Hybrid Architectures for Responsive Space

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ABSTRACT

Hybrid Space Architectures are a key component for a feasible implementation of Responsive Space. The Responsive Space mission to launch and operate a payload in space within days - some studies suggest as short as 72 hours [1] - is only possible with extensive preparation before an actual activation of such a system may occur. Preparation entails the storage and rapid integration of a heterogeneous pool of pre-qualified launchers, satellite platforms, payloads, and systems for operations, and it depends on end-to-end compatibility across the launch, space, and ground segments. Implementing such a system in a cost-efficient way will require a technological ecosystem as a backbone. A technological ecosystem that supports diversified, propagated and hybrid architectures across low earth orbit. In particular, the space segment must host a wide range of platforms and payloads to satisfy the varied functionalities demanded by responsive space missions.

These demands hugely overlap with those of Hybrid Space Architectures. At the DLR RSC³, we are working on establishing and propagating such an ecosystem in Germany and across Europe. In this paper we will present ongoing and planned activities in this field, how the DLR is contributing and how we think these activities can be translated and adapted into a backbone for Hybrid Space Architectures and Responsive Space. Hybrid in the way we understand it should not be limited to a mix of civil/commercial and military capabilities. It needs to be extended to a mix of space-borne sensors, a mix of different satellite owners/providers and companies and a mix of different satellite sizes and orbits. We argue for the importance to analyse and understand all these different aspects of Hybrid Space Architectures and derive the platform implications from there. These will vary by use case. The RSC³ is currently analysing maritime situational awareness and RF monitoring use cases. To enhance our capabilities, we are establishing a diverse test bed at our site in Trauen. It will be based on commercially available platform and payload systems that can be integrated rapidly and qualified for compatibility utilizing a hardware-in-the-loop approach. This paper will also include an outlook on a future on-orbit mission concept that aims to bring those technologies and concepts to space.

1.0 RESPONSIVE SPACE NEEDS HYBRID ARCHITECTURES

The vision for Responsive Space is to be able to react in a timely manner to a broad spectrum of scenarios in the operational domain of space. Scenarios can range from attacks and threats by foreign actors, to damages and failures from natural disasters, to quickly launch new disruptive technologies to sustain superiority in the domain [2]-[4]. Thus, increasing the overall resiliency for the space operational domain significantly. Because the scenarios are numerous and heterogeneous, a flexible responsive-space capability is required. Rather than a monolithic solution, the capability should resemble a toolbox that offers a range of response options tailored to each situation.

To structure the different elements comprising the toolbox, it has been proposed to take a layered approach to Responsive Space [5]. This approach uses a tactical, operational and strategic layer to cover the whole range of elements [6].

The tactical layer is often perceived as the main focus of Responsive Space. It includes very fast tools and concepts to react within hours, days and weeks to demands in the space domain. The operational layer adds all the elements, which are required to keep the Responsive Space toolbox operational and compliant with the rules and regulations of the "real world". These include fields like storage, logistics, supply chains, purchasing, contracts, licensing, training, import/export regulations and command structures. Without these elements the tactical tools and methods would be impossible to deploy. It is assumed that these elements usually take months and years to be implemented. The strategic layer includes the long-term elements of Responsive Space. They lay the groundwork for the efficient and feasible activation of the Responsive Space toolbox both now and in the future. It focuses on policy and governance, economics, regulations but also on standardization, building of infrastructure and the industrial base. The following chapters will examine these layers, provide examples and show how they relate to Hybrid Space Architectures. But before, some terms and definitions to ensure consistency within this paper:

Response Time: Time from the moment a demand to activate a Responsive Space capability is communicated until it is fulfilled by the Responsive Space system (usually by delivering data from space to the client).

Hybrid: In this paper, every heterogeneous space system has some kind of (and usually multiple) hybrid features. A hybrid feature could be the use of different satellite designs or generations within a space system (like the sentinel program) [7]. It could also be the use of different orbits within a space system (like the multi orbit capability IRIS^2) [8]. Or – as it is most often understood – the mixture between commercial and institutional systems for the same purpose. [9] Those aspects are further explored in Chapter 2.

Space as an operational domain: Space as a warfighting domain also includes elements on the ground. Elements such as launch infrastructure, ground stations and even facilities for satellite manufacturing are critical to sustain any military space operation. They are therefore also part of the operational domain and of any Hybrid Architecture that will be discussed in this paper.

