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A Distributed Space-Weather Sensor System using Small Satellites

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Abstract

Space weather is becoming increasingly important for space and terrestrial activities and is likely to transition to an operational service. Small satellites are ideally suited for space-weather measurements given the need for making simultaneous measurements across both small and large volumes of space. The "Nanosatellites for D3S" Phase 0/A study for ESA was initiated in early 2021 with the objective to assess the feasibility of using nanosatellites for future operational space weather monitoring missions in near-Earth space as part of ESA's Distributed Space Weather Sensor System (D3S) - which itself forms part of the wider ESA Enhanced Space Weather Monitoring System. The study team consortium is highly experienced including sub-contractors supporting SSTL from MSSL, Imperial College London, and VZLU. Surrey Space Centre and Northumbria University are also providing expert consultancy.

In the first part of the Phase 0 study, a survey of the measurement requirements and potential space weather instruments was carried out, alongside an investigation into recent relevant nanosatellite missions and future nanosatellite technologies. This was followed by an analysis and trade-off of high level mission architecture concepts eventually converging down to two of the most promising mission architecture concepts, which were further analysed in the latter half of the Phase 0 study.

The objective of the first Phase 0 mission architecture concept was to provide near-real time measurements of radiation, thermal plasma and Ionospheric neutrals/plasma, via a constellation of 20x SSTL-21 satellites, in a single LEO orbital plane. The objective of the second Phase 0 mission architecture concept was to provide near-real time measurements of radiation, the Ionosphere and the Thermosphere, via a constellation of 6x 16U SSTL-Cube satellites, in a single LEO orbital plane. The orbit selected for both missions was a 500-600km Sun-Synchronous LEO Orbit with an LTAN of 10:30am. Both missions assumed an operational in-orbit spare satellite. The estimated launch date assumed for the missions was 2025.

The Phase 0 study was completed in March earlier this year, with ESA selecting the second mission architecture concept to take through into the Phase A study, which kicked off straight after completion of the Phase 0 study. This paper mainly describes the details of the Phase 0 study, as well as touching on the current status of the Phase A study.

Keywords: Nanosatellites, Space Weather, SSTL-21, 16U SSTL-Cube

Acronyms/Abbreviations

AOCS: Attitude and Orbit Control System
BGAN: Broadband Global Area Network
D3S: Distributed Space Weather Sensor System
DHS: Data Handling System
DRAMA: Debris Risk Assessment & Mitigation Analysis
EFF: Earth Facing Facet

EOL: End-Of-Life
ESA: European Space Agency
GEO: Geostationary Orbit
GPS: Global Positioning System
GTO: Geostationary Transfer Orbit
HEO: High Earth Orbit/Highly Elliptical Orbit
ISL: Intersatellite Link
KSAT: Kongsberg Satellite Services AS
LEO: Low Earth Orbit
LTAN: Local Time of Ascending Node
MEO: Medium Earth Orbit-
OAP: Orbit Average Power
RTE: Real-Time Earth
SFF: Space Facing Facet
SSTL: Surrey Satellite Technology Limited
TM/TC: Telemetry/Telecommand
TRL: Technology Readiness Level

1. Study Overview

Space Weather describes the variations in the space environment between the Sun and the Earth. Space weather can negatively affect systems on and around Earth including: Spacecraft (and astronauts), aircraft and ground based infrastructure. ESA is currently developing the Enhanced Space Weather Monitoring System to monitor Space Weather between the Sun and the Earth. Part of this will include a “Distributed Space Weather Sensor System” (D3S) with the objective to address “near-Earth” observations in LEO, MEO, GEO and HEO.

Space weather instruments are generally very small with modest mass, power, size and data rate resource requirements, which enables the possibility for implementation on very small and low cost satellites. Additionally, advances in the miniaturisation of spacecraft technology means that very small satellites are now much more capable than they were 10-20 years ago. In turn, these two factors mean that multiple numbers of such satellites can be built and launched to provide highly capable, distributed space weather systems (e.g. constellations) with affordable mission costs. This can enable the possibility of regular multi-point measurement coverage around the required orbit(s). Therefore very small satellites (including nanosatellites) can be a vital resource to provide space weather measurements as an input to future space weather operational services. This stimulated ESA interest in the prospect of implementing such nanosatellites to provide near Earth observations as part of ESA’s D3S system. As a result, SSTL was selected to lead an 18 month ESA-funded Phase 0/A study titled “SSA P3-SWE-LIII Nanosatellites for D3S” and the Phase 0 study kicked-off in January 2021. The study objective was to assess the feasibility (including latency, lifetime, reliability etc.) of using nanosatellites for future operational space weather monitoring missions in near-Earth space as part of ESA's D3S System.
During the first part of the ESA D3S Space Weather Nanosatellites Phase 0 study, an analysis of the measurement requirements and potential space weather instruments was carried out, in parallel with an investigation into recent relevant nanosatellite missions and future nanosatellite technologies which could be used on future ESA D3S Nanosatellites. This was followed by an analysis and trade-off of a wide range of high level mission architecture concepts, eventually converging down to two of the most promising mission architecture concepts proposed for further study. These two mission architecture concepts (Mission Architecture 1 and Mission Architecture 2) were analysed and developed in further detail throughout the second half of the Phase 0 study [1] and [2].

