

# Modular, Serviceable and Demisable Small Satellites: Engineering a Resilient European Space Defence Architecture

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## Abstract

Europe's defence, security, and critical-infrastructure missions are becoming increasingly dependent on small satellite constellations for communications, intelligence, surveillance and reconnaissance, navigation resilience, environmental awareness, and strategic situational understanding. Yet most small satellites remain engineered as disposable assets: launched as integrated mission products, operated until failure or obsolescence, and then replaced through subsequent launch campaigns. This replacement-led model creates strategic fragility, increases lifecycle cost, constrains operational adaptability, pollutes the atmosphere and oceans, and adds to the long-term sustainability challenge in congested orbital environments.

This paper proposes an integrated engineering doctrine for European small satellites based on three mutually reinforcing design principles: Design for Manufacture, Design for Service, and Design for End-of-Life. The intent is to shift small satellite development away from bespoke, disposable mission units and toward modular, serviceable, and demisable orbital infrastructure. Drawing on collaborative activity between Leicester Space Park, the Satellite Applications Catapult, and the University of Oxford, the paper examines how modular spacecraft architectures can be optimised for repeatable manufacturing while remaining compatible with future in-orbit servicing, inspection, upgrade, reconfiguration, and responsible

disposal. Emphasis is placed on the Catapults' Rendezvous Operations (RPO) facility, as a ground-based validation environment for service-ready spacecraft architectures, sensor suites, docking interfaces, capture mechanisms, robotic access, and operational concept development.

For defence and security users, modular serviceability offers a route to increased operational availability, faster payload refresh, reduced dependence on repeated replacement launches, and improved resilience against environmental degradation and adversarial interference. Equally, Design for End-of-Life ensures that enduring capability does not come at the expense of orbital sustainability. The paper concludes that Europe's future defence space architecture should not be defined solely by launch rate or constellation size, but by the ability to manufacture, sustain, adapt, and responsibly retire spacecraft as part of a sovereign and resilient space infrastructure ecosystem.

**Key Words - Small Satellites, Modular Spacecraft, In-Orbit Servicing, ISAM, RPO, Space Architecture, Demisable Spacecraft, Design for Manufacture, Orbital Sustainability, Sovereign Capability.**

## 1. INTRODUCTION

European defence, security, and critical-infrastructure missions are increasingly dependent on space-based systems. Small satellites now support, or are expected to support, a widening set of functions including resilient communications, intelligence, surveillance and reconnaissance, maritime

domain awareness, environmental monitoring, navigation augmentation, disaster response, and strategic warning. As space becomes more operationally significant, the assumptions that shaped earlier generations of small satellite development are becoming increasingly constrained.

The dominant small satellite model remains replacement led. A spacecraft is designed, integrated, launched, operated, and then replaced when it fails, degrades, exhausts consumables, becomes technologically obsolete, or no longer matches user requirements. This model has advantages: it supports rapid iteration, permits mission-specific optimisation, and reduces the requirement for complex on-orbit maintenance. It is also consistent with many commercial small satellite business models, where low unit cost and rapid launch cadence are treated as acceptable substitutes for long-term serviceability.

However, the replacement-led model creates strategic weaknesses when applied to defence and security missions. First, it assumes continued access to launch, production capacity, payload supply chains, and ground infrastructure. Second, it assumes that operational requirements will remain sufficiently stable over the lifetime of a spacecraft. Third, it assumes that failed or obsolete spacecraft can be replaced quickly enough to preserve operational effect. Fourth, it accepts the accumulation of orbital objects as a consequence of capability refresh. These assumptions are increasingly fragile in a contested and congested orbital environment.

For European defence users, this creates a practical challenge. A constellation may be resilient in a statistical sense if it consists of many spacecraft, but this does not automatically make it operationally sustainable, affordable, or adaptable. A degraded sensor, failed propulsion system, obsolete communications payload, compromised avionics unit, or mission-specific change may still require replacement of the whole spacecraft. At scale, this approach risks turning orbital resilience into a continuous replenishment burden.

This paper argues that Europe should complement replenishable small satellite constellations with an engineering doctrine focused on endurance, serviceability, and responsible disposal. The central proposition is that small satellites should evolve from disposable mission products into maintainable, upgradeable, and demisable orbital assets. This does not imply that every small satellite must be serviced, recovered, or upgraded. Rather, it means that spacecraft architectures should be designed so that future servicing, inspection, upgrade, reconfiguration, and safe end-of-life pathways are technically credible from the outset.

The proposed doctrine integrates three design principles:

- **Design for Manufacture**, enabling repeatable, scalable, and sovereign European production.
- **Design for Service**, enabling future inspection, capture, repair, refuelling, upgrade, or reconfiguration.
- **Design for End-of-Life**, ensuring that spacecraft can be safely disposed of, demised, recovered, or reused without adding unnecessary long-lived orbital risk.