1.1 Rapid Deployment – Into Space in 7 Days

The Responsive Space Rapid Deployment method aims to launch one or more satellite into space and begin operations as fast as possible. For example, the US Tactical Responsive Launch program [10]. This capability can be a powerful deterrent to foreign actors who plan to attack space assets. Use cases for a Rapid Deployment require Response Times in the realm of days. Some as short as 72 hours [1]. A possible implementation of this method on the tactical level utilizes pre-built and pre-qualified satellites that are stored in close proximity to the launch site, where a launcher is kept on standby. Compatible ground stations are available ready for immediate use. To increase the flexibility of the system, multiple launch sites, launchers, satellite configurations and ground stations can be used. After the activation of the system, the proper combination of launcher, launch site and satellite will be chosen, all relevant systems will be quickly activated, and run through an accelerated checkout campaign. The satellite will be transported and mounted to the launcher, a proper orbit will be the selected and the required launch license will be given, along with any necessary safety measures, such as clearing of air space. After the launcher deployed the satellite successfully it needs to be taken into operation immediately and deliver its data to the client within a few orbits.

On an operational level, such a solution would require compatibility between all relevant segments, as well as extensive training and preparation. The complexity of the Rapid Deployment system increases drastically with the mission profiles it shall support. It is highly likely that commercial service providers need to be part of such a solution. Either to build, store or activate the required systems quickly enough. A critical requirement will also be the financial viability. As keeping the systems in standby state might require extensive costs. If this cost is too high, the political will and the deterrent factor of the Rapid Deployment capability might be decreased significantly.

On a strategic level, an important element to cost-efficiently implement such a solution, are common standards between commercial and institutional providers of satellites, launchers and ground stations. Another element is the availability of low-cost satellites, launchers and ground stations. This is more likely if there is a significant and regular demand on those commodities.

This is why Rapid Deployment has major synergies with Hybrid Space Architectures, if they are compatible among each other.

- Resiliency of Hybrid Space Architectures can be increased significantly, if a compatible Rapid Deployment capability is implemented. Foreign actors are deterred from diminishing the Hybrid Space Architecture by attacking single satellites, as they can be replaced quickly. Also, failures of single satellites can be quickly recovered.
- Hybrid Space Architectures can be a source of the common standards Rapid Deployment needs urgently.
- Hybrid Space Architectures might bring the demand for needed elements of a Rapid Deployment capability, such as satellites, payloads, launchers and ground stations.

1.2 Storage in Space – Reconfiguring On-Orbit Assets

Rapid Deployment is not the only option that should be considered as a Responsive Space Capability. There might be situations in which even a Response Time of a few days is too long. In other cases a rapid launch could not feasible due to weather, launch site availability or financial constraints. For these cases it should be considered to use assets, that are already on orbit and skip the launch. In this paper, we call this concept Storage in Space. Storage in Space reconfigures satellites or constellations that are already in space to rapidly meet new demands and requirements. Reconfiguration could be as simple as changing software or reroute data on the ground, but could also mean to do complex orbit manoeuvres or to change the whole concept of operations.

One possible implementation of this idea is to rapidly lower the orbit of a satellite or a constellation from Low Earth Orbit (LEO) to Very Low Earth Orbit (VLEO), for example from 500 km to 250 km. For an optical sensor, this orbit manoeuvre would effectively double the resolution [11]. The trade-off would be the consumption of fuel and overall reduction of the lifetime of the spacecraft. This allows for a hybrid model where a commercial entity operates and monetizes the assets in LEO-Mode as per usual with a medium to high resolution and rapidly maneuverers to VLEO-Mode in case of an urgent need, thus increasing the performance and being able to meet military requirements as long as needed. For VLEO-Mode a shift from commercial to military operators could be considered as well. Also, elliptical Orbits could be chosen to gain temporarily the advantages of VLEO but in turn reduce fuel and life time less.

On an operational level this solution requires commercial/institutional network that allows for fast exchange and reconfiguration of capabilities. It would be needed to equip satellites with capable propulsion and to use flexible, reconfigurable payload that could adapt to different orbits.

On a strategic level, this solution requires a good understanding of the VLEO but also strong Hybrid Space Architecture is needed. This Architecture should provide well defined data interfaces between commercial and institutional users.

The Storage in Space solution is an essence a hybrid architecture with the added requirement for rapid reconfiguration and orbit flexibility. Using these synergies will result in a more flexible and resilient space architecture.

