Extending the Sensing Reach of Spacecraft with Autonomous Science Nodes

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Abstract

Conventional planetary spacecraft concentrate propulsion, power, communications, computation, environmental protection, and scientific instrumentation within individual, functionally complete vehicles. This architecture is effective for conventional missions but can constrain exploration of extreme environments in which spacecraft survivability, access, or deployment becomes the dominant limitation. This paper presents the Autonomous Science Node (ASN), a complementary mission architecture in which a conventional mothership deploys large populations of approximately 1 kg, mechanically hardened microprobes designed to perform limited scientific and environmental measurements rather than reproduce the capabilities of a complete spacecraft. The architecture combines a strict mass constraint, spherical encapsulation, distributed mechanical loading, and unconventional high-energy deployment to enable nodes designed to survive deployment environments that would otherwise preclude conventional small spacecraft. First-order analytical assessments are presented for node mass allocation, deployment loading, candidate encapsulation materials, power sources, communications, imaging, and radiation-protection approaches. The analysis further examines population-level mission characteristics, including redundancy, distributed environmental sampling, attrition tolerance, and the use of an ASN as a mechanically protected intermediate stage for secondary payloads. Representative applications are considered to illustrate the architectural flexibility of the approach. The analysis demonstrates a complementary architecture in which a capable primary spacecraft can retain high-value functions while a large population of simple, survivable nodes extends scientific reach, spatial coverage, and mission resilience.

1 Introduction

Planetary exploration spacecraft are conventionally designed as autonomous, functionally complete vehicles. Propulsion, navigation, power generation and storage, communications, computation, thermal management, environmental protection, and scientific instrumentation are integrated into each spacecraft so that the vehicle can independently accomplish its assigned mission. This architecture is highly effective for individual spacecraft carrying substantial payloads, but it also imposes a fundamental constraint on the exploration of extreme environments: every scientific measurement requires a spacecraft capable of transporting, protecting, powering, and communicating the system performing the measurement.

The Autonomous Science Node (ASN) architecture considered in this work adopts a fundamentally different approach. Rather than treating the spacecraft as the fundamental unit of planetary exploration, or attempting to miniaturize the entire spacecraft, ASNs physically separate spacecraft functions via individual, 1kg micro-probes that operate in a swarm-based ecosystem.

Instead of providing propulsion and navigation for each ASN, a mothership provides transport and deployment infrastructure while the micro-probes or ASNs provide orbital relay nodes and large populations of highly specialized remote sensors and mission tools. An individual ASN is therefore not required to be a complete spacecraft and instead operates as a wireless extension of the mothership. It becomes a functional element of a larger distributed spacecraft system.

This distinction fundamentally changes the design problem associated with very small planetary probes. The objective is to determine which functions must physically accompany the scientific measurement tool and which can be externalized to the distributed system. A node may therefore be designed almost entirely around its interaction with the target environment, while transportation, long-range communication, system-level computation, and other infrastructure are provided by other elements of the architecture. The resulting node can be smaller, simpler, less expensive, customized for one scientific purpose, and more tolerant of individual failure than a conventional autonomous spacecraft performing the same scientific function.

The architecture builds upon a previously developed tether-based deployment system capable of imparting very high release velocities to large populations of low-mass payloads [1]. The companion analysis demonstrated release velocities of up to approximately 14 km/s and established a deployment architecture in which hundreds to thousands of 1 kg payloads can be released from a rotating deployment system composed of 1km radial tethers. This transportation, targeting, and deployment capability is treated as a system-level resource rather than a capability that must be reproduced by each scientific node.

This physical separation of function also changes the relationship between mission success and individual node survival. A conventional planetary spacecraft is generally a single-point scientific asset: loss of the spacecraft eliminates its associated measurement capability. In contrast, an ASN swarm is not only tolerant of node loss, but node loss may be an intentional aspect of the mission strategy. Individual nodes may be consumed by deployment uncertainty, atmospheric entry, radiation exposure, impact, or intentional sacrifice without significantly compromising the scientific objective of the overall mission. Node failure becomes a characteristic of the architecture to be incorporated into system-level performance, intentionally or not, rather than an event that necessarily terminates or significantly compromises the mission.

This property is particularly important for planetary environments in which conventional spacecraft architectures impose severe limitations on access. A scientific node entering the atmosphere of a gas giant does not require the propulsion, communications, power, and operational lifetime expected of an independent spacecraft if the node's measurement can be performed during a short environmental interaction. The measurement data can subsequently be relayed to a craft outside of the danger zone or to the mothership. Similarly, a node intended to interact with the surface or atmosphere of a highly hostile body can be specialized for that interaction without carrying the infrastructure required to survive and operate as a complete spacecraft. The architecture therefore permits scientific objectives to be assigned to nodes whose designs are optimized for the environments in which those functions occur.

The feasibility of the approach therefore depends primarily on whether the resulting nodes can be constructed within the imposed mass constraint while satisfying the mechanical, energy, communications, and environmental requirements of the intended mission. This work therefore treats the approximately 1 kg ASN allocation as an architectural requirement rather than as a target to be relaxed as subsystem capabilities increase. The analysis then addresses the resulting requirements and common design elements for general node construction including power generation, communications, packaging, and deployment. Particular emphasis is placed on the use of commercially available or near-commercial components and established materials wherever practical, with the objective of demonstrating that the proposed architecture does not depend on speculative subsystem technologies.

The purpose of this work is consequently not to propose a single optimized planetary mission. Rather, it is to establish and quantify a distributed spacecraft architecture in which the individual scientific node is no longer required to function as an independent spacecraft. The analysis demonstrates how the combination of high-velocity distributed deployment, large node populations, functional separation, node-level specialization, and tolerance of individual node loss can produce useful scientific capability within an approximately 1 kg allocation. Example scientific missions are subsequently used to illustrate realistic application of this design across extreme planetary environments of high scientific value.

2 Prior Work and Architectural Distinction

2.1 Distributed Spacecraft Architectures

The distribution of spacecraft functions among multiple physical elements is an established area of spacecraft systems research. [2, 3] Distributed spacecraft architectures have been investigated for formation flying, interferometry, cooperative sensing, resource sharing, and other missions in which multiple spacecraft collectively provide capabilities that would otherwise be concentrated within a single vehicle. [4]

These architectures establish an important precedent for the ASN approach: spacecraft functions need not necessarily be physically co-located. [5] However, distributed and fractionated spacecraft generally retain the spacecraft or spacecraft module as the fundamental functional unit. As a result, each participating vehicle or module remains responsible for a defined portion of the spacecraft-level capability, and the system is subsequently integrated through inter-vehicle communication and coordination.

2.2 Spacecraft Swarms and Multi-Agent Exploration

Spacecraft swarms extend distributed architectures by employing populations of relatively small spacecraft or autonomous agents to provide spatial diversity, redundancy, cooperative sensing, and tolerance to individual vehicle failure. [6, 7] Such architectures have been proposed for Earth observation, space science, planetary reconnaissance, and other applications in which a population of agents can provide capabilities that are difficult or expensive to obtain with a single spacecraft. Heterogeneous swarm architectures further allow individual agents to perform different functions while contributing collectively to a common mission objective. [8]

The use of large populations introduces an important architectural property for planetary exploration: scientific capability need not depend on the survival of every individual vehicle. When measurements are distributed across a population, the loss of individual agents can be incorporated into the mission design rather than necessarily constituting a mission-ending failure. The population can consequently provide redundancy, spatial coverage, and statistical resilience that are difficult to obtain with a single spacecraft. [6]

The ASN architecture shares these characteristics but differs in the role assigned to the individual node. Prior art associated with probe swarms consist of multiple spacecraft whose collective behavior produces a mission capability. In the ASN architecture, the population is instead composed of nodes that are deliberately relieved of spacecraft-level functions that can be provided elsewhere in the system. The ASN swarm is therefore not a collection of small spacecraft, but a distributed spacecraft architecture in which the scientific node is itself a deliberately incomplete element.

2.3 Miniaturized and Low-Mass Planetary Spacecraft

The reduction of spacecraft mass and volume has been an important objective of planetary mission development. CubeSats, nanosatellites, and other small-spacecraft architectures have demonstrated that increasingly capable instruments and spacecraft subsystems can be implemented at substantially reduced mass.[9, 10] Interplanetary small-spacecraft concepts have extended these approaches beyond Earth orbit, including architectures employing large populations of extremely low-mass vehicles for asteroid belt study.[11]

These developments demonstrate that substantial spacecraft capability can be achieved through miniaturization. They do not, however, eliminate the fundamental architectural requirement that an individual spacecraft carry the functions necessary to perform its assigned mission. Miniaturization reduces the mass of those functions; it does not necessarily eliminate them.

The ASN architecture approaches the mass problem from a different direction. Rather than asking how much a complete spacecraft can be reduced, it asks which spacecraft functions are actually required at the location of a scientific measurement. Functions that do not require physical presence at the measurement site are assigned to other elements of the distributed system. The approximately 1 kg ASN allocation therefore represents neither a conventional spacecraft mass budget nor a target for progressively smaller spacecraft. It represents the mass allocated to the minimum physical node required to perform a specified scientific function.

2.4 Architectural Distinction of the Autonomous Science Node

The distinction between the ASN architecture and previous distributed, swarm, and miniaturized spacecraft concepts is therefore primarily architectural rather than technological. The present work does not propose that distributed spacecraft, spacecraft swarms, functional decomposition, or spacecraft miniaturization are themselves new concepts.[3, 11, 10] Instead, it combines these established principles around a specific architectural constraint: an individual ASN is not required to be an independent spacecraft.