The integration of these principles is the key focus. A spacecraft designed only for manufacturing may not be serviceable. A spacecraft designed only for service may be too complex, expensive, or persistent at end-of-life. A spacecraft designed only for demise may not support operational

endurance. A future European defence architecture requires these requirements to be treated not as sequential add-ons, but as a single system-level design doctrine.

## 2. STRATEGIC AND OPERATIONAL DRIVERS

### 2.1 INCREASING DEFENCE DEPENDENCE ON SMALL SATELLITES

Small satellites have moved from experimental and secondary mission roles into increasingly central positions within national security and critical-infrastructure architectures. Their advantages are well understood lower unit cost than traditional large spacecraft, shorter development timelines, easier constellation scaling, distributed risk, and compatibility with a broad range of payloads. For defence and security users, small satellites offer the potential for proliferated sensing, responsive communications, rapid technology insertion, and increased mission diversity.

The attraction of proliferated small satellite architectures is particularly strong in a defence context. A distributed constellation can be harder to disable than a single monolithic spacecraft. It may provide greater coverage, shorter revisit times, and improved tolerance to individual satellite failures. It also creates the possibility of mission-specific replenishment, where new payloads or updated capabilities are launched as operational needs evolve.

However, proliferation alone is not the same as resilience. A constellation composed entirely of disposable assets may still depend on fragile ground-based production pipelines, launch access, specialist components, and international supply chains. It may also require repeated replacement simply to sustain baseline capability. In a benign commercial environment, this may be acceptable. In a crisis, or during periods of constrained launch access, supply-chain disruption, or adversarial interference, the limitations become more significant.

### 2.2 THE LIMITS OF REPLACEMENT-LED RESILIENCE

The traditional lifecycle of a small satellite can be summarised as build, launch, operate, degrade, dispose, and replace. This model treats the spacecraft as an integrated consumable. Subsystem failure, payload obsolescence, propulsion depletion, or mission change generally cannot be addressed by replacing a module or upgrading the platform in orbit. The default response is to launch a new spacecraft, but this has several consequences.

First, it increases lifecycle cost. Even when unit spacecraft costs are low, the cumulative cost of repeated design, integration, test, launch, commissioning, and disposal can be substantial. The cost is particularly significant where payloads, secure communications systems, or mission-specific assurance requirements are involved.

Second, it slows operational adaptation. Defence requirements may evolve faster than conventional spacecraft replacement cycles. A spacecraft that cannot be upgraded in

orbit may become operationally misaligned before the end of its physical life.

Third, it creates a dependency on launch availability. If replenishment is the only route to recovery, then capability is constrained by launch cadence, launch geography, regulatory approval, range access, and geopolitical dependencies.

Fourth, it can increase orbital sustainability risk. Even if spacecraft are designed to comply with disposal guidelines, a replacement-led model generates a continuous flow of new orbital objects. In congested orbital regimes, the long-term acceptability of this model may be challenged by regulators, insurers, operators, astronomers, and the wider public.

Finally, it may not be consistent with the strategic language used by European governments. If space is treated as critical infrastructure, then spacecraft cannot only be considered expendable devices. Critical infrastructure is normally maintained, inspected, repaired, upgraded, and retired and responsibly and space systems should be moving toward the same logic. The need for sovereign space capabilities in lieu of relying on traditional alliances and partnerships increasingly driving both European nations to change attitudes and consider new approaches.

### **2.3 SOVEREIGN CAPABILITY AND EUROPEAN INDUSTRIAL RESILIENCE**

For Europe, the issue is not only technical. It is also industrial and strategic. A resilient space defence architecture requires more than access to satellites. It requires the ability to manufacture, validate, sustain, adapt, and responsibly retire those satellites through sovereign or trusted supply chains.

This paper uses the term sovereign capability pragmatically. It does not imply that every component must be domestically produced by a single nation, nor that Europe should isolate itself from international collaboration. Rather, it means that Europe should possess sufficient industrial, technical, test, and operational depth to avoid dependency on external actors for critical sustainment functions.

In this context, modularity becomes strategically important. A modular spacecraft architecture allows common spacecraft elements to be manufactured at rate while mission-specific modules are developed, integrated, or replaced as required. It supports distributed industrial participation, enables small and medium-sized enterprises to contribute specific modules or subsystems, and allows defence users to separate platform procurement from payload or mission-system refresh.

Serviceability extends this logic into orbit. If spacecraft are designed with accessible modules, prepared interfaces, capture features, and validated servicing operations, then Europe can begin to treat orbital assets as maintainable infrastructure. This creates demand not only for spacecraft manufacturers, but also for servicing providers, robotics companies, interface developers, test facilities, insurers, mission planners, autonomy providers, and standards bodies.

Design for End-of-Life completes the architecture. A sovereign European space capability must not be built on an assumption of indefinite orbital accumulation. Spacecraft

should be designed to demise, dispose, recover, or be reused in ways that are consistent with future orbital sustainability requirements. The enduring spacecraft must not become the enduring debris object.