Mission Architecture 1 was to provide near-real time measurements of radiation, thermal plasma and Ionospheric neutrals/plasma, via a constellation of 20 satellites using the SSTL-21 platform. Mission Architecture 2 was to provide near-real time measurements of radiation, the Ionosphere and the Thermosphere, via a constellation of 6 satellites using the 16U SSTL-Cube platform. The orbit selected for both missions is a 500-600km Sun-Synchronous LEO Orbit with an LTAN (Local Time of Ascending Node) of 10:30am and the satellites will be evenly spaced around a single LEO orbital plane; both missions assume an operational in-orbit spare satellite. The estimated launch date for the missions is currently 2025. An overview of the Phase 0 study work flow is presented in Figure 1-1.

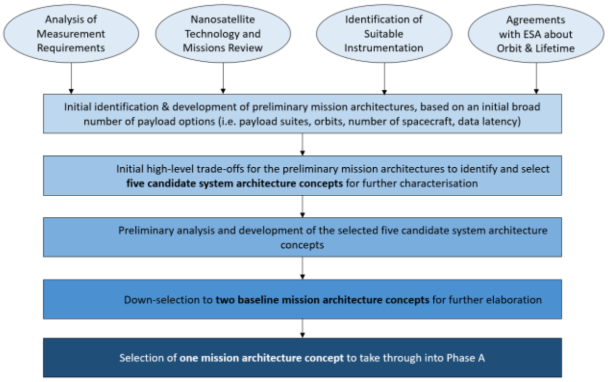

Figure 1-1: Phase 0 Study Work Flow

The consortium for the study is highly experienced including sub-contractors supporting SSTL from the Mullard Space Science Laboratory (MSSL) (UK), Imperial College London (UK) and VZLU (Czech Republic). The Surrey Space Centre at the University of Surrey (UK) and Northumbria University (UK) are also providing expert consultancy.

2. Measurement Requirements and Instrumentation Analysis

The measurement requirements for the D3S system were initially provided by ESA as part of the study. The requirements relate to all elements of the D3S system (hosted payloads, small satellites, nanosatellites). The measurement requirements cover a range of space weather effects including:

- Auroral Measurements
- Magnetospheric Charged Particle Measurements (high energy ion, mid energy ion, Suprathermal ions and electrons and thermal energy particles)
- Electromagnetic Field Measurements
- Ionospheric Measurements
- Thermospheric Measurements

As part of this study, the requirements were reviewed and updated where possible. The assessment of the measurement requirements was undertaken by comparing the stated requirements with existing instrumentation or existing knowledge of the measurables, comparing spatial resolution with orbital configurations, cadences and latencies, and by discussing with potential stakeholders their requirements for data availabilities for data assimilation into space weather models. The space weather data can largely be placed into three (overlapping) categories:

1) Alert data
- Needed in near-real-time and is therefore a driver of latency and coverage (~ 5 minutes)
- Some measurement criteria are designed to match current alerts and are only applicable at GEO

2) Data assimilation
- Needed on the timescale of model updates (radiation belt models ~ 1 hour; atmospheric models ~15 minutes)
- Coverage has local time as well as latitudinal dependencies

3) Database building/post event analysis
- Effectively no constraint on timeliness
- Higher quality measurements which are post-processed may be desired

The ESA D3S nanosatellites mission will provide data for operational services, and therefore the aim is to get full coverage within the required latency. This therefore becomes a major driver of the spacecraft system design. The descriptions of the measurement requirements provide information on the expected use of the measurements. By mapping the available instrumentation to the measurement requirements and comparing the various groupings of those requirements, it was possible to assess the appropriateness of the various instruments for the mission studies. The measurements were grouped together in different ways including by the Space Weather Effect measured, by measurement Timeliness and by measurement Cadence.

By reviewing recent public presentations, published literature and from discussions with direct contacts, a shortlist of 38 potential instruments was created that (a) are capable of making the necessary science measurements and (b) can also be accommodated on a nanosatellite. The instruments are all provided by organisations in ESA member states. The candidate instrument include: 2x Auroral instruments, 19x Radiation instruments, 2x Magnetometers, 4x Thermosphere instruments, 6x Ionosphere instruments and 5x Micro-particle instruments.

The 38 potential payloads were analysed and compared based on science topic/region of interest covered, measurement requirements covered, instrument specification (mass, power consumption, volume, data rate and Technology Readiness Level) and a down-selection to 10 candidate payloads was then made for use in the different Phase 0 Mission Architecture Concepts. The instruments all have a high Technology Readiness Level (TRL), suitable for a rapid development to launch.