The ASN architecture instead separates system functions according to their physical locality. Functions that must occur at the measurement site remain on the ASN, while functions that can be performed remotely are provided by other elements of the mission swarm ecosystem. A simplified representation is in Table 1.

Table 1: Spacecraft Ecosystem

Resource	**Purpose**
Mothership	Guidance, Transportation, Targeting, Deployment, Measurement, Short-range/Long-range Communication
ASNs	Measurement, Short-range Communication

Under this architecture, the ASN itself is not equivalent to a miniature spacecraft. Instead, the ASN constitutes the smallest physical element required to perform a particular scientific function within the larger distributed system, and that function can both be varied and specialized.

This distinction permits the mass, complexity, and survivability requirements of the node to be optimized independently of functions that need not accompany it. An ASN intended to measure radiation, sample an atmospheric constituent, observe a cryogenic liquid, or interact with a planetary surface need not share a common spacecraft architecture beyond the interfaces required to participate in the distributed system. Where appropriate, ASNs can be designed to harvest energy from specific environments, transport payloads, carry sampling mechanisms, or other functions that would otherwise require dedicated spacecraft subsystems. The resulting node is consequently not merely a smaller spacecraft. It is a specialized and remote physical interface between the distributed spacecraft system and the environment under investigation. The node can therefore be specialized around its scientific and environmental function rather than around the requirements of being an autonomous spacecraft.

2.5 Relationship to Previous ASN Deployment Work

The high-velocity tether deployment architecture supporting the present concept was developed and analyzed in previous work [1]. These analyses established the transport and underlying rotational deployment mechanics and demonstrated, for one case, release velocities approaching 14 km/s together with the capability to deploy large populations of low-mass payloads. The tether-based deployment geometry permits payloads to be released over a full rotational plane, while temporal and spatial distribution can be controlled through the location of the mothership or timing of the individual releases. The deployment process developed in the companion work exposes the ASN payload to acceleration levels in excess of 6000 g, establishing a primary mechanical survivability requirement for the ASN.

The present work treats this previously established deployment capability as system-level transportation infrastructure and survivability requirement rather than as a subject of further development. The mothership therefore performs a function analogous to a transportation system utilizing conventional spacecraft technologies and approaches, while the ASN is designed solely around the scientific and environmental requirements of the node and its survival of deployment. An illustrative population of approximately 400 ASNs is used in the analyses presented herein; the achievable population is ultimately dependent on launch vehicle payload capacity and mission-specific deployment requirements.

The significance of this relationship is that the mothership and ASNs are not independent spacecraft architectures operating in parallel. They are functional elements of a single distributed system. The subsequent sections examine the resulting ASN architecture and demonstrate that, just as the mothership can use conventional materials and well-established strategies, this separation of role and the ASN architecture can be implemented using Off-The-Shelf (OTS) or near-OTS components, materials, and engineering approaches.

3 Autonomous Science Node Engineering Architecture

3.1 Design Requirements

The Autonomous Science Node (ASN) is defined as a low-mass scientific node intended to operate as an element of a larger distributed spacecraft system. The baseline node mass is constrained to approximately 1 kg, with the physical architecture optimized around the scientific function and environmental conditions of the intended deployment.

The principal design parameters adopted for the baseline ASN are summarized in Table 2.

Table 2: Baseline ASN design parameters.

Parameter	**Baseline**	**Basis**
Node mass	1 kg	Architectural allocation
Maximum diameter	100 mm	Packaging constraint
Deployment velocity	Up to 14 km/s	Material limitations
Deployment G-forces	6000+ g	Dependent on deployment velocity
Internal protection	Encapsulated volume	Deployment survivability
Power	Mission dependent	Mission dependent
Communications	Short range	Distributed architecture
Scientific payload	Environment-specific	Node specialization

The 1 kg allocation is treated as an architectural constraint rather than a performance target to be increased when additional capability is required. Consequently, subsystem selection is driven by the minimum functionality required to perform the intended scientific measurement.

To note: commercial component specifications are used where appropriate to establish representative component mass, volume, power, or energy characteristics. These values are treated as design inputs rather than qualification data. Component survivability under the proposed deployment environment remains an engineering validation requirement and is not assumed solely from commercial datasheet specifications.

3.2 Structural Architecture

The baseline ASN employs a compact spherical structure to minimize external surface area relative to enclosed volume and to provide approximately uniform load paths during high-velocity deployment and subsequent environmental interaction. The baseline structure consists of an encapsulating medium surrounding a measurement tool (optional), power and processing subsystem, and communication subsystem. Other features may be a protective, metal shell, additional internal shielding, or other features that might be necessary for specific missions.

For an idealized spherical ASN, the total node mass can be approximated by

$$m_{\mathrm{ASN}} = \rho_{\mathrm{enc}} \left(V_{\mathrm{ASN}} - V_{\mathrm{hw}} \right) + m_{\mathrm{hw}} + m_{\mathrm{science}} \tag{1}$$

where ρ_{enc} is the density of the encapsulation medium, V_{ASN} is the external volume of the spherical node, V_{hw} is the volume occupied by embedded hardware, m_{hw} is the mass of the embedded power, processing, communication, and other engineering hardware, and m_{science} is the mass of the scientific measurement payload.

A representative mass closure was performed to assess whether the nominal 1 kg ASN allocation is compatible with the component classes described above. The estimate uses a configuration incorporating 27 betavoltaic cells, low-power communications and processing electronics, two compact optical sensors, and a nominal 10-cm-diameter polycarbonate encapsulation. The resulting allocation is shown in Table 3.

Table 3: Representative mass closure for a 1-kg ASN configuration.

Component	**Representative Mass (g)**
Power generation/storage	81.5
Communications	1.0
Processing/control	0.4
Scientific payload (2 MEMS cameras)	8.0
Encapsulation/structural protection	628.0
Subtotal	718.9
Remaining mass allocation	281.1
Total allocation	1000.0

The representative configuration therefore closes within the nominal 1 kg mass allocation, with more than 281 g remaining for additional structure, thermal components, communications hardware, wiring, interfaces, or other mission-specific requirements. The estimate is conservative with respect to encapsulation volume because the calculation does not credit the displacement of encapsulant by the internal components. For this configuration, the resulting constraint is therefore more strongly volumetric than mass-limited.

The spherical geometry proposed eliminates preferred stress orientations and distributes external loads over the surface. Internal components are arranged to minimize unsupported voids and to provide mechanical coupling between the payload volume and encapsulation medium. Where practical, the internal volume is occupied by solid-state components, or other mechanically coupled materials rather than leaving large internal cavities.

3.3 Mechanical Survivability

Mechanical survivability is a fundamental requirement of the baseline ASN architecture because the nodes are subjected to the extreme acceleration environment associated with tether deployment. The previously developed 1 km-class tether architecture supports release velocities substantially above those required for the baseline ASN mechanical case. The present analysis adopts a release velocity of approximately 7.9 km/s and the corresponding previously established 6363 g acceleration condition as the nominal mechanical design case, while the broader architecture has demonstrated release velocities approaching 14 km/s. [1]

For a 1 km tether, the relationship between tangential velocity and angular velocity is

$$v = \omega r \tag{2}$$

Therefore,

$$\omega = \frac{v}{r} \tag{3}$$

For a tip velocity of 7.9 km/s and a tether length of 1000 m,

$$\omega = \frac{7900\,\mathrm{m/s}}{1000\,\mathrm{m}} = 7.9\,\mathrm{rad/s} \tag{4}$$

The corresponding rotational speed is

$$\mathrm{RPM} = \frac{\omega}{2\pi}(60) \tag{5}$$

giving

$$\mathrm{RPM} = \frac{7.9}{2\pi}(60) \approx 75.5\,\mathrm{RPM} \tag{6}$$

The centripetal acceleration at the tether tip is

$$a_c = \frac{v^2}{r} \tag{7}$$

Thus,

$$a_c = \frac{(7900)^2}{1000} = 62\,410\,\mathrm{m/s^2} \tag{8}$$

Expressed as a multiple of standard gravitational acceleration,

$$G = \frac{a_c}{g} \tag{9}$$

where

$$g = 9.806\,65\,\mathrm{m/s^2} \tag{10}$$

Therefore,

$$G = \frac{62410}{9.80665} \approx 6363\,g \tag{11}$$

For a 1 kg ASN, the corresponding inertial force is

$$F = ma \tag{12}$$

Therefore,

$$F = (1\,\mathrm{kg})(62\,410\,\mathrm{m/s^2}) \approx 62.4\,\mathrm{kN} \tag{13}$$

The ASN is not designed as a hollow enclosure containing independently supported components. Instead, the baseline architecture favors solid-state components and fully encapsulates the internal assembly within a structural medium selected to penetrate available voids and cavities. The resulting node behaves mechanically as a single, approximately spherical solid assembly, although its internal density and material properties are heterogeneous because of the differing mass properties of the embedded components and encapsulation material. This configuration eliminates internal free volume and minimizes relative motion between components during high-acceleration deployment.

The proposed deployment configuration further distributes the mechanical load through an enclosing basket of Kevlar fibers rather than through a single point attachment. The resulting load path is therefore governed by distributed contact between the support fibers and the spherical ASN. The combination of distributed external loading and monolithic internal encapsulation is expected to reduce internal component-to-component motion and localized mechanical loading.

Candidate encapsulation and structural materials were screened using representative mechanical properties for polycarbonate (PC), high-density polyethylene (HDPE), polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), and acrylonitrile butadiene styrene (ABS), as summarized in Table 4. These materials provide a representative range of density, stiffness, strength, and elastic response for evaluating a low-cost spherical ASN structure.

