a space vehicle capable of delivering this many satellites to GEO and deploying the swarm, available by a date in line with the programme plan.

The need for this additional radiation shielding adds to the mass and volume requirements of the satellites when compared to LEO CubeSats, and it was found that, when including 20% margins, the payload and platform systems required would take up 32.62kg and 15.22U of mass and volume respectively. It was therefore concluded that it is feasible for the requirements for these parameters to be met, with some careful management of the mass.

The quantity of power possible to be generated onboard a 16U CubeSat was also a significant constraint on the system development; there is very limited space for solar arrays and batteries, and as the system is intended to operate for 100% of the time (excluding time when the satellites are in the shadow of the Earth), there is limited ability for power reserves to be built up. It was determined that the peak power generation possible is likely to result in very limited power remaining for non-payload operations. It is therefore suggested that developments are required in payload efficiency and power generation capability.

2.2. System Concept Definition

In order to define the system concept of operation, the modes of operation were first defined, being split into channel sounding and communication mode. Channel sounding is a key element of the proposed system, used to measure and update the signal path from the gateway to each user, through every satellite. The initialisation and maintenance of this data will be aided by a number of terminals placed at fixed key locations across the service area. These measurements are important in order to maintain the coherence of incoming signals at the user, so that the multi-satellite signal can be detected. The communications mode of operation is illustrated in Figure 4, showing the formation of coherence at the user, having used the channel sounding measurements to apply time and phase shifts at the ground station.

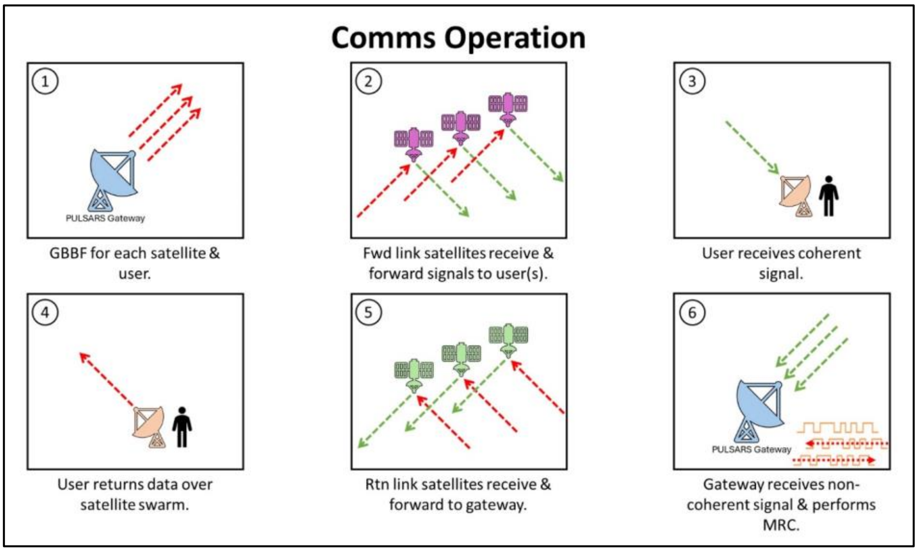

Figure 4: Communication mode of operation.

A link analysis was subsequently carried out to determine the data rate possible to be delivered to service users, using available data and assumptions on the space, ground and user systems. Assuming minimal coherence losses and an antenna gain of 24-30dBi, it was determined that a data rate of 80.8 Mbps is possible to be delivered to each of 10 users. This is sufficient for the transfer of non-live video, image and text information over the system, suitable for the PPDR use case.

Due to the gain requirements derived from the link analysis, a fold-out array was selected for preliminary design of the system, due to its small form factor when stowed and low complexity of deployment when compared to other options.

The results of forming coherence using a satellite swarm of 10km diameter in a modified ring formation is seen in Figure 5.

The resulting coherence region is only a few hundred metres in diameter, far smaller than that possible with a traditional, monolithic satellite system. There are areas of repeated power outside of the user service region which may result in increased interference with other users of this or other systems, which is a risk which will need to be mitigated. It should be noted however that very few of these areas exceed half power of the beam centre, and due to the low link margins at the user, this may not have a significant effect. Further analysis integrating antenna patterns and mitigation techniques will be needed to verify this.

An investigation was also carried out into random timing errors in the system introduced by elements such as the ground segment and satellite clock stability and unaccounted for atmospheric effects. It was found that the overall acceptable timing error is expected to be below 50ps for operation in C-band, which placed a high requirement on the payload performance.

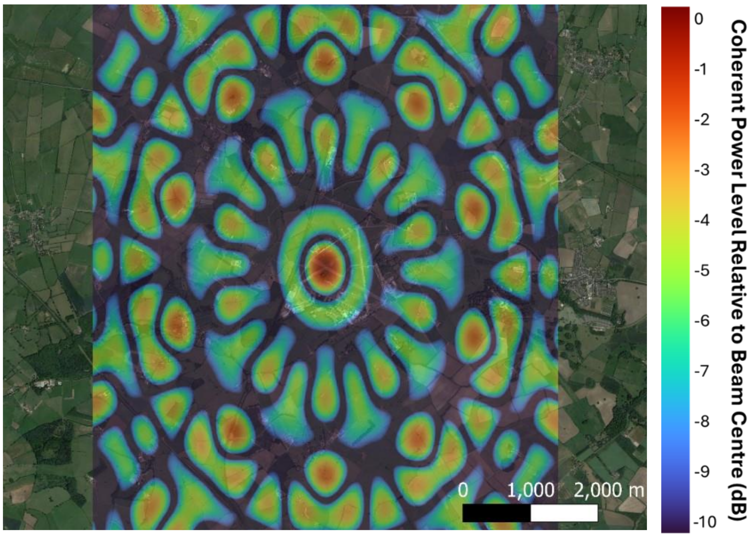

Figure 5: Coherent beam footprint analysis.