3. CubeSat Technology and Missions Review

Recent years have seen rapid technology developments in the small satellite sector and there has been a significant increase in the capability of electronic technology as well as in the miniaturisation of components and equipment. Due to the underlying technology developments, nanosatellites (especially in the CubeSat form factor) have been able to take on more challenging tasks, moving from their traditional role as technology demonstrators, to being able to carry out far more complex commercial and scientific missions that would previously have required much larger spacecraft. This has sparked an interest in using nanosatellites for operational space weather services as part of the D3S infrastructure.

A review of the latest technology developments for nanosatellites was carried out during the Phase 0 study, covering all spacecraft subsystems as well as complete nanosatellite solutions. An investigation into nanosatellite missions of the last decade was also carried out, focussing on but not limited to those relating to space weather, as well as their reported achievements and “lessons learned”. The results of the technology review showed a large number of high TRL units and subsystems designed for use of nanosatellites, and that nanosatellite technology in general should be considered mature enough for operational services with low latency requirements. Furthermore, because of advancements in the area of nanosatellite propulsion systems, manoeuvres such as deployment/phasing and orbit maintenance for CubeSat and nanosatellite constellations is becoming more available. It has also been shown that inter-satellite links (e.g. communication between LEO and GEO satellites), as well as communication via ground station networks, can be implemented for a nanosatellite constellation in LEO. This is enabled by recent developments in all nanosatellite subsystems, namely communication and power systems, as well as in the increase of available on-board computing power, even on the smallest CubeSats.

4. Mission Architectures Trade-Off

In order to examine the trade-space of possible mission architectures during the Phase 0 study, a preliminary set of 20 mission architecture concepts was defined. To feed into this, a LEO orbit was agreed with ESA to be most suitable as a basis for all these mission architectures for a number of reasons:

- The science requirements can be met from LEO orbits,
- The majority of rideshare opportunities are to LEO,
- The radiation environment is more benign that MEO, GTO and GEO orbits.

Various considerations were made in terms of the architecture designs, including:

- Architectures that included all example candidate instruments;
- Architectures that ensured no overlap of measurement requirements;
- Radiation, Ionosphere/Thermosphere or Plasma only architectures;
- Low, medium and high power architectures;
- Low, medium and high instrument mass architectures.

Once the 20 mission architectures had been defined, requirements were derived on the system including the need for Inter-Satellite Links in order to meet the latency requirements, the need for instrument booms, and instrument accommodation requirements (e.g. pointing direction). This information was then used to feed into an initial trade-off to determine the most suitable platform size for each of the different mission architectures (either an 8U, 12U or 16U SSTL-Cube or the SSTL-21 platform). Further iterations and trade-offs were then carried out to narrow down the number of architectures initially down to 5, and then finally to 2 following further study (see Figure 4-1) which would be analysed in more detail throughout the second half of the Phase 0 study. Five different trade-off parameters were selected including:

- Mission Cost
- Complexity/Feasibility/Risk
- Use Case
- Number of Mission Requirements Met
- Latency

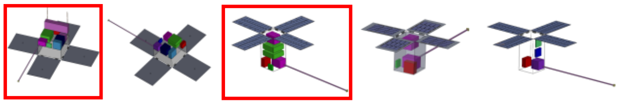

Figure 4-1: The initial 5 down-selected mission architectures which were eventually down-selected to 2 (highlighted by red boxes) for further analysis in the second half of the Phase 0 study

5. Key Requirements and Drivers for the Two Selected Mission Architectures

The two down-selected mission architecture concepts (Mission Architecture 1 and Mission Architecture 2) were analysed and developed in further detail throughout the second half of the Phase 0 study. Mission Architecture 1 is to provide near-real time measurements of radiation, thermal plasma and Ionospheric neutrals/plasma, via a constellation of 20 satellites using the SSTL-21 platform. Mission Architecture 2 is to provide near-real time measurements of radiation, the Ionosphere and the Thermosphere, via a constellation of 6 satellites using the 16U SSTL-Cube platform. Both mission architectures assume the use of an ISL via BGAN.

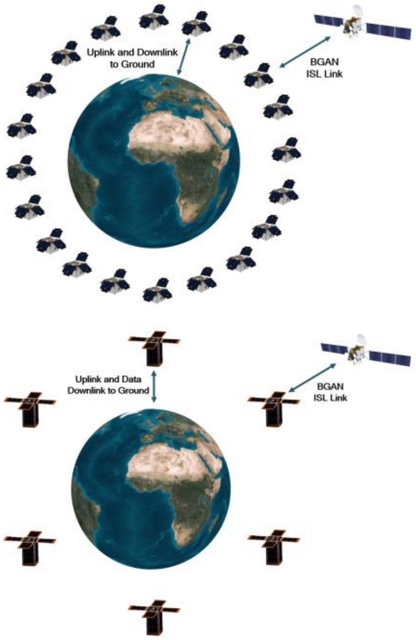

Figure 5-1: Mission Architecture 1 (top) and Mission Architecture 2 (bottom)

These two mission architecture concepts have a common set of key requirements and design drivers, which apply to both missions.