Table 4: Representative Mechanical Properties of Candidate ASN Encapsulation Materials [12]

Property	**PC**	**HDPE**	**PEEK**	**PMMA**	**ABS**
Density, ρ [kg/m^3]	1210	960	1310	1190	1050
Young's modulus, E [GPa]	2.2	0.74	3.9	3.22	2.29
Yield strength, σ_y [MPa]	62.9	29	80	72	47.5
Tensile strength [MPa]	65	29	103	64	55
Poisson's ratio, ν	0.37	0.40	0.38	0.35	0.388

These properties provide the initial material inputs for structural screening but do not by themselves predict the deformation of the completed ASN. Because the node is a heterogeneous solid assembly, the actual response depends on the geometry and distribution of encapsulated components, the properties of the encapsulation medium, the contact conditions imposed by the Kevlar support basket, and the transient nature of the deployment event. In particular, polymer response can be sensitive to strain rate.

3.4 Preliminary Structural Assessment

The baseline ASN structural configuration consists of a solid polycarbonate encapsulation supported by a distributed Kevlar sling basket. The Kevlar members do not attach directly to the encapsulation; instead, each continuous loop leaves the common tether attachment region, contacts the spherical surface, and returns to the attachment region. The resulting configuration distributes the deployment load over the encapsulation rather than applying the full inertial load at a discrete structural attachment.

For a conservative preliminary assessment, a design acceleration of $6500\,g$ is assumed. For a 1 kg ASN, the corresponding inertial load is

$$F = ma = (1)(6500)(9.80665) \approx 63.7\text{ kN}. \tag{14}$$

The basket contains 14 continuous Kevlar loops, with two load-bearing segments per loop. Assuming symmetric loading and a 10° angle between each segment and the deployment axis, the tensile load in each segment is

$$T = \frac{F}{2N\cos\theta} = \frac{63.7\text{ kN}}{2(14)\cos(10^\circ)} \approx 2.31\text{ kN}, \tag{15}$$

where $N = 14$ is the number of loops and $\theta = 10^\circ$ is the segment angle relative to the deployment axis.

For a Kevlar cross-sectional area of 1.30 mm^2 per segment, which is 1/14th of the main tether thickness area of 0.176 cm^2, the corresponding tensile stress is

$$\sigma_K = \frac{T}{A_K} = \frac{2.31\text{ kN}}{1.30\text{ mm}^2} \approx 1.78\text{ GPa}. \tag{16}$$

This value is below the nominal tensile strengths reported for representative Kevlar 29 and Kevlar 49 yarns [?]. These published values are typical material values rather than product-specific specifications and therefore are used here only as a preliminary screening basis. Detailed hardware design would require consideration of termination efficiency, bending, abrasion, manufacturing variability, and the properties of the selected commercial Kevlar product.

The Kevlar basket transfers the resulting load to the polycarbonate encapsulation through distributed contact along the spherical surface. As a first-order global screening calculation, the total inertial load is conservatively distributed over the projected area of the 100 mm diameter sphere,

$$A_{\text{proj}} = \pi R^2 = \pi(50\text{ mm})^2 \approx 7854\text{ mm}^2. \tag{17}$$

The resulting equivalent average compressive stress is therefore

$$\sigma_{\mathrm{PC}} = \frac{F}{A_{\mathrm{proj}}} \approx \frac{63.7\ \mathrm{kN}}{7854\ \mathrm{mm}^2} \approx 8.1\ \mathrm{MPa}. \tag{18}$$

Using the assumed polycarbonate yield strength of 62.9 MPa, the corresponding yield safety factor is

$$SF_{\mathrm{PC}} = \frac{62.9}{8.1} \approx 7.8. \tag{19}$$

The corresponding elastic strain, using an elastic modulus of 2.2 GPa, is

$$\epsilon = \frac{\sigma_{\mathrm{PC}}}{E} = \frac{8.1}{2200} \approx 0.0037, \tag{20}$$

or approximately 0.37%. If conservatively applied over the full 100 mm characteristic dimension, this corresponds to an elastic dimensional change of approximately

$$\delta_{100} = \epsilon L \approx (0.0037)(100\ \mathrm{mm}) \approx 0.37\ \mathrm{mm}. \tag{21}$$

For comparison, over a 3 mm characteristic dimension representative of an embedded component feature, the corresponding strain-induced dimensional change would be approximately

$$\delta_3 = \epsilon(3\ \mathrm{mm}) \approx 0.011\ \mathrm{mm}, \tag{22}$$

or approximately 11 μm.

These calculations constitute a first-order structural screening rather than a detailed three-dimensional contact or transient dynamic analysis. The results indicate that the proposed encapsulation remains within the assumed elastic regime under the nominal deployment load, while the distributed Kevlar basket provides a load path that avoids a discrete attachment interface in the polycarbonate. Detailed contact, termination, and dynamic structural analysis would be appropriate during subsequent hardware development and qualification.

The analytical calculation establishes the magnitude of the deployment loading, while the baseline analysis will evaluate candidate materials using the distributed Kevlar-basket load configuration under the 6363 g design condition. The resulting stress and deformation fields will determine whether the baseline monolithic construction provides sufficient structural integrity and protection of the encapsulated components.

Where a mission imposes additional environmental requirements, structural reinforcement can be added without changing the underlying ASN architecture. A 4 mm-thick aluminum outer shell represents one candidate hardened configuration for missions involving extreme radiation, impact, or other severe external environments. The reinforced configuration can be evaluated using the same mechanical model to quantify the reduction in deformation and stress.

The resulting architecture therefore separates the minimum mechanical requirements of an ASN from mission-specific hardening. A baseline node can be constructed as a fully encapsulated solid-state assembly, while additional structural or environmental protection is introduced only when required by the intended mission.

3.5 Power Architecture

Power generation is treated as a node-specific engineering function. The required power is determined by the scientific measurement, processing, communications, and environmental requirements of each node rather than by a common spacecraft bus architecture. For many applications, ceramic capacitors, solid-state or semi-solid-state batteries, or betavoltaic power sources may be considered, depending on mission duration, power demand, and environmental constraints. [13, 14, 15] The selection criteria for the power system of an ASN are

- Deployment survivability ($> 6000\ g$)
- ASN longevity requirement (days, months, years)
- Environmental survivability (radiation, cold, heat)
- Environmental opportunity (power harvesting)

Ceramic capacitors, betavoltaic sources, and solid-state or semi-solid-state batteries offer architectures in which the active energy-storage or generation elements can be packaged without large volumes of free liquid. Their survivability under the ASN deployment environment, however, remains a qualification question rather than an established property of the technology classes. [13, 15]

Table 5: Betavoltaics and Battery/Capacitor Design Considerations [16, 13, 14, 15]

Parameter	**Betavoltaics**	**Battery***	**Capacitors****
Voltage Output/unit	2 V	4 V	Var
Wattage Output/unit	5 μW [13]	Var	Var
Dimensions	0.5 cm^3	0.4 cm^3	0.008 cm^3
Operational Lifespan	10–20 yrs	10–20 yrs	40+ yrs
Energy replenishment	No	Yes	Yes

*Representative commercial semi-solid-state battery specification. **Selected component/design input; not a universal capacitor material property.

3.5.1 Betavoltaics

A common consideration for betavoltaic architecture has to do with its extremely low power generation. This limits the application of betavoltaic power generation to ultra-low-power systems and applications in which electrical energy can be accumulated over time. If betavoltaics are used for ASNs, a hierarchical power-management strategy would be required to accumulate energy and schedule higher-power operations. This would be best represented with betavoltaic cells trickle charging a capacitor bank, then as power reaches a threshold, it can power different devices based on schedule or priority.

A power management strategy using betavoltaic batteries would be represented by the following:

$$P_{\text{gen}} = N P_{\text{cell}}, \tag{23}$$

where N is the number of cells and P_{cell} is the output of an individual cell.

Within the available volume of a 100 mm-diameter ASN, an illustrative allocation of 27 betavoltaic cells would occupy approximately 13.5 cm^3, assuming a nominal cell volume of 0.5 cm^3 per cell. The cell dimensions are based on the selected commercial betavoltaic package, while the 27-cell allocation and resulting volume are architectural calculations. [13]

$$P_{\text{gen}} = 27\,(5\,\mu\text{W}) = 135\,\mu\text{W}. \tag{24}$$

For approximately constant generation, the accumulated electrical energy over an interval t is

$$E_{\text{gen}} = P_{\text{gen}} t. \tag{25}$$

The available energy is determined by the difference between generated energy and the integrated subsystem load:

$$E_{\text{available}} = \int_0^t \left[P_{\text{gen}}(\tau) - P_{\text{load}}(\tau)\right] d\tau. \tag{26}$$

This formulation permits energy storage and scientific activity to be scheduled around the low continuous power available from the primary generator. High-power operations such as imaging and transmission can be performed intermittently while energy accumulates between measurement events.

Existing OTS electronics can demonstrate the feasibility of this strategy. MEMS mirrors and photodiode assemblies are often represented in 2-D bar code scanners and operate on milliamps, sufficient for millivolt betavoltaic energy generators.

Table 6: Estimated Energy Budget for Representative ASN Operations Based on 27 Betavoltaic Cells

Operation	**Power**	**Duration**	**Energy**	**Recharge Time**
MSPM0 μC (Active)	92.3 μW	100 ms	9.2 μJ	0.07 s
Communication Receive	9.9 mW	100 ms	1.0 mJ	7.4 s
Communication Xmit	99 mW	100 ms	10 mJ	74 s
Image Acquisition	375 mW	100 ms	37.5 mJ	4.6 min
Housekeeping (Standby)	1.3 μW	Continuous	Continuous	N/A

The event-based energy budget provides a framework for evaluating mission feasibility and establishes the relationship between continuous power generation, stored energy availability, and achievable operational cadence. Although there will be resource availability limitations per node, in a swarm of 400 nodes, sampling density would be high (discussed in Section 4.6).

