

Democratizing Space: India's frugal space innovation provides key lessons for emerging nations

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Space exploration is often assumed to require very large budgets, which can deter emerging space programmes before they begin. India's recent missions have helped shift perceptions of that cost barrier by showing that major milestones can be achieved on budgets in the tens of millions. In 2023, Chandrayaan-3 landed near the Moon's south pole on a budget of about \$75 million (1, 2). A decade earlier, India's Mars Orbiter Mission (Mangalyaan, 2013) reached Mars orbit for roughly \$74 million, about one-seventh the cost of NASA's MAVEN orbiter (3, 4).

These examples do not imply that high-investment programmes such as Artemis or MAVEN are inefficient, nor that lower mission cost is always preferable. Instead, they illustrate how frugal innovation can be effective when mission goals and risk tolerance permit. Here, "frugal" refers to disciplined mission scoping, reuse of proven designs, and procurement choices that reduce cost while making risk trade-offs explicit (5).

Using India's space programme as a case, we argue that mission-selection criteria and procurement rules should reward disciplined scoping, cost-conscious engineering, and modular reuse and iteration. Such rules can help governments, firms, universities, and international collaborations to learn by flying missions, produce scientific results, and deploy operational systems in orbit. This enables a mix of complementary, tightly scoped missions that can, where feasible, sit alongside larger flagship missions.

Frugal Missions

ISRO's recent missions illustrate frugal space innovation in practice.

Mars Orbiter Mission (Mangalyaan), launched in 2013, made India the first Asian nation to reach Mars orbit. Costs were contained by reusing mission-proven technologies and tightly limiting mission scope. The spacecraft design drew heavily on India's Chandrayaan-1 lunar orbiter, saving development time and expense (6).

In 2023, Chandrayaan-3 made India the first nation to achieve a soft landing near the Moon's south pole and only the fourth country to accomplish a lunar soft landing overall (7). The Indian team completed the mission on a budget that was orders of magnitude below

cumulative Artemis spending. Of course, Artemis is a fundamentally different mission class. It is a multi-mission, crewed exploration programme designed to return astronauts to the Moon and establish a sustained presence, requiring human-rated systems and infrastructure. These have no counterpart in a small robotic lander-rover mission. Reflecting the broader scope, projected cumulative Artemis spending through FY2025 is approximately \$93 billion, with the estimated production and operations cost of a single Space Launch System/Orion launch around \$4.1 billion (8). Chandrayaan-3 highlights a complementary lesson: tightly scoped robotic missions can deliver reliable lunar landing capability and targeted surface science at low cost. This complementarity is demonstrated by Chandrayaan-3's success just days after Russia's far costlier Luna-25 mission failed (9).

ISRO's cost-efficient approach has also enabled collaboration with established agencies. For example, the NASA-ISRO Synthetic Aperture Radar mission (NISAR) launched on 30 July 2025 aboard ISRO's GSLV is now entering commissioning, with early data releases supporting hazards and climate applications (10,11). NISAR illustrates how cost-efficient platforms and launch services can complement high-end instruments, delivering sustained, policy-relevant Earth-observation data.

Cost-Effective Space Mission Design

India's recent missions provide practical takeaways for frugal space programmes. These takeaways are not unique to ISRO, nor do they imply that lower mission cost is always optimal; rather, they illustrate how design and governance choices shape cost and risk.

Focused Objectives and Scope Control. ISRO often designs missions around a small set of near-term goals, typically combining a capability demonstration with a few targeted measurements. Clear requirements make trade-offs explicit—such as smaller payload suites or shorter operational lifetimes—which reduces integration complexity, limits scope creep, and lowers development risk. Mangalyaan and Chandrayaan-3 illustrate what this approach can deliver at modest cost. Other agencies are not less disciplined; they may simply pursue broader mission value propositions that legitimately raise cost (e.g., maximizing scientific return or meeting stringent requirements and safety standards for crewed missions) (11). The policy takeaway is to align scope with purpose and make scope-risk-assurance trade-offs explicit, while maintaining a portfolio that mixes frugal missions with occasional high-investment flagships.