These key requirements and design drivers for both of the mission architectures include:

1. A latency of 5 minutes (on a best efforts basis) between payload data capture and payload data downlink
2. A nominal 3 year mission lifetime with a launch in 2025
3. Launch on a European launch vehicle
4. A circular LEO sun-synchronous orbit (LTAN of 10:30am) with an initial orbit altitude of 500-600km.
5. Payload resource requirements (mass, volume, peak power)
6. Payload accommodation requirements (a number of payloads needed to be positioned on particular facets of the spacecraft, with detectors pointing in certain directions)
7. 100% duty cycle power provision for the payload instruments
8. Redundant platform avionics

For Mission Architecture 1, it was assumed that measurements of the Ionosphere are required every 5 minutes around the entire orbital plane; this was the primary driver for needing 20 spacecraft in the constellation (19 operational + 1 spare). For Mission Architecture 2, it was assumed that radiation measurements are required every 5 minutes but measurements of the Ionosphere and Thermosphere can be acquired less frequently; these assumptions were the primary driver for needing 6 spacecraft in the constellation (5 operational + 1 spare).

6. Mission Architecture Concepts Overview

The following section provides an overview of the two mission architecture concepts that were selected following the architectures trade-off during the first half of the Phase 0 study.

6.1 Mission Architecture 1

Mission Architecture 1 consists of 20 spacecraft (19+1 operational spare) which fly in an evenly spaced constellation around a single orbital plane. The initial operational orbit is a 500-600km Sun-Synchronous orbit with an LTAN of 10:30am. Payload data downlink will be carried out via L-Band BGAN Intersatellite Link (ISL) to the Inmarsat Geostationary spacecraft with onward downlink to the Inmarsat ground stations, and also directly to the KSAT ground station network using S-band. It is assumed that telemetry and telecommand will be carried out via the SSTL Guildford ground station, or via another compatible ground segment (e.g. the Viasat RTE Network) using S-Band. An overview of Mission Architecture 1 is provided in Table 6-1.

Table 6-1: Mission Architecture 1 Overview

Mission Overview	
Mission Objective	Provide near real-time measurements of: Radiation (Solar Energetic Particles & Radiation Belts), Thermal Plasma, Ionospheric Neutrals & Plasma
Mission Lifetime	3 Years
Launch Date	Estimated 2025
Number of Spacecraft	20 (19 + 1 operational spare)
Orbit	500-600km Sun-Synchronous Orbit, 10:30am LTAN
Launch	Dedicated Vega-C
Payloads	Radiation Monitor (x2), Magnetometer, Plasma Monitor, Langmuir Probe (x4), GPS Receiver, Ion and Neutral Mass Spectrometer
Platform Type	SSTL-21 (an SSTL-Micro platform)
Spacecraft Mass	74.21kg (including unit and system margin)
Propulsion	Xenon resistojet system, 5.2kg of Xenon propellant, provides 30m/s delta-V
Power	72.8W OAP provided at End-of-Life, 14Ah Li-Ion battery
Communications	S-Band TM/TC, L-Band BGAN Inter-satellite Link
Redundancy	Fully redundant avionics, single string payloads

An overview of the payloads that have been baselined for Mission Architecture 1 is provided in Table 6-2. It has been assumed that all payload instruments on-board Mission Architecture 1 have a 100% duty cycle.

Table 6-2: Mission Architecture 1 Payload Overview

Instrument	**Measurement**	**Volume (mm)**	**Mass Without Margin (kg)**	**Power Consumption Without Margin (W)**	**Data Generation Rate Without Margin (kbps)**
Plasma Monitor	0-30 keV Electrons & Protons	130x130x140	2.35	1	0.3
Langmuir Probes	Electron density	122x61x109	0.95	11.25	16
Ion and Neutral Mass Spectrometer	Thermal, Oxygen, Nitrogen, Neutrals, Ions, velocity measured in heavier variant	100x100x50	0.3	1	0.5
Radiation Monitor (x2) and Magnetometer	0.3-8 MeV Electrons, 1 MeV - 1 GeV Protons, 100 MeV/n – 1 GeV/n ions, ±60,000nT magnetic field, 1 nGy/h – 6 Gy/h dose	96x96x119 (plus 800mm boom)	2 (2x1)	6 (2x3)	3.68 (2x1.84)
GPS Receiver	GNSS	95x70x43.2	0.5	5	1 (estimate)
		Total	**6.1**	**24.25**	**21.48**

Figure 6-1 provides an overview of the Concept of Operations for Mission Architecture 1. A dedicated Vega-C launch vehicle is the current baseline for this mission architecture concept. Upon release from the launch vehicle, the spacecraft will phase evenly around the orbital plane (each spacecraft separated by 18.9°).