3.5.2 Solid State Batteries (SSB)

If SSBs are to be used for ASNs, a simpler power management strategy can be used, but the cost is the short-term availability for that power unless there is a regeneration opportunity from the environment. This is, of course, a matter of ASN purpose and design.

For specialized nodes that harvest energy from environments, the energy model permits an environmental energy source to supplement or replace continuous low-power generation:

$$E_{\text{harvested}} = \int_{t_0}^{t_1} P_{\text{harvest}}(t)\, dt. \tag{27}$$

This permits the power architecture to be specialized to the environment rather than imposing a common power-generation technology on every ASN.

3.5.3 Ceramic Capacitors

Ceramic capacitors represent an opportunity for trickle charge energy storage and high-intensity energy delivery for short events. Should they be used for ASNs, they offer a high capacity for energy, but the cost is their comparatively low power density, the short-term availability for that power, or the necessity for a power regeneration strategy. This regeneration can be through betavoltaic power cells, SSBs, or environmental sequestration. If capacitors are used only, then their best application would be for an ASN with a very short, but power demanding application and the capacitors would need to be pre-charged prior to deployment.

3.6 Scientific Payload Architecture

The ASN scientific payload is designed primarily as a measurement interface within the distributed spacecraft system rather than as an independent spacecraft instrument suite. A deployed scientific node therefore needs to accommodate a sampling strategy that aligns with power and communication capability, as well as environmental considerations like temperature and radiation.

3.7 Communications Architecture

The ASN communications system is designed primarily for communication with other nodes within the distributed spacecraft system or with the mothership. A deployed scientific node therefore does not necessarily require a deep-space communications subsystem capable of establishing an independent Earth link when the mission architecture provides an alternative data-return path through the mothership or other nodes.

For a radio-frequency local link, the received power can be approximated using the Friis transmission equation:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2, \tag{28}$$

where P_t is transmitter power, G_t and G_r are transmitter and receiver gains, λ is wavelength, and R is the separation between nodes.

The free-space path loss is

$$L_{\mathrm{FS}} = 20 \log_{10} \left(\frac{4\pi R}{\lambda} \right). \tag{29}$$

The communication link is therefore governed primarily by node separation, transmitter power, antenna gain, receiver sensitivity, and required data rate. Because the ASN is not required to establish a direct Earth link, these parameters can be optimized for local communication rather than deep-space transmission.

The long-range data-return link is provided by higher-level elements of the spacecraft system. The detailed deep-space optical communications analysis established in previous work is therefore not reproduced here; only the local ASN communication requirements are considered in the node-level engineering analysis.

3.8 Processing and Node Autonomy

Local processing is restricted to functions required to acquire, condition, store, and transmit scientific observations and to maintain node health. Computationally intensive interpretation is not required when raw or minimally processed observations can be forwarded to another node or to the mothership.

A representative node operating sequence is

$$\text{Deploy} \rightarrow \text{Acquire} \rightarrow \text{Measure} \rightarrow \text{Store} \rightarrow \text{Transmit} \rightarrow \text{Sleep}. \tag{30}$$

The node may transition between these states according to available energy, environmental conditions, measurement opportunities, and communications availability. This permits the processing and power requirements to remain proportional to the scientific function rather than to the requirements of autonomous spacecraft operation.

3.9 Engineering Closure

The baseline engineering architecture is evaluated against four primary constraints: mass, physical volume, available energy, and environmental survivability. These constraints are coupled. Increasing structural protection increases mass; increasing shielding reduces the mass available to the scientific payload; increasing imaging or communications activity increases energy demand; and environmental specialization changes the appropriate power, structural, and sensing architecture.

The resulting design problem can therefore be expressed as

$$m_{\text{supportmedium}} + m_{\text{power}} + m_{\text{science}} + m_{\text{communications}} + m_{\text{processing}} \leq m_{\text{ASN}}, \tag{31}$$

with

$$m_{\text{ASN}} \approx 1\,\text{kg}. \tag{32}$$

Similarly, the energy balance must satisfy

$$E_{\text{generated}} + E_{\text{stored}} \geq E_{\text{science}} + E_{\text{communications}} + E_{\text{processing}} + E_{\text{overhead}}. \tag{33}$$

These relationships provide the primary engineering closure criteria for the ASN. A node design that cannot satisfy the mass and energy constraints is not recovered by increasing spacecraft-level capability; instead, the affected scientific function must be simplified, specialized, or reassigned to another node.

The resulting architecture therefore establishes a quantitative basis for evaluating specialized ASNs within the larger distributed spacecraft system. The following section applies this architecture to representative scientific environments in which the ability to distribute sensing, tolerate individual node loss, and specialize individual nodes produces capabilities that are difficult to obtain with conventional planetary spacecraft.

4 Operational Architecture

The ASN architecture is intended to operate as a distributed extension of a conventional spacecraft rather than as a population of independent spacecraft. The primary spacecraft, hereafter referred to as the mothership, provides transportation, navigation, bulk power, long-range communications, and other spacecraft-level infrastructure. Autonomous Science Nodes (ASNs) are deployed from the mothership when and where their specialized functions are required. The resulting architecture separates functions according to the environment in which they must be performed: the mothership remains responsible for functions that can be performed from a relatively benign spacecraft environment, while ASNs provide the physical and computational interface to environments that the mothership may be unable or unwilling to enter.

This separation is central to the architecture. The ASN does not reproduce the complete functionality of a conventional spacecraft at reduced scale. Instead, it carries only the functions that must accompany the science payload into the target environment. Transportation and spacecraft-level infrastructure are therefore amortized across the entire ASN population.

4.1 Mothership–ASN Functional Decomposition

The operational architecture consists of three principal elements: the mothership, the tether deployment system, and the ASN population. The mothership establishes the mission trajectory and provides the infrastructure required to transport and support the population. The tether deployment system converts the mothership's orbital state into the release conditions required for ASN deployment. Individual ASNs subsequently execute mission-specific operations without requiring independent propulsion systems.

The functional decomposition can therefore be expressed as

$$\mathcal{M} = \mathcal{M}_{\text{transport}} + \mathcal{M}_{\text{infrastructure}} + \mathcal{M}_{\text{deployment}} + \mathcal{M}_{\text{science}} \tag{34}$$

where $\mathcal{M}_{\text{transport}}$ represents interplanetary and planetary-system transportation, $\mathcal{M}_{\text{infrastructure}}$ represents functions such as navigation, high-power generation, long-range communications, and bulk data handling, $\mathcal{M}_{\text{deployment}}$ represents local distribution of ASNs, and $\mathcal{M}_{\text{science}}$ represents the measurements and environmental interactions performed by the distributed nodes.

The principal architectural objective is to minimize the subset of these functions that must be replicated at the node level. If N ASNs are deployed, functions retained exclusively at the mothership are incurred approximately once, while functions that must be duplicated at every node scale with N. The total system resource requirement can therefore be represented conceptually as

$$R_{\text{total}} = R_{\text{mothership}} + NR_{\text{ASN}}, \tag{35}$$

where R may represent mass, power, volume, cost, or another system resource. The ASN architecture seeks to minimize R_{ASN} by retaining infrastructure-intensive functions at the mothership.

This relationship does not imply that infrastructure can be completely centralized; rather, it identifies the functions for which duplication at the node level provides insufficient mission benefit to justify the associated mass, power, and volume.

This decomposition becomes increasingly advantageous as the number of deployed nodes increases. A function that would otherwise require substantial hardware on every spacecraft can instead be centralized when that function does not need to physically accompany the scientific measurement.

4.2 Deployment Sequence

Following arrival in the target planetary system, the mothership establishes the orbital or flight condition from which ASN deployment will occur. The tether deployment system then produces the required release velocity and direction for individual nodes. The mothership may subsequently repeat the process to populate multiple trajectories or environmental regions.

A representative operational sequence is:

1. The mothership performs interplanetary transfer and establishes the required mission trajectory.
2. The mothership enters the selected deployment orbit or flight condition.
3. The tether system is deployed and rotated to establish the required release state.
4. An ASN is released at the prescribed phase angle and tangential velocity.
5. The ASN transitions to autonomous operation following release.
6. The ASN performs its assigned sensing, communication, or environmental-interaction function.
7. Data are transmitted directly to the mothership, relayed through other ASNs, or transmitted through another mission-specific communications path.
8. The process is repeated until the required node population or spatial distribution has been established.

The deployment process therefore transforms a single mothership trajectory into a population of independently operating mission elements. Importantly, the ASN does not require an independent propulsion system to accomplish this distribution. Its initial trajectory is established by the deployment mechanism.

For an idealized release from a rotating tether, the release velocity can be represented as

$$v_{\mathrm{rel}} = \omega r, \tag{36}$$

where ω is the tether angular velocity and r is the effective release radius. The resulting inertial velocity of an ASN is the vector sum of the mothership velocity and the release velocity:

$$\mathbf{v}_{\mathrm{ASN}} = \mathbf{v}_{\mathrm{MS}} + \mathbf{v}_{\mathrm{rel}}. \tag{37}$$

The corresponding specific orbital energy relative to the central body is

$$\epsilon = \frac{v_{\mathrm{ASN}}^2}{2} - \frac{\mu}{r_{\mathrm{MS}}}, \tag{38}$$

where μ is the gravitational parameter of the central body and r_{MS} is the mothership's radial distance from that body at release.