1.3 Accelerated Mission Development - The Responsive Space Ecosystem

The two concepts presented earlier (Rapid Deployment and Storage-in-Space) excel when a response is needed within days. However, they rely on extensive prior knowledge, strict pre-qualification, and therefore offer limited flexibility – only pre-selected capabilities can be delivered. When a mission can tolerate a longer lead-time but demands greater flexibility, a different Responsive Space capability is required. Examples include:

- Introduction of a disruptive technology that could confer a strategic edge,
- sudden shifts in geopolitics,
- supply-chain disruptions, and
- unanticipated capability gaps.

Such cases can still be addressed within the responsive space framework by leveraging the Responsive Space Ecosystem. In this paper we refer to this approach as Accelerated Mission Development. The concept follows the conventional satellite development lifecycle but compresses it so that Response Times of 6–12 months become realistic. Commercial provider already promise such schedules [12]. We anticipate that Accelerated Mission Development will become the most frequently used responsive space capability because it aligns closely with civilian and commercial demand and is not confined to strictly military missions. Applications include:

- Technology demonstrations,
- Replacement of aging spacecraft, and
- Scaling existing constellations

This solution is called leveraging the Responsive Space Ecosystem because it re-uses operational and strategic elements of other Responsive Space Capabilities (two of them described above) to accelerate satellite timelines. Some of these elements are:

- Interoperable satellite components that are tested, qualified and readily available
- Interfaces, preferably based on available standards, between payload and satellites as well as satellites and launchers and satellites and ground stations
- Reconfigurable software both onboard and on the ground
- Trained personnel and common operation procedures
- Commercial/institutional partners that can be interchanged to supply the required capabilities

In Accelerated Mission Development these elements are combined to deliver cost-efficient adaptations of prequalified systems that meet client-specified capabilities within the target timetable.

On an operational level this requires suitable facilities, experienced personnel and procedures to adapt and modify these systems. It needs to account for spectrum allocation and launch-licensing. It is applying the same operational and strategic elements as the solutions above such as standard interfaces between launchers, satellites and ground stations.

On a strategic level this needs a mature Responsive Ecosystem. It will need an interchangeable supply chain, in which subsystems or service providers can be changed in a reasonable amount of time and without jeopardising mission success. It will rely on multiple interchangeable providers for satellite components, payloads, launchers, ground stations and operators. It will need networks of ground stations and launch sites.

A Hybrid Space Architecture can provide the foundation of compatible and interchangeable elements that this solution needs. In turn the Accelerated Mission Development will increase the flexibility and resilience of the Hybrid Architecture. Both can be built upon the same ecosystem. Therefore, it is beneficial to combine the demands and the requirements for Responsive Space and Hybrid Architectures to accelerate the formation of such an ecosystem.

2.0 REQUIREMENTS FOR A HYBRID ARCHITECTURE

To include Responsive Space requirements into Hybrid Space Architectures can be very beneficial, as stated above. This chapter will go into more detail on how these requirements could look like. They will be separated into launch segment, space segment and ground segment. This paper will put an emphasis on space segment requirements although it should be mentioned that for this STO group “Platform Implications for Hybrid Space Architectures for NATO Missions” should also consider launchers and ground stations as platforms as they play a critical role in the operational domain of space.

2.1 Launch Segment

Multiple Launch providers – To create diverse Launch opportunities, the Launch Segment shall utilize multiple launch providers. Ideally, this would a mixture of commercial and institutional owned launch providers.

Multiple Launch sites – To be able to launch from different locations, the launch segment shall utilize multiple launch sites. Ideally ranging from high, to medium to low inclination sites. The sites shall be secured against hybrid warfare threats like sabotage and cyber-attacks and able to be defended against conventional attacks to increase resilience during crises. Air, sea and mobile land launch shall also be considered to increase launch flexibility.

Multiple Launcher sizes – In order to launch different satellite sizes or entire formations/constellations of satellites, the Launch Segment shall utilize different launcher sizes. Ideally micro, small, medium and heavy lift launchers are available. Ideally with an option to reach Geostationary Orbit (GEO) as well as LEO and VLEO Orbits.

Stored and ready to be used Launchers – To address timely launch capability, the Launch Segment shall utilize stored launchers that are held in a ready-to-launch-state.

Standard interfaces – To achieve interoperability across the space and Launch Segment, standard interfaces shall be used between launcher and satellites. These Interfaces shall ideally support small, medium and large satellites.

