

Space computing in the era of intelligence: Key technologies and standardization research

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Abstract – With the rapid evolution of space missions to autonomy and intelligence, space computing has become the strategic priority of the global space science and technology competition.

Through space-based intelligent infrastructure, it enables a paradigm that seamlessly integrates networking and computing to provide computing-as-a-service at any time and anywhere in space. This paper reviews representative global practices and key technologies, and it develops a standardization framework covering six dimensions: general foundation, intelligent computing payload, computing system, space-based models, ground digital twin, and application and service management. By synthesizing existing standardization efforts and identifying areas that remain partially covered or unaddressed, the framework is intended to support system interoperability, reliable engineering implementation, and collaborative innovation in large-scale space computing systems.

Keywords – Distributed systems, interoperability, space computing, standardization framework

1. INTRODUCTION

Driven by the rapid expansion of space applications such as real-time Earth observation, high-precision positioning, and space science experiments, space data and computational tasks are experiencing explosive growth. From 2021 to 2031, space data traffic will reach more than 560 EB, with the total volume expected to increase 14-fold over the next decade ^[1]. However, two major constraints exist. First, reliance on satellite-to-ground transmission nevertheless creates bandwidth and latency bottlenecks, while cloud-contaminated or irrelevant observations reduce the value of transmitting. On-board filtering and compression are therefore needed to mitigate this problem ^[2]. Second, the restricted processing power of traditional individual satellites cannot support increasingly complex analytics and computing workloads. Additionally, the intensive energy consumption of AI on Earth poses severe challenges; it is estimated that by 2045, the power required for terrestrial computing will exceed the current total global electricity capacity ^[3]. Consequently, the traditional paradigm relying on ground-based computing is no longer sufficient for increasingly complex space missions, motivating moving processing closer to spaceborne data sources and driving an urgent global demand for enhanced space computing capabilities.

Leveraging the maturity of satellite manufacturing and large-scale launch technologies, alongside advancements in satellite networking, cloud-edge-terminal computing, and the improved performance of Commercial Off-The-Shelf (COTS) components ^[4], performing complex computational tasks in orbit has become a major trend.

In this paper, space computing refers to a novel distributed computing paradigm that deploys and coordinates computing, storage, networking, data, and intelligent processing resources across spacecraft and ground infrastructure. It executes tasks close to the position of data generation when appropriate and provides interoperable computing services across heterogeneous nodes, while accounting for node mobility, intermittent links, radiation effects, and stringent power and thermal constraints [4], [23].

In terms of technical scope, on-board processing typically refers to mission-specific data processing within a single spacecraft and lacks inter-satellite collaboration. Satellite edge computing emphasizes latency-sensitive processing near data sources, whereas space cloud computing aggregates and orchestrates resources across multiple space-based nodes to provide elastic services. When the capabilities of satellite edge computing and space cloud computing are coordinated as shared infrastructure, they can be incorporated into the broader framework of space computing. Space computing also encompasses the complete technology stack, from hardware clusters and operating systems to application services. By comparison, satellite networks are centered on communications and networking, whereas space computing is computation-centric, with networking serving as its supporting infrastructure.

Currently, computing paradigms such as space edge computing and space cloud computing have emerged. The development of space computing infrastructure is a complex system engineering task. From an industrial perspective, it involves cross-organizational collaboration across the value chain, where heterogeneous resource management and system-level interoperability are essential prerequisites for resource sharing. From an engineering implementation standpoint, spacecraft and their payloads are inherently difficult to maintain or replace once launched into orbit. The high costs of launch and operations demand that systems exhibit exceptional reliability and fault tolerance. Consequently, a comprehensive standardization framework and key technical standards are urgently needed to ensure the high quality construction of space computing capabilities.

By reviewing representative cases globally, this paper identifies key technologies, constructs a standardization framework, and defines core technical standards. This study aims to provide a theoretical reference and practical basis for the standardization roadmaps of international organizations such as ITU-T in the field of space computing, fostering open innovation and collaborative development within the global space computing industry.