For a bound two-body trajectory, the resulting semimajor axis is

$$a = -\frac{\mu}{2\epsilon}. \tag{39}$$

These relationships establish an important separation between the transportation and mission functions. The tether system determines the initial conditions of the ASN trajectory, while the ASN itself need not reproduce the propulsion and guidance functions normally required to establish that trajectory.

4.3 Population-Level Operation

For a population of N nodes, the number of surviving nodes at time t may be represented as

$$N_{\text{surv}}(t) = N_0 \left[1 - F(t)\right], \tag{40}$$

where N_0 is the initial population and $F(t)$ is the cumulative fraction of nodes lost by time t.

Under an independent-node approximation, and with the probability that an individual node remains operational at time t represented by $p(t)$, the expected surviving population is

$$E[N_{\text{surv}}(t)] = N_0 p(t). \tag{41}$$

The architecture therefore permits a deliberate distinction between *node reliability* and *mission reliability*. A mission need not require every ASN to survive if the scientific objective can be satisfied by the surviving population. Additionally, should a node or population of nodes fail, the mothership may deploy replacements as resources and planning allow.

For a measurement requiring at least k successful nodes from an initial population of N_0, the probability of satisfying the requirement can be expressed, under an independent-node approximation, as

$$P(N_{\text{surv}} \geq k) = \sum_{i=k}^{N_0} \binom{N_0}{i} p^i (1-p)^{N_0 - i}. \tag{42}$$

This population-level reliability is one of the principal benefits of deploying large numbers of low-mass nodes. Increasing the population can provide mission-level robustness without requiring each individual node to achieve the reliability normally expected of a primary spacecraft.

4.4 Distributed Communications

Communication within the ASN architecture is similarly distributed. An ASN may communicate directly with the mothership when geometry and link margin permit, communicate with another ASN acting as an intermediate relay, or perform a direct downlink when the mission architecture provides sufficient optical or radio link capability.

The architecture can therefore be represented by a communication graph

$$G = (V, E), \tag{43}$$

where V represents the mothership and active ASNs and E represents available communication links between nodes.

For a given node i, the available communication paths may include

$$i \to \text{MS}, \tag{44}$$

for a direct ASN-to-mothership link, or

$$i \to j \to \text{MS}, \tag{45}$$

for a relay through another ASN j.

This topology allows communications architecture to be selected according to mission geometry rather than imposing a universal communications requirement on every ASN. Nodes operating in favorable geometries may transmit directly, while nodes obscured by terrain, atmospheric conditions, or orbital geometry may use neighboring nodes or the mothership as relays.

The architecture also permits communication roles to change during a mission. A node initially assigned to science operations may subsequently serve as a relay, while a node approaching the end of its operational lifetime may prioritize transmission of stored observations rather than continued sensing.

4.5 Data Collection and Load Balancing

Distributed science creates a corresponding opportunity for distributed data collection. Rather than requiring every ASN to maintain continuous communication with the mothership, nodes may buffer observations locally and transmit when a suitable communication opportunity becomes available.

For a node producing data at an average rate $\dot{D}_i$ and transmitting at rate R_i, the local data storage requirement over an interval Δt is approximately

$$D_{\text{buffer},i} \geq \max \left[0, \int_0^{\Delta t} \left(\dot{D}_i - R_i\right) dt\right]. \tag{46}$$

This allows sensing and communications to be temporally decoupled. A node may therefore continue scientific operation during periods when communication is unavailable, followed by a later data-transfer interval.

At the population level, this creates an additional form of load balancing. If multiple nodes observe overlapping regions or phenomena, the loss or temporary unavailability of an individual node does not necessarily prevent collection of the corresponding measurement. The population can therefore provide temporal and spatial redundancy without requiring identical operational states across all nodes.

4.6 Operational Scaling

The principal scaling characteristic of the architecture is that increasing the number of ASNs primarily increases the number of available environmental interfaces rather than duplicating the entire spacecraft infrastructure.

If the effective scientific coverage provided by one node is C_{ASN}, an idealized upper-bound aggregate coverage for N independent nodes is

$$C_{\text{total}} \approx N C_{\text{ASN}}, \tag{47}$$

subject to overlap, communications constraints, trajectory dispersion, and other mission-specific limitations.

The corresponding scaling differs from an architecture in which each node must independently provide transportation, navigation, power generation, and long-range communications. In the ASN architecture, these functions are provided at the system level and shared across the node population.

The result is a deliberate trade between individual-node capability and population size. Rather than maximizing the capability of an individual spacecraft, the architecture seeks an operating point at which sufficiently capable nodes can be manufactured, transported, deployed, and lost in large numbers while maintaining useful aggregate mission performance.

5 Example Mission Applications

5.1 Purpose and Scope

The preceding sections establish the Autonomous Science Node (ASN) as a distributed spacecraft architecture intended to operate under environmental conditions that impose severe constraints on conventional spacecraft systems. The architecture does not depend on a single environmental adaptation, but instead combines low node mass, distributed functionality, autonomous operation, long-duration low-power systems, and population-level redundancy.

This section illustrates how these architectural properties can be applied to several representative planetary environments. These examples are not intended as complete mission designs. Rather, they provide concise engineering demonstrations of how the ASN architecture can be adapted to environments in which conventional spacecraft architectures face significant limitations.

Three application classes are considered: high-radiation exploration within the Jovian system, long-duration operation in cryogenic environments, and secondary deployment from a larger spacecraft to provide spatially distributed measurements. In each case, the analysis focuses on the most immediate engineering constraints and demonstrates that the proposed architecture provides a physically reasonable means of addressing them.

5.2 High-Radiation Exploration of the Jovian System

The Jovian system provides a particularly demanding environment for spacecraft. Radiation exposure can impose cumulative degradation on semiconductor electronics, sensors, power systems, and communication hardware. A conventional spacecraft must allocate substantial mass and complexity to radiation shielding and component qualification, while mission reliability remains dependent on the continued operation of one spacecraft. [17, 18, 19]

The ASN architecture approaches this problem differently. Rather than designing a spacecraft for minimal exposure to high radiation environments, the ASNs are designed as radiation-tolerant extensions of the mothership. The mothership is then exposed only as necessary to deliver the ASNs and spends the remainder of the mission safely away from radiation risks.

For imaging applications, the ASN architecture can further reduce dependence on conventional focal-plane electronics through the use of radiation-tolerant MEMS-based optical systems coupled to photodetectors. Long-duration, low-power operation can be supported by betavoltaic power sources and ceramic capacitors as previously discussed, while localized shielding in the form of aluminum and titanium layers as well as HDPE encapsulation can protect the most radiation-sensitive processing and communication components. [20, 18, 21, 22]

This architecture could provide a distributed, long-duration science presence within the Jovian system, in which spatially and temporally separated measurements are used to characterize regional and temporal variations in geological, thermal, or atmospheric phenomena. Alternatively, ASNs could be delivered into the cloud layers of Jupiter, including regions such as the Great Red Spot, with different ASNs delivering visual, spectrographic, thermal, gas-composition, pressure, and wind measurements during a sacrificial descent.

This approach's value to targets such as Io and Europa, where the environmental penalty associated with conventional spacecraft electronics can dominate spacecraft mass, complexity, and mission lifetime, is of particular value. [23, 17] The ASN architecture instead treats radiation exposure as an expected source of node attrition that can be accommodated through shielding, component selection, and numerical redundancy.