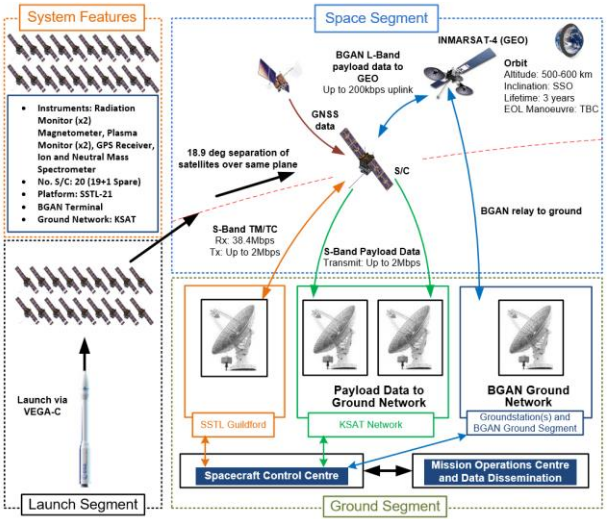

Figure 6-1: Mission Architecture 1 Concept of Operations (CONOPs)

6.1.1 System Budgets

An overview of the delta-V budget for Mission Architecture 1 is provided in Table 6-3. The budget takes into account the estimated delta-V required for launcher injection error correction, constellation phasing around the orbital plane, an allocation for 2 collision avoidance manoeuvres per year and any delta-V needed for an end-of-life de-orbit manoeuvre (only needed if the spacecraft is in an orbit of 600km). No orbit maintenance is necessary to be performed as the spacecraft will remain above an acceptable altitude of 400km for the entire mission duration.

Table 6-3: Mission Architecture 1 Delta-V Budget

Altitude	500km	550km	600km
Launcher Injection Error Correction (m/s)	8.31	8.22	8.14
Constellation Phasing (m/s)	2.21	2.19	2.17
Collision Avoidance (m/s)	1.66	1.64	1.62
End of Life De-Orbit (m/s)	0	0	8.15
Total Delta-V Needed (m/s)	12.18	12.05	20.08
5% Margin (m/s)	0.61	0.6	1
Total Delta-V Needed Inc. Margin (m/s)	12.79	12.65	21.08

The mass and power budgets for the spacecraft are presented in Table 6-4. To create the power budget, a reference day composed of 15 orbits was generated to model the spacecraft over the course of the day carrying out payload operations and downlinking via the BGAN ISL. The power budget assumes that the BGAN ISL is operated every 5 minutes for a duration of 1 minute (i.e. the BGAN ISL has a 20% duty cycle). The power budget also assumes that there are 7x 500 second contacts with a ground station each day for telemetry and telecommand operations.

Table 6-4: Mission Architecture 1 Mass and Power Budget

Sub-System	Mass Without Margin (kg)	Mass Inc. Margin (kg)	Sub-System	Orbit Average Power (W)
AOCS	7.07	8.04	AOCS	11.0
Power	7.75	9.21	Power	1.5
Communications	0.80	0.84	Communications	3.4
Propulsion	5.85	6.91	Propulsion	0.0
OBDH	4.75	5.36	OBDH	7.0
Environment	0.35	0.37	Environment	1.6
Structure	13.23	15.56	Structure	0.0
Harness	2.27	2.38	Harness	0.0
Payload	8.42	8.84	Payload	32.3
Sub-System Total	50.49	57.52	Sub-System Total	56.7
System Margin (20%)	-	11.50	System Margin (20%)	11.3
Dry Mass	50.49	69.02	Battery Charge Losses	3.7
Propellant	5.18	5.18	Total Power Consumption	71.7
Launch Mass	55.67	74.21	Power Generated	72.8
			Margin	1.5%

6.1.2 Mechanical Overview

The spacecraft is based on the SSTL-21 platform (part of the SSTL-Micro platform range), and accommodates two bi-fold deployable solar arrays which deploy in the ±Y directions and provide an end-of-life worst case orbit average power of 72.8W. The avionics, power system, propulsion system, reaction wheels and payload equipment are accommodated inside a structural stack made up of discrete modules; the AOCS sensors and magnetorquer rods are positioned on the outside of the structural stack. The Space Facing Facet (SFF) houses the separation system, the thruster for the propulsion system, S-Band communications antennas, BGAN antennas, GPS antennas, the sun sensors. The +Z payload panel on the Earth Facing Facet (EFF) accommodates the star trackers and additional S-Band communications antennas, along with one radiation monitor, the GPS receiver and the Ion and Neutral Mass Spectrometer. The second radiation monitor and the plasma monitor are mounted on the +X side of the module stack, and the magnetometer payload is accommodated on a boom on the –X face of the spacecraft.