### **3. AN INTEGRATED ENGINEERING DOCTRINE**

The proposed doctrine is based on the integration of three design principles: Design for Manufacture, Design for Service, and Design for End-of-Life. Each principle is individually familiar. The novelty lies in treating them as co-equal architectural requirements for future small satellites, particularly those supporting defence and critical-infrastructure missions.

#### **3.1 DESIGN FOR MANUFACTURE**

Design for manufacture concerns the ability to produce spacecraft efficiently, repeatably, and at appropriate rate. In the small satellite sector, this usually implies modular assembly, standardised test flows, reduced bespoke engineering, simplified interfaces, common production tooling, and compatibility with industrialised assembly, integration, and test processes.

For defence and security users, design for manufacture has several advantages. It allows spacecraft platforms to be produced in batches, held at partial readiness, or configured late in the production cycle for specific missions. It reduces the cost and schedule burden associated with bespoke spacecraft development. It also allows industrial capacity to be distributed across European suppliers, provided interface control and quality assurance are sufficiently mature.

A manufacture-oriented modular architecture may include:

- a common structural bus.
- standardised payload bay or cassette.
- modular avionics bay.
- replaceable power subsystem.
- modular propulsion or disposal subsystem.
- repeatable harness and data interfaces.
- standard mechanical datum scheme.
- standard ground support and test access.
- common environmental test configuration.
- late-stage mission module integration.

The key manufacturing benefit is repeatability. A common architecture allows AIT processes, test plans, work instructions, tooling, metrology, and quality controls to be reused across multiple spacecraft. It also supports parallel production of modules, reducing bottlenecks and enabling multiple suppliers to contribute without redesigning the entire spacecraft.

However, Design for Manufacture alone can lead to closed architectures. A module may be easy to install on the ground but impossible to access in orbit. A spacecraft may be fast to assemble but incompatible with robotic servicing. A structure may support efficient production but include persistent components that complicate end-of-life disposal. For this reason, manufacturability must be integrated with serviceability and demise from the outset.

### 3.2 DESIGN FOR SERVICE

Design for Service means that a spacecraft is intentionally engineered to support future inspection, capture, docking, repair, refuelling, module replacement, upgrade, or reconfiguration. It does not require that every spacecraft will be serviced. Rather, it ensures that servicing is not made impractical by avoidable architectural decisions.

Serviceability has both external and internal dimensions. Externally, the spacecraft must present features that allow a servicing vehicle to locate, approach, inspect, capture, stabilise, dock with, or otherwise interact with it. Internally, the spacecraft must be arranged so that relevant modules can be accessed, removed, replaced, isolated, or upgraded without destroying the vehicle or creating unacceptable operational risk.

A serviceable small satellite may include:

- prepared capture or docking interface/
- cooperative fiducials or navigation markers.
- clearly defined approach corridors.
- keep-out zones and access envelopes.
- alignment features and datum references.
- robotic-compatible fasteners, latches, or release mechanisms.
- externally accessible module covers.
- modular electrical and data connectors.
- safe-mode configuration for servicing.
- load paths compatible with capture and manipulation.
- separation features for demating or replacement.
- software and autonomy modes to support servicing operations.

The engineering challenge is to avoid treating the servicing interface as a late addition. A capture fixture added after the spacecraft has been designed may not align with structural load paths, thermal constraints, field-of-view requirements, deployment mechanisms, or end-of-life assumptions. Similarly, a replaceable payload module is only useful if the module can be safely accessed, mechanically released, electrically isolated, and replaced without unacceptable contamination, collision, or debris generation.

Serviceability should therefore be treated as an architectural property. It affects mechanical design, avionics, software, thermal control, operations, safety, verification, and mission assurance. It also has implications for standards and interoperability. A servicing ecosystem cannot scale if every spacecraft requires a bespoke approach, unique tooling, or mission-specific interface negotiation.

### 3.3 DESIGN FOR END-OF-LIFE

Design for End-of-Life ensures that the spacecraft can be responsibly retired, demised, recovered, transferred, or reused. It includes but is not limited to design for atmospheric demise. It also includes passivation, controlled disposal, reduction of persistent fragments, safe handling of stored energy, and compatibility with future recovery or recycling concepts.

For small satellites in low Earth orbit, atmospheric re-entry is often the assumed disposal pathway. However, not all

spacecraft components demise equally. High-melting-point materials, dense optical elements, reaction wheels, tanks, batteries, and certain mechanisms may survive re-entry. As regulatory expectations increase, design-for-demise will need to move from a compliance exercise to an architectural principle.