Cost-Conscious Engineering. ISRO seeks reliability through simplicity by tailoring component choice and testing/verification effort to tightly defined requirements and an explicit risk tolerance. It favours heritage subsystems and, where feasible, space-qualified commercial components, introducing new technologies selectively; for example, the Mars Orbiter Mission used a single versatile liquid-fuel engine rather than multiple specialised units, reducing parts count and integration complexity (12). This is not to suggest that redundancy or rigorous verification are unnecessary: missions with low risk tolerance or human-rating requirements can justifiably add backup systems and testing, and flagship science missions may warrant higher-performance payloads when the science case demands it. ISRO shows that when objectives are deliberately narrowed, fit-for-purpose

assurance and targeted instruments can still deliver flight-proven results at much lower cost. The practical implication is to scale assurance requirements to mission risk, rather than applying flagship-level standards by default.

Domestic Technology Development (Selective Localisation). Local sourcing is not always cheaper. The case for localisation is managing lifecycle risk in strategic bottlenecks—especially where foreign procurement brings licensing constraints, limits on technical data transfer, or geopolitical exposure. After cryogenic technology transfer constraints in the early 1990s, ISRO invested in an indigenous cryogenic upper stage to reduce dependence, accepting higher near-term costs (13). The practical takeaway is selective localisation: build domestic strength where dependence is risky, and source internationally when it is cheaper and reliably available.

Reuse and Iterative Learning. Reuse and iterative learning are central to India’s frugal approach. ISRO leverages flight-proven designs, ground infrastructure, and operational experience across missions, reducing development time and lowering integration risk (14). This strategy spreads technical and financial risk across a sequence of missions rather than concentrating it in a single all-or-nothing effort. In practice, it argues for reusable platforms, modular designs, and incremental upgrades, so that teams can build capability step by step within tight budgets.

Capability Ladder and Iterative Decomposition. Iterative learning is common across space agencies; ISRO’s distinctive feature is decomposing complex objectives into smaller, sequential missions. Chandrayaan-1 built an orbital mapping and mission-operations capability. Chandrayaan-2 attempted an integrated orbiter–lander–rover mission. Chandrayaan-3 narrowed the objective to demonstrating safe landing and roving using a refined lander–rover configuration (1, 7). Notably, Chandrayaan-3 also reused communications support from the still-orbiting Chandrayaan-2 orbiter, enabling faster learning at lower marginal cost. Figure 1 summarises this decomposition-and-reuse logic as a capability ladder. The policy takeaway is that deliberate decomposition of objectives can reduce risk while sustaining momentum in capability development, particularly for agencies pursuing robotic missions under budget constraints.