Training – To sustain operational readiness, the Launch Segment shall regularly exercise Responsive Launch scenarios.

2.2 Ground Segment

Multiple locations – To be more resilient the Ground Segment shall use multiple ground station locations. Ideally with the possibility to relocate fast and efficiently.

Civili-military integration – To allow for hybrid operations, the Ground Segment shall use civilian operators but allow military operators to take over operations quickly in times of crisis.

Secure Links – Links between the Ground Segment and Space Segment shall be secure. Ideally, they shall be resistant to jamming and spoofing.

Secure sites – Ground Segment sites shall be secured against hybrid and conventional threats like sabotage, cyber-attacks, electronic warfare, drone, artillery and missile strikes.

Flexible ground stations – To allow for cross compatibility and rapid reconfiguration, the Ground Segment should be able to service multiple satellites. It shall be able and interchange ground stations and satellites quickly.

Multi-orbit capability – The Ground Segment shall be able to serve multiple orbits. Ideally VLEO, LEO, MEO and GEO shall be covered.

Multi-frequency support – The Ground Segment shall be able to work with multiple frequencies. Ideally from amateur radio to S-Band, X-Band Ku and Ka Band shall be possible.

Training – To sustain operational readiness, the Ground Segment shall regularly exercise Responsive scenarios, like accelerated commissioning and early operations, switching from civilian to military operators or mixing and matching satellites and ground stations quickly.

2.3 Space Segment

Interoperable Payload/Platform interfaces – To allow for fast mixing and matching, payloads and satellite platforms should feature compatible, interoperable and standardized interfaces.

Multiple satellite classes – To account for different use cases, the space segment shall support multiple satellite classes. Ideally micro, small, medium and large satellites shall be possible.

Fast AIT – The Space Segment shall support an accelerated Assembly, Integration and Testing (AIT) of satellite systems. Ideally, AIT can be finished within a week for new systems and within a few hours for already pre-qualified, stored systems.

Stored and Standby – To allow rapid deployment, the space segment shall use stored and ready to be used satellite systems. Ideally, they can be reactivated and transported to the launch site within a couple of hours.

Secure links – Links between the Space Segment and Ground Segment shall be encrypted. Ideally, they shall be resistant to jamming and spoofing.

In-space connectivity – To increase availability of the space segment, satellites shall feature inter satellite links (ISL) to relay satellites. Ideally this results in a continuous (24 h) availability of the satellites to be commanded or to downlink data.

Software defined – The Space Segment shall be reconfigurable by software. The software, the satellites are running on shall be flexible. Ideally the software is modular and easily and safely extended.

Multi Orbit Capability – The Space Segment shall be able to operate from multiple orbits. Ideally, VLEO, LEO, MEO and GEO are supported. Ideally, the Space Segment has the ability to manoeuvre between Orbits.

Serviceable – the Space Segment shall allow for on-orbit servicing by utilizing standard interfaces. Ideally manoeuvring (De-Orbiting), refuelling, repairing and modifying satellites shall be supported.

Cybersecure – The Space Segment shall be hardened against cyber threats.

Training – To sustain operational readiness, the Space Segment shall regularly exercise Responsive scenarios such as rapid activation of stored satellites, on-orbit reconfiguration as well as rapid modification and testing on ground.

3.0 ACTIVITIES OF THE RSC³

The German Aerospace Center (DLR) established the Responsive Space Cluster Competence Center (RSC³) in 2020 to coordinate research on Responsive Space. Since its inception, RSC³ has pursued the topics outlined in this paper. Numerous ongoing and planned activities at RSC³ directly address Hybrid Architecture; they are summarised below..

3.1 Hybrid Architecture for Maritime Security

The RSC³ is involved in a project for Maritime Security, where it is proposing a Hybrid Architecture. The project (EMSV) aims to create a collection of real time services in order to observe and protect critical maritime infrastructure, like off-shore windfarms or deep-sea cables. The project focuses on the Baltic Sea. The services gathered and developed in EMSV will be demonstrated in two scenarios combining the air, space and sea domain. The scenarios will cover threats on critical infrastructure above and below sea level. The project kicked-off in 2025 and will run until 2027.