A demisable small satellite architecture may include:

- demisable structural materials where practical.
- avoidance or minimisation of unnecessary high-melting-point components.
- battery and pressure-system designs that reduce ground casualty risk.
- passivation of stored energy.
- propulsion systems sized for reliable disposal.
- modular elements designed either to demise or to be recovered.
- separation strategies that do not create persistent debris.
- material selection consistent with environmental impact considerations.

Design for End-of-Life interacts with serviceability in important ways. A spacecraft designed for long-term servicing might otherwise use robust, persistent, mechanically durable structures that complicate demise. Conversely, a spacecraft optimised purely for demise may not tolerate the mechanical loads associated with capture, docking, or module replacement. The objective is not to maximise any single property, but to balance endurance, serviceability, and responsible disposal.

### 3.4 INTEGRATED DOCTRINE

*Table 1 — Integrated Design Doctrine for Modular, Serviceable and Demisable Small Satellites*

Principle	Engineering Focus	Operational Benefit	Sustainability Benefits
<b>Design for Manufacturing</b>	Standard modules, repeatable AIT, common interfaces, distributed supply chain	Faster production, lower cost, late mission configuration	Reduced bespoke waste and improved production efficiency
<b>Design for Servicing</b>	Capture features, robotic access, module replacement, docking compatibility, servicing modes	Repair, upgrade, refuel, reconfigure, inspect	Reduced need for full spacecraft replacement
<b>Design for End-of-Life</b>	Demisable materials, passivation, disposal reliability, recovery pathway	Reduced long-term liability and safer operations	Lower debris and casualty risk

The central premise is that these principles should be considered simultaneously at the earliest stages of spacecraft design. The architecture should not ask whether a spacecraft is manufactured, serviced, or disposed of. It should ask how each of those lifecycle phases informs the others.

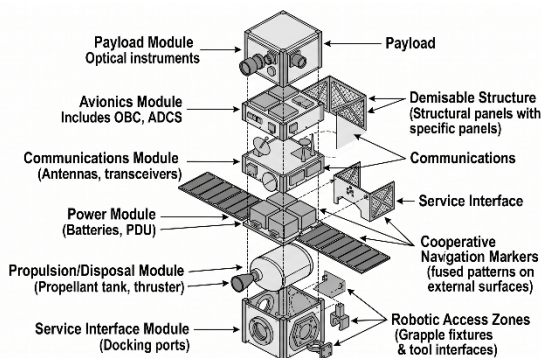
#### 4. REFERENCE ARCHITECTURE FOR A MODULAR, SERVICEABLE AND DEMISABLE SMALL SATELLITE

This section outlines a reference architecture rather than a fixed spacecraft design. The intent is to identify the minimum architectural features that allow a small satellite to be manufactured repeatedly, serviced where valuable, and retired responsibly. The architecture is therefore best understood as a validation framework: a practical model against which candidate spacecraft designs, interfaces, modules, and servicing concepts can be tested.

The proposed architecture comprises a common spacecraft bus with standardised mechanical, electrical, data, and servicing interfaces. Mission-specific capability is provided through replaceable modules, while the core bus provides power distribution, data handling, attitude control, thermal management, propulsion, structural support, and end-of-life functionality. A representative configuration would include a payload module, avionics module, power module, communications module, propulsion and disposal module, service interface, demisable structural bus, cooperative navigation features, and defined robotic access zones.

The service interface is one of the most important elements of architecture. It provides a repeatable mechanical boundary between the client spacecraft and a future servicing system. It should support alignment, capture, retention, load transfer, release, and safe separation without imposing excessive mass or complexity on the spacecraft. The interface should therefore define a clear reference plane, coordinate system, datum scheme, lead-in geometry, capture surfaces, latching or retention features, structural load paths, access volumes, tool clearances, and demate features.

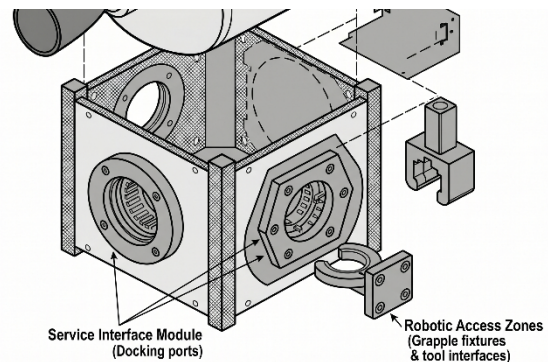
**Figure 1** - Diagram of a modular small satellite showing payload, avionics, power, propulsion/disposal, communications, service interface, demisable structure, cooperative navigation markers, and robotic access zones.



The interface should also be compatible with both ground integration and orbital servicing where possible. This allows

the same architectural logic to support manufacturing, assembly, integration, test, and servicing validation. Load paths are particularly important. A capture or docking event introduces mechanical loads that may not be present in a conventional disposable spacecraft design. If the servicing interface is not structurally integrated, capture loads may pass through sensitive payloads, panels, tanks, or appendages. The reference architecture therefore treats capture load paths as a primary structural design case rather than secondary accommodation.