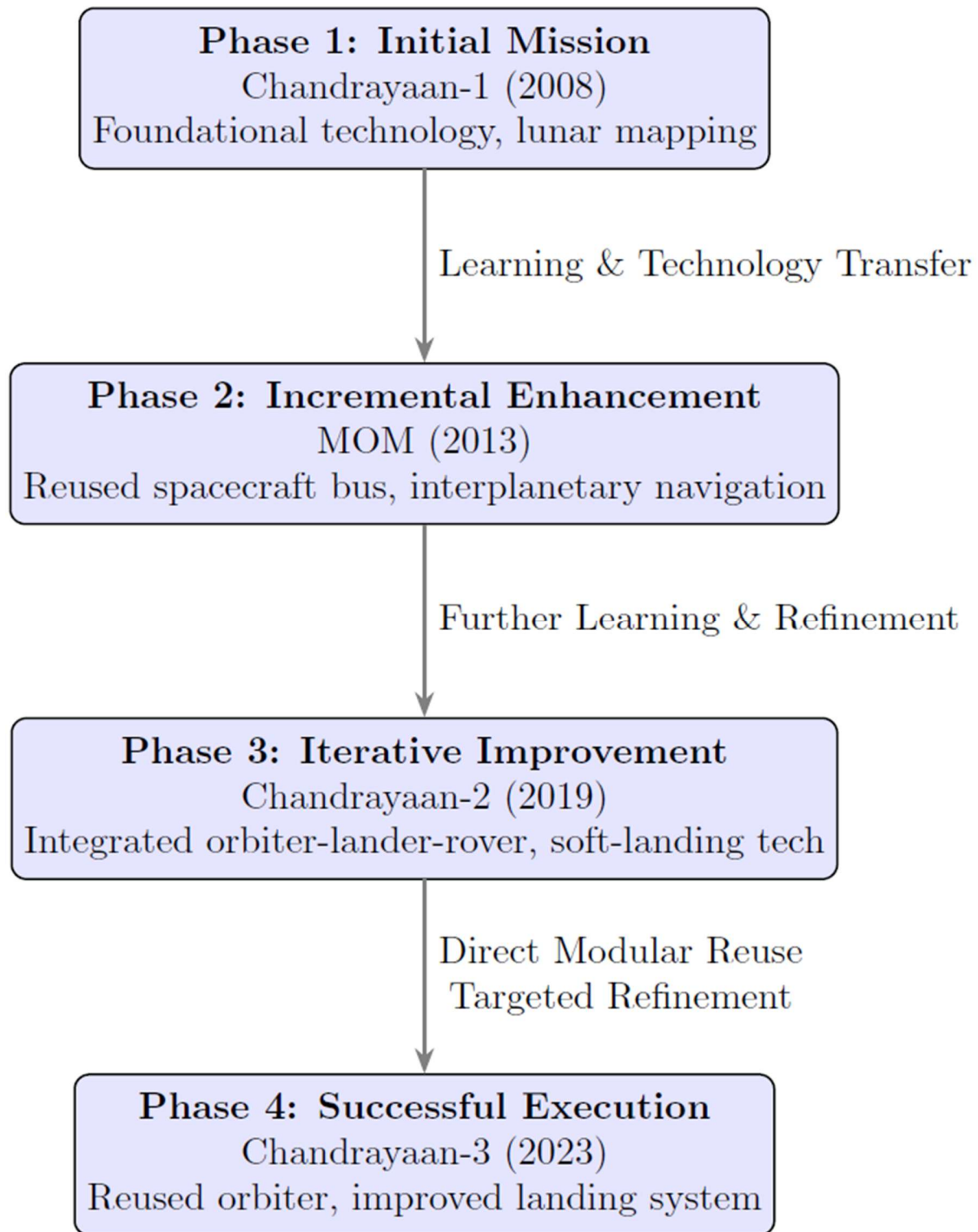


Figure 1. ISRO's iterative learning approach and modular reuse strategies reduce mission costs and risks.

Implications for Global Policy

Frugal space missions matter for global policy because they make Earth observation and access to orbit more scalable. Governments can reinforce this effect through how they fund and buy space capability—for example, by purchasing services where appropriate rather than relying only on bespoke systems.

Earth-observation satellites—whether low-cost or high-end—provide data for flood and drought monitoring, climate-adaptation planning, and precision agriculture. Frugality matters because it makes these services deployable and sustainable at scale. For example, ISRO's RISAT-2B Earth-observation satellite, launched in 2019, supplies data used to support agriculture and disaster management (15). Lower mission and launch costs allow more frequent updates, wider coverage, and operational continuity. This scaling effect is directly relevant to the UN Sustainable Development Goals on disaster risk reduction, climate resilience, and sustainable agriculture. It helps more countries and institutions operationalise Earth observation consistently, including in lower-income settings.

When missions costing tens of millions rather than billions can yield significant scientific and practical outcomes, investments in space become more feasible for governments and institutions in developing countries. A decade ago, many universities and startups faced a bottleneck: even when small satellites could be designed, access to affordable launch and integration opportunities was often prohibitive. Today, standardised small-satellite platforms and lower-cost commercial and rideshare launches make access to orbit far easier. These options let teams launch and operate their own satellites and payloads, while building capability in payload design, systems engineering, and mission operations.