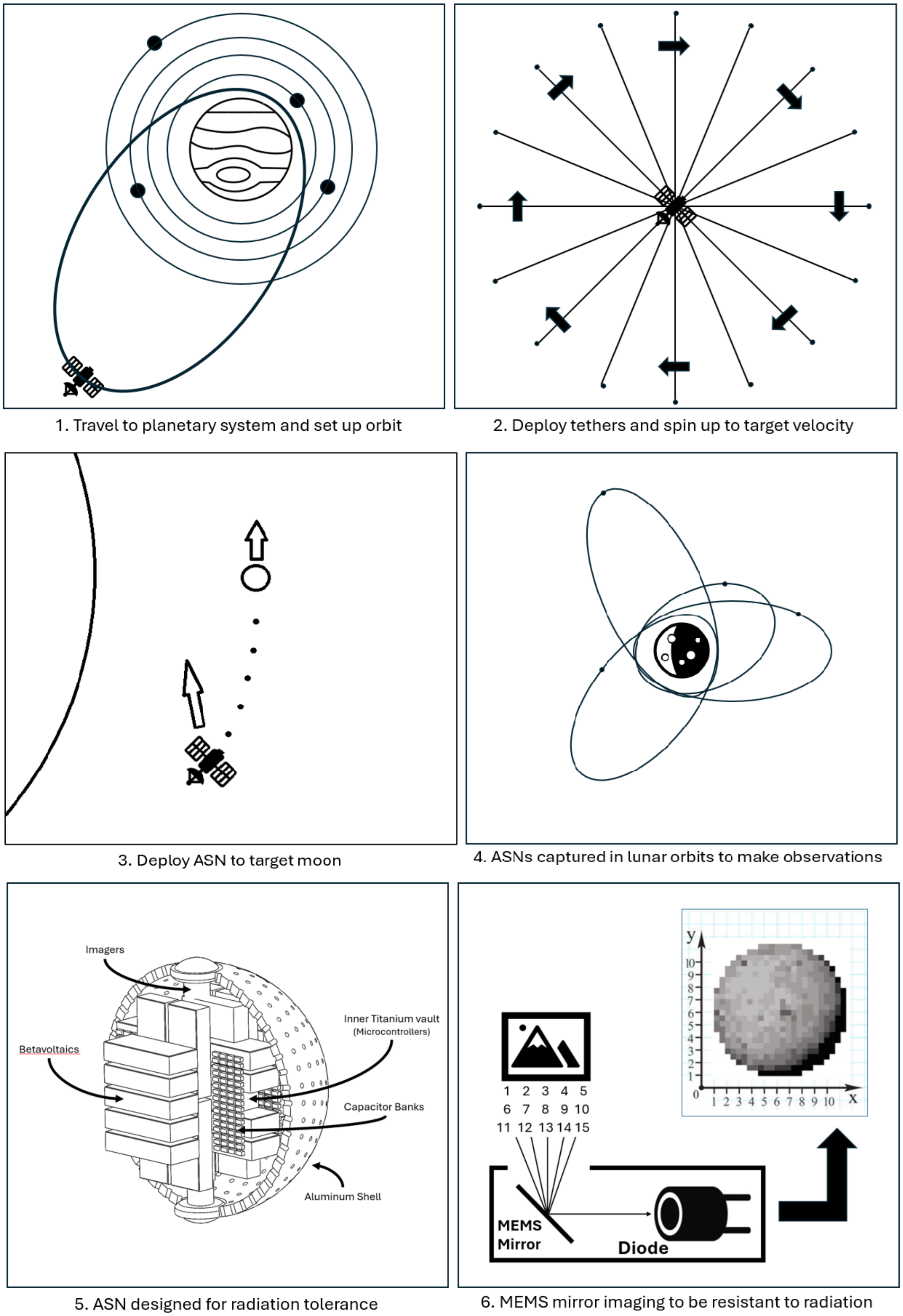

Figure 1: Conceptual application of the ASN architecture to high-radiation exploration in the Jovian system. The architecture distributes mission functionality across a population of independently operating nodes rather than relying on continuous operation of a single spacecraft.

5.3 Cryogenic Environments and Long-Duration Operation

The same architectural principles of design for sacrificae and environmental tolerance can be applied to environments in which temperature, rather than radiation, represents the dominant spacecraft constraint. Outer Solar System bodies and permanently shadowed or cryogenic environments can impose temperatures at which conventional batteries, semiconductor devices, lubricants, and other spacecraft components cannot operate without thermal management.

In such environments, the ASN architecture can treat power generation and thermal management as coupled functions. Solid-state or other low-temperature-compatible storage technologies can be selected where appropriate, while a small radioisotope heat source can provide continuous thermal input to maintain the internal node environment above critical component limits.

The objective is not to maintain the entire external spacecraft structure at an elevated temperature. Instead, the node can be designed as a thermally isolated volume in which a small continuous heat source offsets conductive and radiative losses.

For a first-order feasibility assessment, the thermal requirement can be represented as

$$P_{\mathrm{th}} \geq P_{\mathrm{loss}}, \tag{48}$$

where P_{th} is the thermal power available from the radioisotope source and P_{loss} represents the total steady-state thermal loss from the protected internal volume.

A detailed thermal design would require specification of insulation properties, geometry, external temperature, contact conductance, component operating temperatures, and mission duration. Such analysis is beyond the scope of this application example. The important architectural observation is that the required thermal power can be treated as a continuous low-level resource rather than as a conventional high-power spacecraft subsystem.

This distinction becomes particularly valuable for small nodes. Because the ASN has no requirement to support high-power propulsion or continuous high-bandwidth communications, a substantial fraction of its energy budget can instead be allocated to maintaining a survivable internal environment. The resulting architecture could permit extended operation in environments where external temperatures would otherwise challenge conventional battery-powered systems.

A specialized ASN could also serve as a passive carrier for microfluidic or micro-capillary sampling hardware. For example, embedding a DIC microscope in the ASN could be considered for characterizing material collected from Titan's surface liquids without requiring the node to make assumptions about the presence or absence of specific biochemistries.

A single-magnification, fixed-focal-plane DIC microscope could, in principle, be as small as 10mm in total optical length, with the objective and condenser apertures on the order of 0.5mm. This is limited by the diffraction limit and the DIC beam-shearing requirement, not by the physics of light itself. Smaller than that, and the optics would not resolve the diffraction limit or maintain the DIC interference condition.

Such an ASN design would require dedicated fluidic, optical, thermal, and contamination analyses beyond the scope of the present work, but the versatility of the ASN design maintaining a form-factor of only 1kg is exemplified.

5.4 Secondary Deployment from a Flagship Spacecraft

A third application class arises when an ASN functions as a carrier for a secondary scientific or robotic payload. In this configuration, the ASN population does not constitute the primary spacecraft. Instead, a conventional flagship or carrier spacecraft provides transportation and deployment,

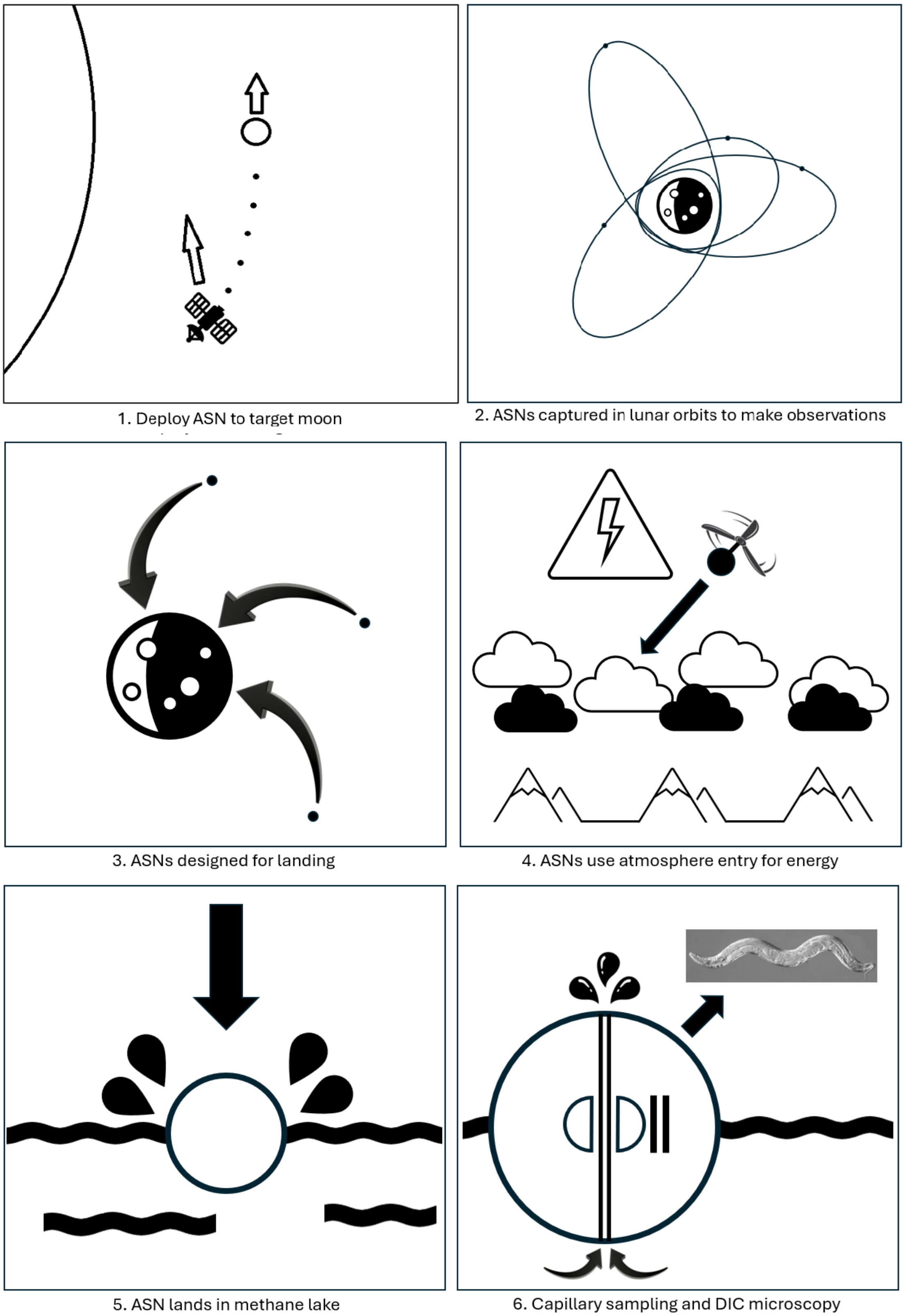

Figure 2: Conceptual application of cryogenic ASN architecture. A small radioisotope source provides continuous thermal input while electrical energy is allocated to sensing, computation, and communication. Although DIC microscopy is illustrated, cryogenic-tolerant ASNs can potentially allow direct liquid methane sampling and analysis.

while each ASN provides a mechanically protected intermediate stage between the high-energy deployment environment and a smaller payload that would otherwise be unable to survive deployment. Following deployment and stabilization, the secondary payload may be released or otherwise activated to perform a mission-specific function.

This architecture is particularly attractive when the scientific objective depends on spatial or temporal coverage over a planetary surface rather than the maximum capability of an individual ASN or orbiting ASN swarm. Although more challenging in design, a conceptual microrotor craft carried within a hardened ASN could provide a potential approach to localized Titan exploration. Such a secondary vehicle could incorporate imaging and thermal-management systems appropriate to the post-deployment environment, but its feasibility would require a separate vehicle-level analysis.

The Cheerson CX-10, as an example, is under 250mm in any axis, weighs under 15g, carries an HD camera and has a flight time of 5–8 minutes. With modification for cold, energy storage, and proper encapsulation, this would be a reasonable example of a secondary payload an ASN could manage. Alternatives would be balloon craft, crawlers, or other deployable systems.