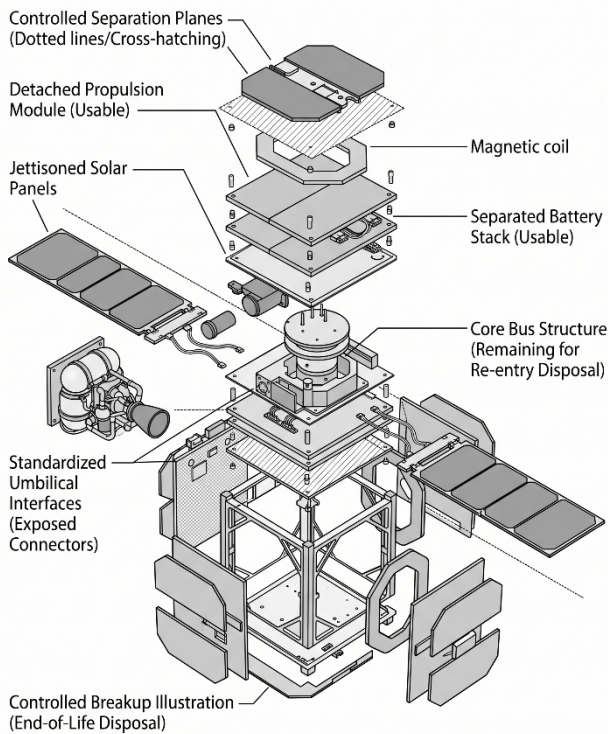
**Figure 2** -Close up of the Service Interface Module and Docking Ports as part of a modular, serviceable and demisable spacecraft.



Modularity must also be distinguished from serviceability. Many spacecraft contain modular internal subsystems that are accessible during ground integration but inaccessible after launch. To enable in-orbit servicing, selected modules must be located, mounted, connected, and released in ways compatible with robotic or semi-autonomous operations. This requires physical access to the module, a clear approach path, reliable release mechanisms, electrical and data isolation, connectors tolerant of orbital conditions, seating verification, software recognition, and safe handling of removed or failed modules.

End-of-life behaviour must be designed into the same architecture. The propulsion and disposal module should support reliable de-orbit, disposal transfer, servicing-assisted disposal, or future recovery depending on orbit and mission. Replaceable modules, covers, latches, or fasteners must not become uncontrolled debris. Failed modules should either remain attached, be captured by the servicer, be transferred to a disposal pathway, or be designed to demise safely. Material selection, stored-energy passivation, tank design, battery design, and structural fragmentation behaviour should all be assessed against end-of-life requirements.

**Figure 3** - Spacecraft demise following separation of usable subsystems e.g. propulsion, solar and batteries.



In this reference architecture, manufacture, service, and demise are not separate phases. They are coupled design constraints. A capture interface should also be assessed for structural integration and end-of-life consequences, and a demisable structure should also be assessed for its ability to tolerate ground handling, launch loads, and potential servicing interactions. The resulting architecture is not simply a modular small satellite, but a lifecycle-managed spacecraft platform.

The architecture should therefore adopt selective serviceability. Not every subsystem justifies orbital replacement capability. Payload cassettes, communications packages, batteries, propulsion elements, or mission-specific processors may provide strong serviceability value, whereas some structural, harness, or deeply embedded components may remain ground-replaceable only. The objective is not universal disassembly, but targeted access to modules whose replacement or upgrade materially improves mission resilience, operational availability, or technology refresh.

Serviceability is not purely mechanical. The spacecraft must include avionics and software modes that support safe inspection, approach, capture, servicing, and post-service verification. These may include cooperative attitude control, servicing safe mode, power isolation, module identification, command authority management, proximity operations support, and health reporting. For defence missions, these functions must be implemented without creating unacceptable cyber or command vulnerabilities. Authentication, encryption, authority transfer, and secure

servicing procedures are therefore part of the architecture, not later operational details.

## 5. VALIDATION THROUGH RPO GROUND INFRASTRUCTURE

A modular and serviceable spacecraft architecture cannot be validated by analysis alone. Rendezvous, proximity operations, docking, capture, robotic access, module replacement, and separation all involve coupled physical behaviours that must be tested under representative conditions. Ground-based validation provides the bridge between architectural intent and operational confidence.

### 5.1 THE ROLE OF RPO VALIDATION

Rendezvous, proximity operations and docking are central to in-orbit servicing. Even where the servicing action is limited to inspection or stabilisation, the servicer must approach the client safely, maintain relative position, understand the client geometry, and avoid collision. For docking, capture, or module replacement, the system must also demonstrate mechanical compatibility, alignment tolerance, load transfer, and controlled separation.