The RSC³ is tasked with designing a proposal for a Hybrid Diversified and Responsive Architecture (HyDRA) for the space domain. The approach includes:

- Deriving requirement profiles for the space architecture from demonstration scenarios and different geopolitical conditions.
- Creating multiple options for space architectures based on the requirement profiles. The aim is to obtain different compositions/mixtures of hybrid elements like:
  - Sovereign or commercial owned/operated satellites,
  - National or international owned/operated satellites
  - Military or civilian owned/operated satellites,
  - Different payloads like SAR, SIGINT and optical,
  - Satellites on different orbits (polar, sun-synchronous, inclined, LEO, MEO, GEO),
  - Different satellite sizes
- Comparing the options and deciding on the best solution using also a cost-benefit analysis.
- Creating an implementation plan for the best option.

3.2 Responsive Space System (REACTs)

RSC³ also leads the European Defence Fund (EDF) project REACTS (Responsive European Architecture for Space). REACTS will provide an interoperable, resilient and scalable Network of Responsive Space Systems (RSS). It shall be able to meet Response Times as short as 72 hours between the notice to alert for launch to data delivery from orbit. The RSS has a strong emphasis on Rapid Deployment. 40 companies and organisations from 13 countries are involved in this project. The RSS follows a holistic and European approach. Sharing of capabilities between states but also between institutional and commercial organisations are a central of the RSS. The System also uses a multi-domain approach and covers the space, ground and launch segment. The project is based on End-User needs (provided by partnered MoDs) and will analyse different architectures, define a concept of operations (CONOPS), create a roadmap and propose interface standards for each segment. REACTS was started in 2023 and is scheduled for completion end of 2025. The final report is available on request to the EC from the partnered ministries of defence (MoDs) under their sole discretion. The project has received funding from the European Defence Fund (EDF) under grant agreement EDF-2022-101121212-REACTS.

3.3 Testbeds for a Responsive Space Ecosystem

As described in Chapter 1.3, realizing Responsive Space Capability in an effective way requires a well-established ecosystem. The RSC³ is conducting several projects to support the formation of such an ecosystem. One important aspect is testing, certification, and demonstration. This is needed for components, subsystems, satellites platforms, payloads but also software, algorithms, interfaces, standards and protocols. To meet this need, the RSC³ is developing several testbeds. The testbeds shall be accessible to all actors within the ecosystem – be it industry, research or End-User – with a low barrier of entry. This shall allow start-ups and non-space organisations to mature their products in the space domain cost-effectively and with minimal risk. In addition, the testbeds shall provide an environment for training and exercise to sustain operational readiness of the Responsive Space Capabilities. Relevant scenarios include rapid integration and on-orbit modification. The following sections describe two concrete approaches in detail .

3.3.1 On-Ground Testbed – LAMA

A typical delay in space missions occurs often during integration of components or subsystems. On paper the components may appear compatible, but once they arrive the integration phase often reveals electrical, mechanical, and software mismatches. These can range from electrical challenges like deviating power demands to mechanical challenges like misaligned connectors to software challenges like missing or faulty functionalities. We refer to these activities as troubleshooting . During satellite development, troubleshooting consumes a large share of engineering effort, which is why low cost assets such as flat-sats or electronics breadboards are widely used.

To reduce the Response Time, troubleshooting must be handled in the preparation phase, ideally, long before an actual demand for a Responsive Space Capability arises. This is what the LAMA (Lab Assembly for Mission Acceleration) project aims to achieve. LAMA is a family of different testbenches that each represent an important aspect of the satellite development and trouble-shooting phase. Mission-critical components will be integrated and tested on the LAMAs in preparation for the actual Responsive Space mission. This allows the engineers to develop and prepare solutions for the trouble-shooting in advance. Once the mission and the required components are selected, the pre validated solutions can be rapidly implemented, enabling execution with minimal risk and delay.

The LAMA project is still in its early development stage. As a starting point, a commercially available CubeSat Platform was chosen as a baseline for the first LAMA prototypes. Currently there are three LAMAs being built and prepared for operations:

1. The Electrical LAMA (El Lama) – Basically a flat sat of the beforementioned CubeSat platform, the El Lama allows the user to connect satellite components, like subsystems or payloads to the standard satellite platform. El Lama comprises an on-Board Computer (OBC), a Communications System (Coms), a Power Distribution Unit (PDU) and an Attitude and Orbit Control System (AOCS). El Lama will be equipped with an RF transmission path to a simulated ground station, an operating system on the OBC and communication protocols based on CubeSat Standard Protocol (CSP). This setup will allow for a functional checkout of

the electrical and software integration of the tested object.