For measurements distributed across a geographic region, the population can provide simultaneous or temporally correlated observations that cannot readily be obtained from a single stationary or slowly moving spacecraft.

The scientific objectives enabled by such a deployment could include distributed atmospheric measurements, characterization of spatially varying environmental conditions, or observations of transient phenomena. The precise sensor suite would depend on the target mission and is therefore intentionally not specified here.

The architectural significance is that the parent spacecraft can serve as a transportation and deployment platform while the ASN population extends the spatial and temporal reach of the mission without requiring each secondary node to contain the complete infrastructure of an independent flagship spacecraft.

5.5 Common Architectural Principles

Although the three application examples represent substantially different environmental challenges, they rely on the same underlying architectural properties.

Table 7: Representative ASN application environments.

Environment	**Primary ASN Adaptation**	**Mission Opportunity**
Jovian moons	Radiation-tolerant components, localized shielding, betavoltaic power, and distributed redundancy	Long-duration distributed observations in extreme radiation environments
Cryogenic environments	Thermal isolation, solid-state energy storage, and continuous radioisotope heating	Persistent low-power sensing at very low temperatures
Secondary deployment	Large sub-populations carried and released by a carrier ASN	Spatially distributed measurements beyond the reach of a single ASN or an orbiting swarm

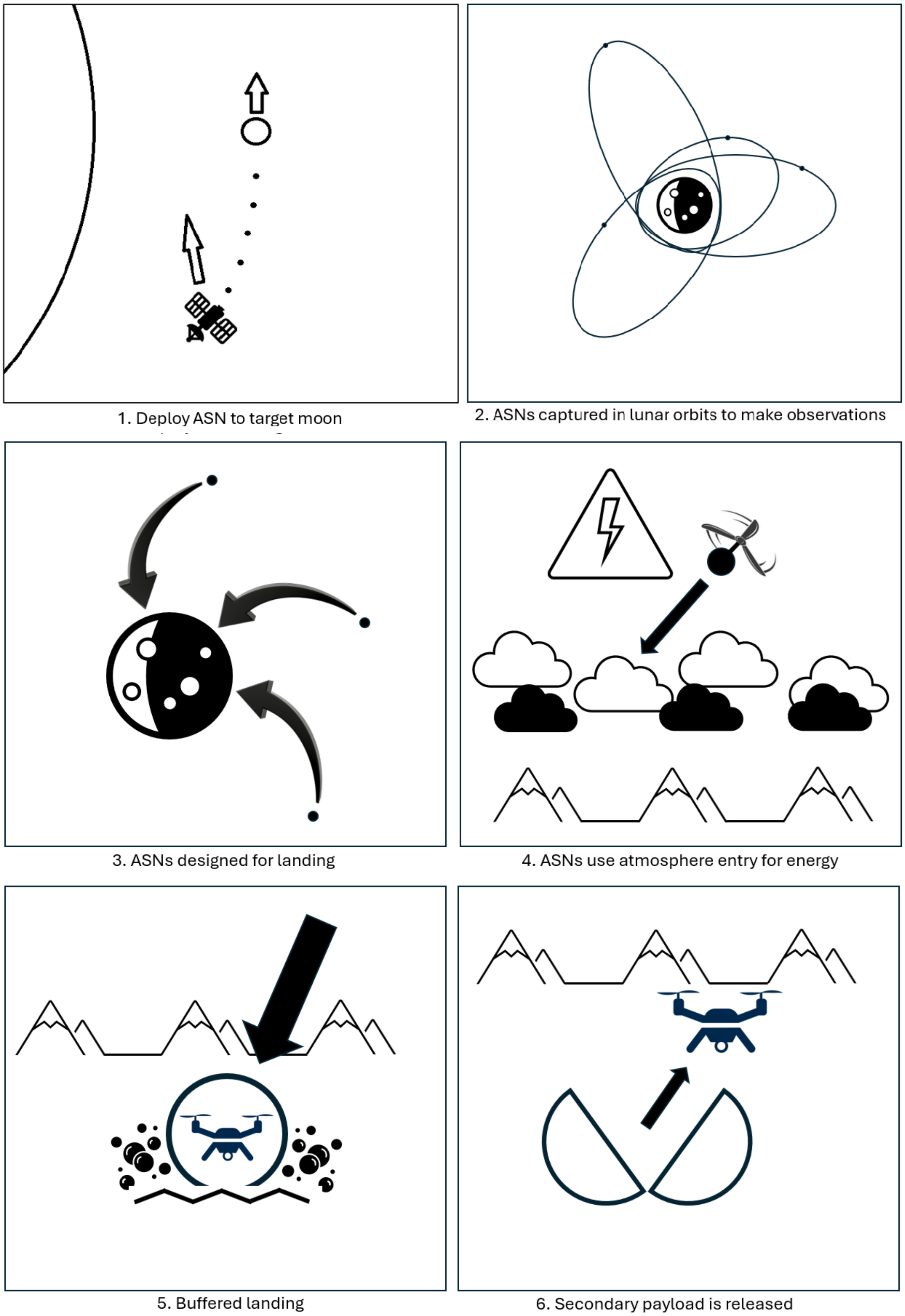

Figure 3: Conceptual secondary deployment architecture in which ASNs transport and release a secondary payload. The secondary payload may subsequently perform complementary scientific functions.

The common principle is not that a single ASN configuration is optimal for every planetary environment. Rather, the architecture separates the fundamental functions of transportation, survival, sensing, computation, communication, and scientific coverage so that each can be scaled according to the environment and mission objective.

This separation permits the same basic distributed architecture to be adapted to substantially different environments without requiring every node to become a miniature conventional spacecraft. In radiation-dominated environments, redundancy and component-level survivability become dominant. In cryogenic environments, thermal isolation and low-power operation become dominant. In secondary deployments, the primary advantage is the multiplication of spatial and temporal measurement capability.

These examples therefore illustrate the broader utility of the ASN architecture: **mission capability can be increased not only by making an individual spacecraft more capable, but by changing the relationship between spacecraft size, environmental survivability, and the number of independently functioning nodes.

6 Discussion

The results presented in this study suggest that the Autonomous Science Node (ASN) architecture is best understood as a complementary architectural element that can extend the capabilities of a conventional mission, not as a replacement for conventional planetary spacecraft. The fundamental distinction is that mission capability is not required to reside entirely within a single spacecraft. A conventional mothership can retain its propulsion, navigation, communications, power, computing, and high-value scientific instruments while deploying a population of substantially smaller nodes into environments or trajectories that would be impractical, inefficient, or excessively risky for the primary spacecraft. In this architecture, the ASNs therefore function as distributed extensions of the mothership rather than independent replacements for it.

This distinction creates several opportunities. First, ASNs can extend measurements into regions that may be unsuitable for a large and expensive spacecraft. Second, a population of nodes can provide spatially distributed measurements that a single spacecraft cannot obtain simultaneously. Third, nodes can provide temporal sampling over extended periods or at multiple locations, potentially capturing transient or evolving phenomena that would otherwise be missed by a spacecraft constrained to a single trajectory. Finally, some measurements do not require the capabilities of a conventional spacecraft at all. In such cases, allocating the measurement to a small ASN may permit additional science to be performed without substantially increasing the complexity or risk of the primary spacecraft.

The resulting architecture is consequently complementary at several levels. The mothership can perform high-value, precision measurements while the ASN population performs distributed or opportunistic measurements. The mothership can provide communications, navigation, timing, and mission coordination while individual nodes remain comparatively autonomous. Most importantly, the population provides a form of mission-level redundancy that is difficult to obtain with conventional spacecraft architectures. Loss of an individual ASN does not necessarily represent loss of a mission-critical spacecraft; instead, population attrition can be accommodated while the surviving nodes continue to contribute measurements. This shifts a portion of mission robustness from the reliability of an individual vehicle to the aggregate performance of a population.

6.1 Relationship to Distributed Planetary Probe Concepts

The ASN architecture shares important characteristics with previous proposals for distributed planetary probes, most notably NASA's ANTS concept. The ANTS concept demonstrates the broader value of distributing planetary science among numerous small spacecraft rather than relying exclusively upon a single vehicle. The ASN architecture is related to this philosophy but represents a different implementation. ANTS envisions a population of comparatively capable small autonomous spacecraft as distributed scientific elements, whereas the architecture presented here emphasizes highly constrained nodes deployed by a larger host spacecraft and designed around an unconventional high-energy deployment mechanism.

This distinction is significant. The ASN is intentionally designed around the constraints imposed by tether deployment and subsequent operation as an extension of a conventional spacecraft. Its limited mass, power, computational capability, communications architecture, and sensing systems are therefore not simply reductions of conventional spacecraft designs. Instead, the architecture allocates to each node only those functions required to survive and operate after deployment, while retaining substantial mission infrastructure aboard the mothership. The result is a complementary architecture in which the population extends the host spacecraft's observational reach without requiring each node to reproduce the capabilities of an independent spacecraft.

The comparison also illustrates a broader design principle: distributed planetary architectures need not employ a single implementation strategy. A population may consist of comparatively capable small spacecraft, as in ANTS-like concepts, or of extremely constrained nodes whose usefulness emerges primarily through their number, deployment geometry, survivability, and cooperation with a host spacecraft. The ASN approach therefore occupies a different point in the design space rather than simply representing a smaller version of an existing distributed spacecraft.