RPO validation supports several functions:

- verification of approach geometry.
- assessment of navigation and lighting conditions.
- testing of docking and capturing interfaces.
- measurement of alignment tolerance.
- evaluation of capture dynamics.
- testing of robotic access and manipulation.
- development of operational procedures.
- training and rehearsal.
- comparison of simulation and physical behaviour.
- generation of evidence for operators, insurers, and regulators.

The importance of validation is heightened by the need for interoperability. If spacecraft manufacturers, servicing providers, and operators are to converge on servicing-ready architectures, they require shared evidence about what works in practice. A paper interface standard is useful, but it becomes substantially more powerful when supported by physical test data.

### 5.2 THE CATAPULT RPO FACILITY AS A VALIDATION ENVIRONMENT

The Catapult's RPO facility provides a national capability for testing and validating rendezvous, proximity operations, docking, and servicing concepts. Its role is particularly relevant for modular serviceable spacecraft because it allows candidate interfaces, spacecraft geometries, robotic operations, and servicing concepts to be examined before orbital deployment.

For the reference architecture described in this paper, a representative validation campaign could include:

- **Interface alignment testing** — assessing whether the servicing interface can tolerate expected approach errors and alignment offsets.
- **Capture mechanism trials** — validating lead-in features, contact behaviour, retention, and release.
- **Robotic access testing** — verifying whether modules can be reached, released, extracted, replaced, and inspected.
- **Lighting and navigation assessment** — evaluating fiducials, markers, reflectors, and sensor visibility under representative illumination.
- **Load-path validation** — measuring mechanical loads during capture, docking, and manipulation.
- **Simulation-to-real correlation** — comparing digital models, autonomy simulations, and physical test outcomes.
- **Concept-of-operations development** — rehearsing approach, inspection, capture, servicing, contingency, and separation sequences.

**Figure 4** – Catapult RPO facility showing servicer interaction with a representative target spacecraft



### 5.3 FROM ARCHITECTURE TO EVIDENCE

A central benefit of RPO validation is that it turns architecture into evidence. This matters because servicing-ready spacecraft require confidence from multiple stakeholders. Manufacturers need confidence that design changes are technically justified. Operators need confidence that serviceability improves mission value. Defence users need confidence that the capability is operationally relevant. Insurers need evidence to reduce price risk. Regulators need evidence that servicing operations can be conducted safely. Investors and programme sponsors need evidence that the concept is credible, and the inherent risks are low.

Ground testing cannot fully replicate the orbital environment. It cannot remove the need for flight demonstration. However, it can reduce risk before flight by exposing mechanical, operational, and architectural issues early. It can identify whether servicing access is obstructed, whether capture features align with structural load paths, whether modules can be removed without creating debris, and whether the proposed servicing sequence is realistic.

The validation environment also supports standards development. Rather than defining servicing interfaces in abstraction, the community can use physical testing to understand tolerances, access envelopes, failure modes, and interface behaviours. This is especially important for small satellites, where mass, volume, cost, and integration constraints are severe.

## 6. DEFENCE AND SECURITY USE CASES

The value of modular, serviceable, and demisable spacecraft is clearest when linked to specific operational use cases. The following examples illustrate how the architecture could support European defence and security missions.

### 6.1 RAPID PAYLOAD REFRESH

Defence payloads can become obsolete faster than spacecraft buses. Optical sensors, RF payloads, processors, encryption systems, communications terminals, and onboard autonomy can all change rapidly. A modular payload architecture would allow the mission element to be upgraded without replacing the entire spacecraft.

This is particularly relevant for Intelligence, Surveillance, and Reconnaissance (ISR), electronic intelligence, maritime surveillance, and communications missions. A common spacecraft bus could be launched with an initial payload and later upgraded as sensors improve or threats evolve. In some cases, a spacecraft could be repurposed by replacing a payload module, extending the utility of the platform beyond its original mission.

### 6.2 RECOVERY FROM PARTIAL FAILURE

Many spacecraft failures are subsystem-specific rather than total. A failed battery, degraded communications unit, propulsion anomaly, avionics fault, or sensor failure may render a spacecraft partially or wholly ineffective even though the rest of the platform remains functional. A serviceable architecture creates the possibility of replacing or augmenting failed modules.

This is not a substitute for good design, redundancy, or mission assurance. Rather, it adds a sustainment pathway. In a defence constellation, recovering selected high-value spacecraft may be more efficient than launching replacements, particularly where orbital position, licensing, commissioning, or payload availability are constrained.

### 6.3 MISSION RECONFIGURATION

Operational requirements can change after launch. A constellation designed for one mission may need to support another. For example, an environmental monitoring spacecraft may become valuable for security operations, or a communications spacecraft may require additional resilience features. A modular architecture allows reconfiguration to be considered as an operational option.

Mission reconfiguration is likely to be selective rather than universal. Power, thermal, orbit, pointing, and data constraints will limit what can be changed. However, even

partial reconfiguration may have strategic value, especially during crisis response or fast-moving operational scenarios.