2.3. Key Technology

The technology used onboard the satellites is intended to be kept as simple as possible, with only frequency conversion and signal amplification taking place onboard. This is to reduce the cost of the space segment and reduce the need for unproven technology to handle the synchronisation necessary for coherent beamforming. It is intended that the payloads will use as much commercial off the shelf (COTS) equipment as possible, with minimal customisation for exact frequency tuning. All the hardware intended for use onboard the spacecraft will require radiation and thermal testing to ensure that they are rated for the operational environment.

At the ground segment, the front end of the ground station will be standard for a satellite communication system, with a parabolic dish antenna used to communicate with the PULSARS satellites. The novelty of the system occurs in the GBBF processing in the back end, where high-speed digital computing hardware will be needed to split the user signals and apply the necessary transformations to them, with knowledge of the user signal paths through each satellite. Separate radiofrequency chains will be required for each satellite due to the slightly different frequencies on which they operate, which although acceptable for a 10 forward link satellite architecture, may introduce problems with size, power and heat at the ground station with larger swarms. Considering the 20-satellite swarm suggested here, the digital processing is thought to be the primary hardware development challenge in the ground segment.

Ideally, the system will be developed with the assistance of an existing operator of GEO satellites, bringing expertise in ground station operations, and granting access to an established site, as well as the limited GEO orbital and frequency rights. These form a key regulatory challenge to the proposed system and will be vital to the realisation of PULSARS.

3. Conclusion

3.1. Project Summary

A primary objective of this project was to establish and test assumptions relating to the design and operation of a swarm formation of CubeSats in GEO and to serve a specific use case. As a result, we have established the performance capabilities of the system as well as the constraints and limitations. This performance assessment and the resulting system design, supports the operation of VSAT services for the public protection and disaster recovery "PPDR" community.

Using an iterative process of assessment, a number of significant changes have been made to the original design concept. This includes the choice of spectrum to be used which has been changed from S-band to C-band for the user-links to optimise the system performance and throughput in the selected use case. Additionally, the feeder link spectrum has been changed from ka-band to C-band to simplify the transponder and antenna design. Another significant design change is the single purpose use of satellites for either a forward transmit function or a return receive function. This is a unique proposition for satellite communications, driven by the limitations and constraints of using CubeSats. Another area of knowledge development is in the choice of waveform for the service which shall now be based upon 5GNR. This will permit ease of integration with user terminals that will increasingly be 5G-compatible in the future.

The project has also determined the optimum power budget for payload, propulsion and station keeping for a 16U platform and in turn the lifetime and graveyard requirements. Other aspects include a greater knowledge of the launch vehicle and orbit transfer requirements.

More generally, this study has qualified the concept of a swarm of CubeSats in GEO and the concept of forming ground coherence regions using this array of spacecraft as well as signal generation and acquisition. These results could be used to inform other similar systems utilising clusters of spacecrafts flying in close proximity.

The use of CubeSats as a basis for operating a swarm of satellites in GEO orbit is challenging. However, the work done in this project has resulted in a workable system design that retains many of the unique and compelling features of the PULSARS concept and which in turn, lends itself well to the PPDR use case. The sparse array formation creates a regional aperture that results in a tight and narrow coherency coverage area which is ideal for agile, secure and targeted communications. Additionally, the PULSARS system can scale to match the demand profile. This project has resulted in a greater level of confidence in the feasibility of the PULSARS design concept.

The results of the project provide a high level of confidence that a VSAT service for the PPDR community is feasible and would provide some key advantages over current and alternative systems. These include the ability to create communications channels anywhere in the coverage region at short notice and under crisis and disaster conditions. In general use, this service extends the reach of PPDR operations, to remote and isolated areas that are not covered by terrestrial cellular services including coastal boundaries. Additionally, this service can track terminals on the move ensuring additional vehicle and aircraft connectivity, when and where needed. Whereas there is an existing supply chain of low-cost C-band VSAT terminals and modems that could be used immediately, the option of using 5GNR MODCOD means that terminal equipment will be more flexible, more readily available and more cost effective in the future.

3.2. Recommendations

Future work on the PULSARS system is suggested to include the further development of technologies critical to the system design. These have been specified throughout the report, and at a high level cover the rating of CubeSat hardware for the geostationary operational environment, and the validation of the ground system data processing required to perform GBBF, confirming that the number of digital signal processing channels required for the system is possible with the necessary timing accuracy. Another key area of study will be modelling the orbit of the proposed satellite swarm, including deployment, operation, and end-of-life manoeuvres.

Feeding into all future work is the need to procure hardware for validating space, ground, and user segments, operating with the chosen frequency bands and waveforms. Following on from and in concert with hardware development, it will be necessary to initialise a partnership with an existing operator of GEO satellites, enabling access to ground equipment such as a satellite gateway, and more importantly the geostationary orbital and frequency rights.

It will later be possible to explore the expansion of the system to additional use cases and with the supplementation of the system with a greater number of satellites, maintaining and expanding the service capabilities past the initial three years.