Figure 6-2: SSTL-21 D3S Spacecraft Concept in the Stowed Configuration

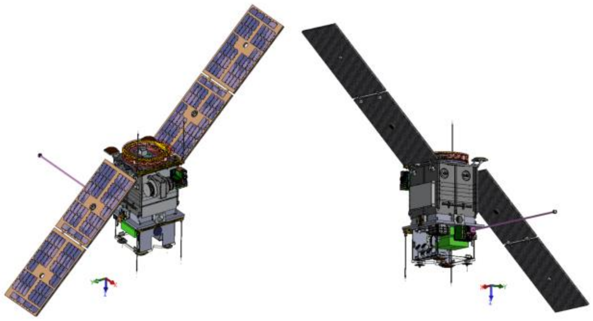

Figure 6-3: SSTL-21 D3S Spacecraft Concept in the Deployed Configuration

6.2 Mission Architecture 2

6.2.1 Overview

Mission Architecture 2 consists of 6 spacecraft (5+1 operational space) which fly in an evenly spaced constellation around a single orbital plane. The initial operational orbit is a 500-600km Sun-Synchronous orbit with an LTAN of 10:30am. Payload data downlink will be carried out via L-Band BGAN Intersatellite Link to the Inmarsat Geostationary spacecraft with onward downlink to the Inmarsat ground stations, and also directly to the KSAT ground station network using S-band. It is assumed that telemetry and telecommand will be carried out via the SSTL Guildford ground station, or via another compatible ground segment (e.g. the Viasat RTE Network) using S-Band. An overview of Mission Architecture 2 is provided in Table 6-5.

Table 6-5: Mission Architecture 2 Overview

Mission Overview	
Mission Objective	Provide measurements of: Radiation, Ionosphere and Thermosphere
Mission Lifetime	3 Years
Launch Date	Estimated 2025
Number of Spacecraft	6 (5 + 1 operational spare)
Orbit	500-600km Sun-Synchronous Orbit, 10:30am LTAN
Launch	16U EXOpod deployer from Exolaunch, Rideshare on Vega-C
Payloads	Radiation Monitor (x2), Magnetometer, Ion and Neutral Mass Spectrometer, Radio Beacon
Platform Type	16U SSTL-Cube
Spacecraft Mass	23.8kg (including unit and system margin)
Propulsion	Water propulsion system, 0.6kg propellant, 21m/s delta-V
Power	45.3W OAP at End of Life 11.4Ah Li-Ion Battery
Communications	S-Band TM/TC, L-Band BGAN Inter-satellite Link
Redundancy	Fully redundant avionics, single string payloads and BGAN ISL

An overview of the payloads that have been baselined for Mission Architecture is provided in Table 6-6. It has been assumed that all payload instruments on-board Mission Architecture 2 have a 100% duty cycle.

Table 6-6: Mission Architecture 2 Payload Overview

Instrument	Measurement	Volume (mm)	Mass Without Margin (kg)	Power Consumption Without Margin (W)	Data Generation Rate Without Margin (kbps)
Ion and Neutral Mass Spectrometer	Thermal, Oxygen, Nitrogen, Neutrals, Ions, velocity measured in heavier variant	100x100x50	0.3	1	0.5
Radiation Monitor (x2) and Magnetometer	0.3-8 MeV Electrons, 1 MeV - 1 GeV Protons, 100 MeV/n – 1 GeV/n ions, ±60,000nT magnetic field, 1 nGy/h – 6 Gy/h dose	96x96x119 (plus 800mm boom)	2 (2x1)	6 (2x3)	3.68 (2x1.84)
Radio Beacon	Radio tomography for scintillation	64x64x18	0.4	2	0
		Total	**2.7**	**9**	**4.18**

An overview of the Concept of Operations (CONOPs) for mission architecture 2 is shown in Figure 6-4. The current launch vehicle baselined for this mission architecture is a piggyback/rideshare on a Vega-C. The current assumption is that each CubeSat will be accommodated inside a 16U EXOpod deployer from Exolaunch. Once the satellites are released from the CubeSat deployer, it is expected that each satellite will carry out a phasing manoeuvre to ensure that the constellation is evenly spread around the orbital plane; each satellite in the constellation needs to be separated by 72° in the orbital plane.