#### **6.4 ADVERSARIAL RESILIENCE**

Space systems are increasingly exposed to adversarial interference. This may include jamming, cyber intrusion, dazzling, spoofing, co-orbital threats, or other forms of degradation. Serviceability does not remove these threats. However, it can improve resilience by enabling inspection, diagnosis, repair, replacement, or reconfiguration after a non-catastrophic event.

For example, a spacecraft affected by a degraded sensor or communications package may be recoverable if the affected module can be replaced. A spacecraft suspected of physical damage may be inspected. A constellation experiencing mission degradation may be adapted by upgrading selected nodes. This shifts the resilience model from passive redundancy alone to active sustainment.

#### **6.5 SOVEREIGN SUSTAINMENT AND STOCKPILED MODULES**

A modular architecture enables defence users to stockpile mission modules, replacement units, or upgrade packages separately from spacecraft buses. This could support faster response and reduce dependency on full spacecraft procurement cycles. It also creates opportunities for European SMEs to supply specialised modules into a wider architecture.

#### **6.6 RESPONSIBLE DISPOSAL AND OPERATIONAL LEGITIMACY**

Defence space operations must remain compatible with orbital sustainability. A future European architecture that increases the number of satellites without addressing disposal, demise, and debris risk may face regulatory, diplomatic, and public resistance. Design for end-of-life is therefore not only an environmental issue. It is also an operational legitimacy issue.

### **7. BARRIERS, TRADE-OFFS AND IMPLEMENTATION CONSIDERATIONS**

The novelty of this approach is attractive, but it is not without cost or risk. Modularity, serviceability, and demise requirements can impose mass, volume, complexity, verification, and programme burdens. These must be addressed honestly if the architecture is to be credible.

#### **7.1 MASS AND VOLUME PENALTY**

Service interfaces, module housings, access panels, latches, alignment features, connectors, and structural reinforcements may increase spacecraft mass and volume. For small satellites, these penalties are significant. The architecture must therefore avoid excessive universal serviceability. Not every component should be replaceable in orbit. The design should focus on high-value modules where serviceability provides clear operational benefit.

#### **7.2 MECHANICAL AND OPERATIONAL COMPLEXITY**

A serviceable spacecraft introduces additional mechanisms and operational modes. These mechanisms must be reliable both during normal operations and during servicing. A failed latch, obstructed access panel, misaligned connector, or ambiguous safe mode could compromise the servicing operation. Simplicity should therefore be a core principle. Passive or low-complexity features may be preferable to elaborate mechanisms where practical.

#### **7.3 STANDARDISATION AND INTEROPERABILITY**

Serviceability only scales if interfaces are sufficiently standardised. However, premature standardisation can freeze immature designs, while excessive flexibility can prevent interoperability. Europe will need a staged approach: reference architectures, test campaigns, interface guidelines, flight demonstrations, and eventually more formal and likely universal standards.

Ground validation facilities can support this process by testing multiple candidate approaches and generating evidence. The objective should be practical convergence rather than standards theatre.

#### **7.4 COMMERCIAL AND PROCUREMENT INCENTIVES**

Manufacturers may not voluntarily add serviceability features if operators are unwilling to pay for them. Operators may not pay unless servicing providers exist. Servicing providers may not invest unless serviceable clients are available. This circular dependency is a classic market-enabling challenge.

Public intervention may therefore be justified, particularly for defence and critical infrastructure. Governments and public agencies can support early architectures, validation environments, demonstration missions, and procurement requirements that create initial demand. This does not require mandating a single design, but it may require specifying serviceability, modularity, and end-of-life behaviours as valued system attributes.

#### **7.5 INSURANCE, REGULATION AND MISSION ASSURANCE**

Servicing changes the risk model for spacecraft. It introduces new operational hazards but may reduce lifecycle risk by enabling recovery, inspection, and disposal. Insurers and regulators will require evidence to understand these trade-offs. Ground validation, simulation, flight demonstration, and operational data will all be needed.

Mission assurance processes must also adapt. A spacecraft designed for future servicing must be verified not only for launch and early operations, but also for later interaction with another spacecraft. This requires new test cases, safety analyses, fault trees, and operational procedures.

#### **7.6 DEFENCE SECURITY CONSIDERATIONS**

Serviceability creates new interfaces, and interfaces can create vulnerabilities. Defence spacecraft must ensure that servicing compatibility does not compromise security. Authentication, command authority, encryption, physical access control, and cyber resilience must be designed into the architecture.