6.2 Potential Application to Europa, Titan, and Independent Exploratory Missions

NASA's Europa Clipper and Dragonfly missions provide useful examples of how an ASN architecture could complement, rather than replace, sophisticated planetary spacecraft. [23, 24] Dragonfly is designed to conduct detailed in-situ investigations of Titan using a highly capable rotorcraft that can repeatedly relocate between scientifically interesting sites. [24] Europa Clipper, in contrast, is an orbital spacecraft designed to conduct repeated close observations of Europa using a suite of sophisticated scientific instruments while operating within the challenging Jovian radiation environment. [23] Both missions illustrate the substantial capabilities that can be concentrated within a single spacecraft. An ASN population could provide an additional layer of distributed capability without displacing those primary functions.

A population of ASNs deployed in conjunction with a Dragonfly-class mission could provide measurements at locations beyond the primary vehicle's operational trajectory or establish spatially separated measurement points across a region. ASNs could also perform distributed reconnaissance and environmental characterization in advance of Dragonfly's arrival. Such observations could identify scientifically attractive locations and allow Dragonfly to concentrate its comparatively scarce mobility, power, and operational resources on targets of greatest interest. In this configuration, the ASNs would not duplicate Dragonfly's capabilities; they would increase the efficiency with which those capabilities are employed.

A similar architecture could complement Europa Clipper. A population of radiation-tolerant ASNs could provide distributed observations across Europa or its surrounding environment while the primary spacecraft concentrates on high-value targets requiring its substantially greater sensing, communications, and computational capabilities. Distributed observations could establish broad environmental context, identify regions or phenomena warranting closer examination, and potentially monitor selected areas over time. The ASNs could therefore act as additional observational assets for the primary mission—effectively providing "extra eyes" without requiring the primary spacecraft to visit or continuously observe every region of interest.

The architecture may be particularly attractive where the required measurement does not justify the complexity of a large spacecraft. Environmental sensing, atmospheric measurements, imaging, and other comparatively low-bandwidth observations could potentially be distributed among numerous nodes, while Dragonfly, Europa Clipper, or another conventional spacecraft remains available for measurements requiring substantially greater mobility, power, computing, communications bandwidth, or scientific instrumentation. In this configuration, the ASN population increases the scientific context available to the primary mission rather than competing with its principal objectives.

Titan and Europa also illustrate the potential value of the ASN's survivability and secondary-deployment concepts. An ASN could serve as a carrier for a smaller scientific or robotic payload whose survival during the initial tether deployment event would otherwise be difficult. A conceptual "micro-Dragonfly," for example, could be carried within a hardened ASN and deployed only after the ASN has survived the initial mechanical environment and reached the conditions required for secondary deployment. The ASN would thereby separate the extreme mechanical requirements of deployment from the requirements of the eventual secondary payload. Such applications remain speculative, but they demonstrate that the architecture can function as more than a terminal scientific sensor.

Perhaps the most consequential difference between an ASN population and a conventional spacecraft is the potential role of intentional expendability. Conventional planetary spacecraft represent substantial investments in hardware, launch mass, integration, and operations, making deliberate loss of a spacecraft an exceptional event. Yet planetary exploration already demonstrates the scientific value of accepting such risk when the resulting measurements justify it. The terminal descent of the Huygens probe, the eventual disposal of Cassini, the controlled end of Juno's mission, and the deliberate impact of DART each illustrate circumstances in which spacecraft were ultimately committed to trajectories or environments from which recovery was not expected. [25, 26, 17, 27] An ASN architecture could make deliberate node loss an explicit component of mission design rather than treating it solely as an exceptional failure condition.

Instead of a single spacecraft performing a terminal measurement sequence at one location, a large population of low-mass nodes could potentially be distributed throughout an environment and intentionally sacrificed to obtain measurements at locations that would otherwise be inaccessible or uneconomical to investigate. On Titan, for example, a population of appropriately designed ASNs could provide distributed observations across the surface, atmosphere, or hydrocarbon-rich regions, potentially including observations of lakes and other targets that would be difficult to access with a conventional spacecraft. The scientific return would derive not from the capability of any individual node, but from the number and geographic distribution of observations.

This capability introduces a different relationship between spacecraft cost and mission risk. A conventional spacecraft must generally be protected from hazards because the loss of the spacecraft represents the loss of a substantial fraction of the mission's scientific capability. For a sufficiently inexpensive and abundant ASN population, some level of attrition can instead become an intentional part of mission design. The objective shifts from maximizing the probability of survival of every spacecraft to maximizing the scientific return of the surviving population. Such a strategy could allow mission planners to investigate environments and trajectories that would be prohibitively risky for a conventional spacecraft.

The principal trade with ASNs is that the capabilities of each node are intentionally limited. Individual nodes cannot provide the power, communications bandwidth, computational resources, mobility, or scientific instrumentation available to a conventional spacecraft. Their value instead derives from architectural aggregation: many nodes can collectively provide observations that no individual node could provide alone. The approach consequently trades individual spacecraft capability for population-level reach, redundancy, persistence, and spatial or temporal sampling.

The analysis presented here does not establish that an ASN population is preferable to conventional spacecraft for all missions. Rather, it demonstrates a complementary architectural option in which a conventional mothership retains its high-value capabilities while using a large population of simple, survivable nodes to access portions of the environment that would otherwise remain under-sampled. The tether deployment system and ASN architecture are particularly well matched to this strategy because the deployment mechanism provides a means of distributing large numbers of low-mass nodes without requiring each node to carry the propulsion and structural systems normally associated with independent spacecraft.

The resulting concept is therefore not fundamentally a proposal for replacing spacecraft with swarms. It is a proposal for *extending spacecraft reach, lowering the cost of distributed science, and improving mission efficiency.* A future planetary mission could employ a capable primary spacecraft for precision investigations while simultaneously deploying hundreds or thousands of ASNs to provide distributed measurements, environmental context, reconnaissance, redundancy, or access to otherwise inaccessible locations. The practical value of the architecture will ultimately depend upon the scientific objectives and environment of a particular mission, but the analysis indicates that the combination of unconventional deployment, extreme node-level simplicity, and population-level capability warrants further investigation.

7 Conclusion

This study has examined the Autonomous Science Node (ASN) as a complementary architecture for extending the capabilities of conventional planetary spacecraft. The analysis demonstrates that a highly constrained, low-mass node can be designed around the mechanical, environmental, power, sensing, and communications limitations associated with unconventional high-energy deployment while retaining sufficient capability to contribute useful scientific observations. The resulting architecture does not seek to reproduce the capabilities of a conventional spacecraft at smaller scale. Instead, it deliberately assigns a limited set of functions to each node and derives additional capability from the number, distribution, survivability, and collective operation of the resulting population.

The distinction is important. A conventional planetary spacecraft concentrates substantial scientific and operational capability within a single vehicle, making spacecraft survival and performance closely coupled to mission success. An ASN population distributes a portion of that capability across many comparatively simple nodes. Individual nodes may be lost without necessarily compromising the mission, while surviving nodes can provide spatially and temporally distributed observations that are difficult or impossible for a single spacecraft to obtain. The architecture therefore introduces population-level redundancy and reach without requiring the primary spacecraft to relinquish its conventional capabilities.

The tether deployment architecture further complements this approach by providing a mechanism for distributing large numbers of low-mass nodes without requiring each node to carry the propulsion, structural, and maneuvering systems normally associated with an independent spacecraft. This enables a conventional mothership to function simultaneously as a sophisticated scientific platform and as a deployment system for a distributed population of simpler assets. The resulting architecture can extend observations into environments that may be unsuitable for the primary spacecraft, provide precursor or contextual measurements, increase temporal or geographic sampling, and enable measurements whose scientific value does not justify the cost or complexity of a conventional spacecraft.

The concept also introduces the possibility of treating intentional attrition as a mission capability rather than solely as a failure condition. Where individual ASN cost and complexity are sufficiently low, nodes may be assigned to trajectories or environments carrying risks that would be unacceptable for a primary spacecraft. The resulting population can provide measurements at locations where conventional spacecraft would be unlikely to be deliberately committed. Similarly, the hardened ASN architecture may provide a means of transporting and subsequently deploying secondary scientific or robotic payloads that could not otherwise tolerate the initial deployment environment.

These characteristics suggest that the ASN architecture occupies a complementary position within the planetary exploration design space. It is neither a replacement for conventional spacecraft nor simply a collection of miniature spacecraft. Rather, it provides a means of extending a capable spacecraft with a population of specialized, survivable, and potentially expendable scientific assets. The value of the architecture consequently arises from the interaction between the primary spacecraft and its distributed extensions: the conventional spacecraft provides capabilities that the ASNs cannot practically reproduce, while the ASNs provide reach, persistence, redundancy, and distributed access that the primary spacecraft cannot efficiently provide alone.

The broader implication is that future planetary missions need not treat spacecraft capability as being bounded by the physical capabilities of a single vehicle. A spacecraft may instead serve as the central element of a larger distributed architecture in which different classes of assets perform different functions according to their cost, survivability, mobility, and scientific capability. Under this model, relatively simple nodes can be used to expand the operational envelope of a sophisticated spacecraft, allowing the primary vehicle to concentrate its resources where they provide the greatest scientific return.

The ASN architecture therefore represents not merely an approach to building smaller probes, but a potential change in how spacecraft capability is allocated across a mission. By extending conventional spacecraft with large populations of simple and survivable nodes, missions may obtain greater geographic reach, improved temporal sampling, increased resilience, and access to environments or trajectories that would otherwise remain impractical. The analysis presented here establishes a basis for further study of such architectures, including detailed node qualification, transient structural analysis, deployment testing, population-level communications and coordination, and mission-specific scientific applications.

Ultimately, the most significant capability of an ASN may not be what the node can accomplish by itself, but what it enables the spacecraft that deploys it to accomplish. In this sense, the ASN does not compete with the conventional spacecraft. It makes the conventional spacecraft more capable.

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