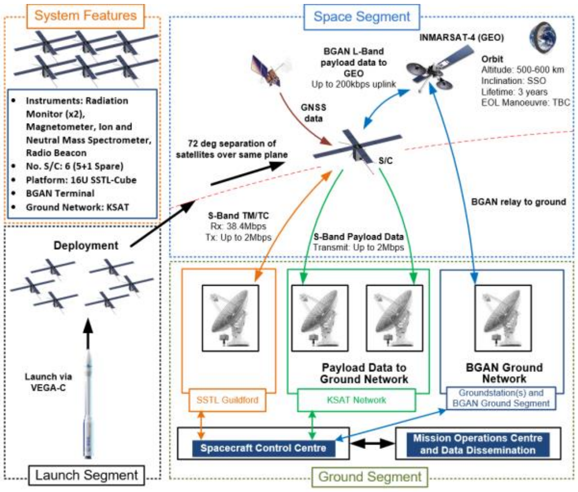

Figure 6-4: Mission Architecture 2 Concept of Operations (CONOPs)

6.2.2 System Budgets

An overview of the delta-V budget for Mission Architecture 2 is provided in Table 6-7. The budget takes into account the estimated delta-V required for launcher injection error correction, constellation phasing around the orbital plane and an allocation for 2 collision avoidance manoeuvres per year. The de-orbit analysis that was carried out using the DRAMA software showed that the spacecraft will de-orbit within the required 25 years after the end of the mission, and as a result, no delta-V is required for an end-of-life de-orbit manoeuvre. No orbit maintenance is necessary to be performed as the spacecraft will remain above an acceptable altitude of 400km for the entire mission duration.

Table 6-7: Mission Architecture 2 Delta-V Budget

Altitude	500km	550km	600km
Launcher Injection Error Correction (m/s)	8.31	8.22	8.14
Constellation Phasing (m/s)	2.21	2.19	2.17
Altitude Maintenance (m/s)	0	0	0
Collision Avoidance (m/s)	1.66	1.64	1.62
End of Life De-Orbit (m/s)	0	0	0
Total Delta-V Needed (m/s)	12.18	12.05	11.93
5% Margin (m/s)	0.61	0.6	0.6
Total Delta-V Needed Inc. Margin (m/s)	12.79	12.65	12.53

The mass and power budgets for the spacecraft are presented in Table 6-8. To create the power budget, a reference day composed of 15 orbits was generated to model the spacecraft over the course of the day carrying out payload operations and downlinking via BGAN ISL. The power budget assumes that the BGAN ISL is operated every 5 minutes for a duration of 1 minute (i.e. the BGAN ISL has a 2.3% duty cycle). The power budget also assumes that there are 7x 500 second contacts with a ground station for telemetry and telecommand operations each day.

Table 6-8: Mission Architecture 2 Mass and Power Budget

Sub-System	Total Mass Without Margin (kg)	Total Mass Inc. Unit Margin (kg)	Sub-System	Orbit Average Power (W)
AOCS	2.3	2.4	AOCS	8.1
Power	1.4	1.5	Power	2.1
Communications	0.4	0.4	Communications	2.9
Propulsion	1.0	1.2	Propulsion	0.0
OBDH	1.5	1.8	OBDH	2.1
Environment	0.3	0.3	Environment	1.6
Structure	4.6	5.5	Structure	0.0
Harness	1.0	1.1	Harness	0.0
Payload	4.6	5.0	Payload	10.0
Sub-System Total	**17.1**	**19.3**	Sub-System Total	**26.8**
System Margin (20%)	-	3.9	System Margin (20%)	5.4
Dry Mass	**17.1**	**23.2**	Battery Charge Losses	**1.9**
Propellant	0.6	0.6	Total Power Consumption	34.0
Launch Mass	**17.7**	**23.8**	Power Generated	**45.3**
			Margin	**25.0%**

6.2.3 *Mechanical Overview*

The spacecraft is based on the 16U SSTL-Cube platform (part of the SSTL-Cube platform range), and accommodates two bi-fold deployable solar arrays in the ±X directions, two tri-fold deployable solar arrays in the ±Y directions, and one body mounted solar panel which provide and End-of-Life (EOL) worst case orbit average power of 45.3W depending on the time of year.

The avionics, power and payload equipment on the SSTL-Cube are accommodated inside a number of PC104 stacks, interconnected by SSTL interface boards. The platform accommodates a water propulsion system that is capable of providing a total delta-V of 21m/s (on a 25kg spacecraft). The communication antennas are located on the EFF & SFF to suit the different operating modes of the spacecraft, along with a BGAN antenna, two star trackers and two sun sensors. The platform is three axis stabilized using reaction wheels and magnetorquers, and is controlled using the SSTL CubeSat CoreDHS on-board computer.

The payload instruments are installed inside the craft along with several "cut-outs" in the spacecraft body panels to provide an unobstructed view for the instrument sensors/apertures. One radiation monitor is accommodated in the top half of the spacecraft, with detectors pointing in the –Z (zenith) direction and the +Y direction, and the second radiation monitor is accommodated in the lower half of the spacecraft, with detectors pointing in the +Y and –X directions. The magnetometer is accommodated on a boom which deploys in the –X direction.