ISRO is one provider among several. In June 2023, India reported having launched 424 foreign satellites for international customers, illustrating how access to orbit has become available at scale (16). The policy significance is not that one agency “does the work” for others, but that more teams can fly instruments, iterate, and build end-to-end mission capability. International capacity-building platforms can make this learning more systematic; for example, the United Nations Office for Outer Space Affairs (UNOOSA) Access to Space for All initiative supports institutions—particularly in developing countries—to deploy CubeSats and build technical capability (17).

Wealthier nations also face budget constraints (18,19). Adopting cost-efficient practices can help established agencies fly more frequently and maintain programme continuity through fiscal cycles. This is less about emulating low-budget missions and more about using smaller, tightly scoped projects to complement large, high-assurance efforts when appropriate.

Frugal innovation, in policy terms, means structuring requirements, risk allocation, and procurement to actively contain complexity and cost growth (5). This approach appears in both newer and established programmes—for example, in NASA's commercial initiatives, including Commercial Orbital Transportation Services (COTS) for ISS cargo capability development, the Commercial Crew Program for crew transportation services, and

Commercial Lunar Payload Services (CLPS) for lunar payload delivery, all of which rely on service procurement and milestone-based or fixed-price contracting (20). In practice, agencies can deploy these approaches selectively, reserving higher-assurance methods for missions with exceptional safety or performance requirements.

Recognizing Limits, Managing Trade-offs

Frugal approaches involve trade-offs in capability, scope, and timing, and they are not appropriate for every mission. India's Mars Orbiter Mission, launched aboard a relatively small rocket, followed a minimum-energy interplanetary transfer to Mars after a sequence of Earth phasing orbits (21). Cost-conscious designs also tend to carry fewer instruments, which can narrow the range of scientific measurements. Chandrayaan-3, for example, prioritised demonstrating safe landing and roving capability, leaving broader scientific objectives to subsequent missions (7).

Some mission classes—including human spaceflight, large space telescopes, and Mars sample-return—inevitably require substantial investment. ISRO itself recognises this, pursuing higher-budget programmes such as the Gaganyaan crewed mission and next-generation launch vehicles (22). The practices highlighted in this paper are not unique discoveries: iterative development, reuse of proven technology, and public-private collaboration are widely used across space agencies. What differs is how these practices are institutionalised. When paired with tight scope control, modular reuse, and explicit cost-benefit discipline, they can deliver flight-proven progress even under constrained budgets—consistent with frugal-innovation logic and evidence on the value of public-private partnerships in space innovation (5, 23).

Frugality therefore complements, rather than replaces, higher-investment missions. It is most effective when applied selectively to well-defined objectives and when assurance requirements are scaled to the mission's risk tolerance, rather than set by default at flagship levels.

A further constraint is the growing congestion of space environments. Congestion is rising in Earth orbit and along transfer routes between Earth and the Moon, increasing collision risk and operating costs for all actors, including emerging space nations (24). Space traffic management (STM) refers to the rules, data services, and coordination mechanisms that help operators avoid collisions as orbital activity grows. One practical illustration is the Traffic Coordination System for Space (TraCSS), developed by the National Oceanic and Atmospheric Administration (NOAA), which aims to provide civil conjunction assessment and risk notification services (25). Debris-mitigation requirements—such as collision-avoidance capability and prompt end-of-life disposal—translate STM principles into operational practice, as illustrated by the U.S. Federal Communications Commission's five-year post-mission disposal rule (26, 27). The governance challenge is to ensure that STM regimes remain inclusive, supporting safety without constraining access for emerging space actors.

Conclusion

Frugal space missions do not replace flagships; they widen access and complement them. International bodies and space agencies, including UNCOPUOS (the United Nations Committee on the Peaceful Uses of Outer Space), should embed scope discipline, reuse, and fit-for-purpose assurance into mission selection and procurement frameworks to support sustainable and inclusive space activity (28).

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