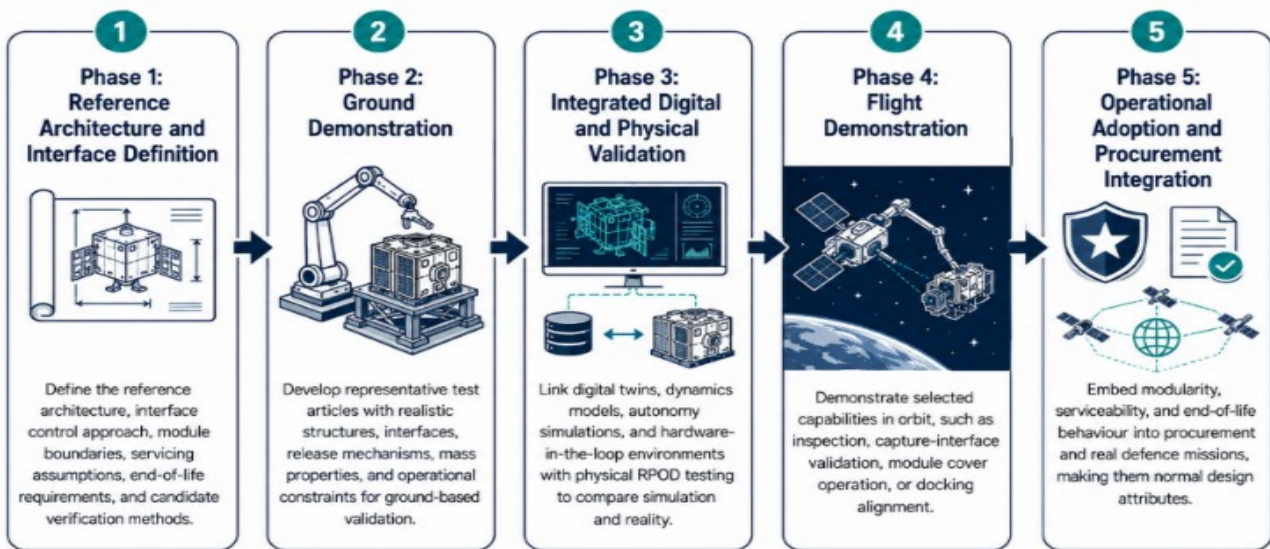


Figure 5 – Phased approach to the development and adoption of modular spacecraft within the European space eco-system

There is also a need to distinguish between cooperative servicing and hostile interaction. A prepared interface may assist friendly servicing, but it should not make adversarial capture or tampering easier. This is a difficult trade-off and should be addressed through operational doctrine, interface design, mission security, and space domain awareness.

### 7.7 INTEGRATION OF MANUFACTURE, SERVICE AND DEMISE AND IMPLEMENTATION

The most important implementation challenge is integration. It is relatively easy to optimise for one lifecycle phase at the expense of another. A highly manufacturable spacecraft may be inaccessible in orbit. A highly serviceable spacecraft may be too heavy or persistent. A highly demisable spacecraft may lack structural robustness for servicing. The doctrine therefore requires concurrent engineering across lifecycle phases.

A credible transition toward modular, serviceable, and demisable small satellites requires phased implementation. The objective should not be to jump directly from conventional disposable spacecraft to fully serviceable orbital infrastructure. Instead, Europe should pursue a staged pathway that builds evidence, industrial confidence, operational demand, and regulatory maturity as illustrated in Figure-5.

## 8. CONCLUSION

Europe’s future defence and security space architecture cannot rely solely on disposable small satellites and repeated replacement cycles. As space systems become more operationally critical, spacecraft must become more maintainable, upgradeable, adaptable, and environmentally responsible. Proliferation remains important, but proliferation without sustainment risks creating a costly and fragile replenishment model.

This paper has proposed an integrated engineering doctrine for modular, serviceable, and demisable small satellites. The doctrine combines Design for Manufacture, Design for Service and Design for End-of-Life into a single architectural approach. It seeks to enable high-rate European manufacturing, future in-orbit servicing, rapid payload refresh, mission reconfiguration, responsible disposal, and sustainment.

The technical challenge is not simply to add docking fixtures to existing spacecraft or to make individual components replaceable. The challenge is to design the full spacecraft lifecycle coherently, from production through operation, servicing, and retirement. Ground-based RPO validation, including facilities such those operated by the Catapult and other organisations e.g. GRALS at ESTEC, will be essential to converting this doctrine from concept into evidence. Such facilities allow docking interfaces, capture mechanisms, robotic access, servicing operations, and sim-to-real assumptions to be tested before flight.

For defence and security users, the implication is significant. A small satellite should no longer be viewed only as a consumable mission asset. It can become part of a sustained orbital infrastructure layer: manufactured at rate, upgraded when needed, serviced where valuable, and responsibly removed at end-of-life. If Europe wishes to build resilient and sovereign space capability, it must be able not only to launch satellites, but to sustain, adapt, and retire them responsibly.

## ACKNOWLEDGEMENTS

The authors acknowledge the contribution of collaborative discussions and development activity involving Leicester Space Park, the Satellite Applications Catapult, the University of Oxford, and associated UK and European partners working across modular spacecraft, in-orbit servicing, RPO validation, and sustainable spacecraft design.

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