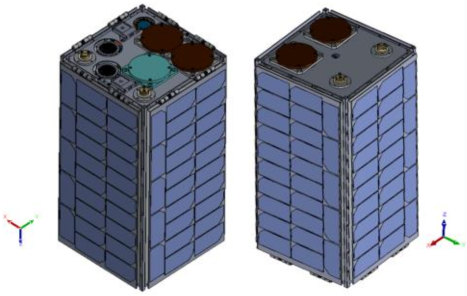

Figure 6-5: 16U SSTL-Cube D3S Spacecraft Concept in the Stowed Configuration

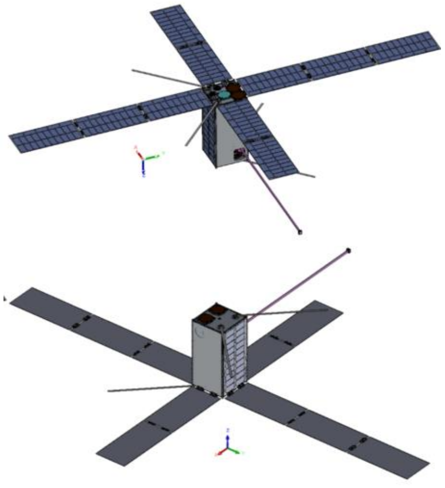

Figure 6-6: 16U SSTL-Cube D3S Spacecraft Concept in the Deployed Configuration

7. Consideration of a Precursor Demonstration Mission

Although the focus of the work during the Phase 0 study was to determine a single baseline mission architecture concept (i.e. 20x SSTL-21 spacecraft or 6x 16U SSTL-Cube spacecraft) to take forward in the Phase A study, another potential alternative that was discussed with ESA is the possibility of flying a precursor demonstration mission beforehand to de-risk the fully operational space weather nanosatellites mission. The demonstration mission would consist of 1 or 2 spacecraft which validate the data products the payloads provide in order to gain an understanding of the performance and prepare their usage in space weather services, and to also demonstrate the required high availability and low latency operations and associated technologies such as the BGAN ISL.

8. Phase 0 Conclusions

The following overarching conclusions can be made as a result of the Phase 0 study:

- The ESA D3S measurement requirements were analysed, followed by the identification of candidate space weather instruments suitable for nanosatellites;
- Reviews of relevant nanosatellite missions & technology was carried out, including analysis of lifetime and TRL;
- Based on the above two bullets, a wide number of mission architectures were identified. These were traded-off, progressively refined and down-selected with increasing levels of definition;
- The final two candidate mission architectures were further studied until the end of Phase 0 (both missions are LEO Sun-Synchronous 500-600km initial altitude; 3 year mission duration)
  - Mission Architecture 1 consists of 20x SSTL-21 spacecraft;
  - Mission Architecture 2 consists of 6x SSTL-16U Cube spacecraft;
- Pros and Cons as well as programmatic considerations of the two analysed mission concepts were compared;
- Demonstration mission options were also investigated (including the impact of such missions) given the technical de-risking advantages and likely funding available from the next ministerial. A demo mission consisting of 1-2 spacecraft was recommended for focus in Phase A.

Based on the provided pros and cons of the two analysed mission concepts and taking programmatic considerations into account, ESA selected Mission Architecture 2 for further study in Phase A. The development of a fully redundant 16U CubeSat platform was seen as better matching the needs of the Space Weather monitoring system and intents of the study.

9. Brief Overview of the Phase A study

The Phase A study kicked off in March 2022, and is now focussing on a demonstration mission of the 16U SSTL-Cube concept with 1-2 satellites, as a verification of the use concept of nanosatellites for space weather monitoring for operational applications is foreseen to come first. Two satellites is ESA’s preferred baseline for the demonstration mission and is therefore the focus of the Phase A study, however the number of satellites can be reduced to one (if a mission with two satellites is shown to be too expensive at the end of Phase A), without compromising the aims of the demonstration mission.

This demonstration mission will then be followed by the implementation of the full 6 spacecraft constellation mission.

10. Current Status of the Phase A Study

The System Design within the Phase A study is still ongoing and not yet frozen.

In this chapter we provide a brief summary of these main design updates of the 16U SSTL-Cube demonstration mission since the Phase 0 study:

- A slightly later launch by the end of 2025
- A slightly longer mission lifetime of 3.5 years, including 3 years of nominal mission lifetime
- The use of two different Radiation Monitors rather than two of the same type (one of which still includes a Magnetometer)
- The Solar Array configuration is now only four bi-folded solar arrays rather than two tri-fold and two bi-fold arrays panels
- The Water propulsion system has been extended to provide a larger Delta-V capability
- Minor updates to equipment choice, sizing and positions in the spacecraft
- Relocation of S-Band antennas onto the solar array

References

[1] Rowe S. and Eckersley S., TN22 - Final Report Version 1 (Release 001), ESA SSA P3-SWE-LIII Nanosatellites for D3S Study, SSTL (ref 0380003), Feb 2022

[2] Rowe S. and Eckersley S., TN22 - Executive Summary Version 1 (Release 001), ESA SSA P3-SWE-LIII Nanosatellites for D3S Study, SSTL (ref 0380051), Feb 2022