2. The Mechanical LAMA (Mecha Lama) – This LAMA consists of the flight rated structure of a 12U CubeSat and related support equipment to assist during assembly. Mecha Lama allows the user to physically integrate the tested object or a model of the tested object into the satellite structure. This will support fit checks and the preparation of assembly procedures as well as the production of the harness or any potential support structures.

3. The Digital LAMA (Digi Lama) – This is a digital representation of the beforementioned CubeSat platform. In essence it is a parameter-based description inside a Model Based System Engineering (MBSE) tool from DLR. This model shall support various system engineering tasks like the configuration- and requirements management and the development of assembly, test and validation procedures. It will also function as a central database and documentation for all LAMA-related testing activities.

Currently the development of this project foresees three phases.

1. Prototype Preparation Phase (2025 – 2026) Build and verify the three LAMA prototypes.
2. Prototype Use Phase (2026 – 2028) Deploy the LAMAs for upcoming DLR satellite missions.
3. Expansion Phase 2027+ Iteratively expand the LAMA portfolio (additional satellite-class support, specialised modules such as an AOCS LAMA, and a virtual-simulation LAMA).

Within a Hybrid Architecture, on ground testbeds such as LAMA can be used to verify compatibility among heterogeneous satellites. A reference to this could be the Space Developments Agency’s (SDA) facility for Transport Layer compatibility testing [13].

3.3.2 On-Orbit Testbed – BIBER

In order to mature technology and reach a high technology readiness level (TRL), space technologies usually require an in-orbit validation or the generation of actual data from space. The barrier of entry to produce this data or to demonstrate capabilities in space is quite high compared to other domains. This requires developing space qualified hardware and either acquiring an existing on orbit platform or launching a custom demonstration mission. This comes with financial investment and risk. Many companies – especially companies who are low on financial or human resources – hesitate to take such risks, even if they have potential technologies that could be used for space applications.

Open On-Orbit Testbeds can provide a low barrier of entry solution to quickly and cost-effectively develop, test, demonstrate and mature space technologies.

A concept for such a Testbed is currently being developed by the RSC³ under the name of BIBER (Beta for Intelligent, Bimodal Electronic Reconnaissance). BIBER focuses on the use case of Radio Frequency Monitoring. It covers activities like the detection, classification and geolocation of world-wide signal sources. It shall provide capabilities specifically targeted at the reduction of the amount of data that needs to be downlinked to earth and increasing the detection probability through collaborative satellites.

BIBER shall provide these capabilities:

1. Use our Data – The data that BIBER is generating shall be distributed among the Ecosystem to be used as reference data for the development or modification of existing solutions like simulators, algorithms or payloads. BIBER shall provide raw data from its payload, as well as important meta data, like satellite telemetry and payload characteristics.
2. Bring your Use Case – The user shall be able to define custom use cases, for example specific Signals of Interests, Time of Interests or Areas of Interest. BIBER shall collect and deliver

data exclusively to the user for these custom use cases.

3. Bring your Software – It shall be possible to upload software from the user to BIBER and execute it on the satellites. The software can be executed directly on the BIBER payload or on the payload computer and demonstrate technologies like on-orbit processing, data reduction or detection algorithms.

4. Bring your Payload – It shall also be possible to test hardware on BIBER. BIBER will feature a standardized payload envelop (standard electrical and mechanical interface) to demonstrate user payloads like an SDR or an Antenna.

For Hybrid Space Architectures, On-Orbit Testbeds should be included as a cornerstone to provide regular opportunities to mature innovative technologies and support new companies or research institutes to contribute to the architectures technological edge. A good example of this is the ESA OpsSat Mission [14]. An added strategic advantage of Testbeds such as this is, that they provide and promote the use of common standards among the ecosystem.

4.0 CONLCUSION

This paper has examined the critical role of Hybrid Architectures in delivering a feasible, cost-effective Responsive Space Capability. Conversely, Hybrid Architectures can leverage Responsive Space assets to react quickly to a wide spectrum of threats and operational demands.

Moving forward, the two concepts must be integrated:

- Technology development (standardised interfaces, modular payloads, multi-orbit platforms, on-orbit servicing, etc.) must continue to mature;
- Collaboration between commercial, institutional, and governmental stakeholders must be fostered so that a common ecosystem can be established.

On that shared foundation a space architecture can be created that is both hybrid and responsive, thereby increasing resilience and enabling effective action in the face of the diverse challenges and opportunities that the space domain presents.

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