2. GLOBAL PRACTICE OF SPACE COMPUTING

Several countries and regions are exploring and implementing space-based computing, space computing, or computing-in-space concepts. In March 2019, the U.S. Space Development Agency (SDA) released its next generation space architecture request for information, in which computing supports tracking, custody, and battle-

management functions^[5]. In 2022, the U.S. Office of Science and Technology Policy published the national In-Space Servicing, Assembly, and Manufacturing strategy^[6]; NASA's 2025 state-of-play report subsequently documented progress across multiple ISAM activity areas^[7]. The European Commission has also advanced a Space Traffic Management initiative to support safe and sustainable space operations^[8]. In Japan, Space Compass, jointly established by NTT and SKY Perfect JSAT, has outlined an integrated space computing network combining optical data relay, Earth observation, and space data center services^[9]. In China, the 2024 Scientific and Technical Challenges in Aerospace identified space computing center construction and operation as a research challenge^[10]. In 2025, Google announced Project Suncatcher as a research moonshot exploring solar-powered satellite clusters equipped with Tensor Processing Units (TPUs) and optical inter-satellite links; its prototype mission is planned for 2027, so the project remains at the research and demonstration stage^[11]. China's 15th Five-Year Plan emphasizes strengthening the space sector^[12]. The China National Space Administration Action Plan (2025-2027) proposes an authoritative, unified, open, and shared commercial-space standardization system and supports innovation in space-resource utilization, manufacturing, and in-orbit servicing^[13].

The core elements of space computing include space computing platforms, intelligent computing missions, computing hardware equipment, and satellite communication networks. The key challenge is to achieve rapid, stable data transmission and accurate computation within the constraints of limited physical space, finite power resources, and extreme space environments.

2.1 Space computing platforms

Regarding space computing platforms, the primary focus lies in satellite computing architectures (edge, cloud, and distributed computing) and resource allocation mechanisms. Red Hat adopts an edge computing architecture, utilizing CodeReady containers and the OpenShift platform to execute ground-developed code on the International Space Station (ISS). Additionally, its Ansible platform supports automated configuration, software deployment, and mission orchestration for space-based systems^{[14][15]}. LEOcloud, in collaboration with Axiom Space and Orbital Assembly, provides hybrid edge-cloud services integrating satellite and terrestrial assets^[16]. The German Aerospace Center (DLR) proposed ScOSA, a distributed heterogeneous on-board computing architecture, which has completed system development and in-orbit verification^[17]. Leyva et al. proposed a Satellite Mobile Edge Computing (SMEC) framework for real-time, ultra-high-resolution Earth observation. By optimizing Central Processing Unit (CPU) frequency, image distribution, and compression parameters, the framework significantly enhances image throughput while reducing energy consumption^[18]. China's Tiansuan Constellation established a cloud-native satellite platform based on Huawei's KubeEdge and the Sedna edge-cloud collaborative AI framework^[19]. StarDetect developed the Xingce space experimental platform and the Haiyue ground simulation environment for full-link on-board simulation

^{[20][21]}. The first satellite of the Oriental Smart Eye (OSE) intelligent remote sensing constellation, launched in 2023, is equipped with an open on-board processing platform, providing a flexible environment for in-orbit scientific validation ^[22]. In 2025, the initial 12 satellites of the Three-Body Computing Constellation were launched. These satellites feature a space-based distributed operating system that enables unified management of computing, storage, and networking resources, supporting in-orbit task orchestration and application monitoring to provide high-reliability, high-performance services ^[23].

2.2 Space intelligent computing missions

On the ISS, HPE and its partners have used Spaceborne Computer-2 to investigate on-board processing for biological analysis, Earth observation, space medicine, and manufacturing ^[24]. Earlier ISS research demonstrated successful DNA amplification in microgravity ^[25], illustrating the value of processing biological data closer to the experiment. AWS, D-Orbit, and Unibap ran cloud and machine-learning software on an orbiting satellite to identify clouds, wildfire smoke, buildings, and ships ^[26]. DARPA's Blackjack program explored autonomous operations and AI for proliferated LEO systems ^[27]. In China, the Tiansuan Constellation has deployed integrated-sensing, remote-sensing inference, and in-orbit service experiments ^[28]. StarDetect focuses on geometric correction, ship identification, water segmentation, and cloud detection. Tsinghua University and partner institutions have developed the Gamma-ray Integrated Detectors (GRID) program for all-sky gamma-ray burst detection ^[29]. Wuhan University's Luojia-2-01 and Luojia-3-01 satellites support in-orbit multi-angle region-of-interest imaging, change detection, and hydrological sensing ^[30]. The Three-Body Computing Constellation has deployed a vision-language model with hundreds of millions of parameters ^[31] for surface activity monitoring and rapid detection of transient astronomical sources.

2.3 Computing hardware

In terms of space computing hardware, HPE's Spaceborne Computer-2 comprises HPE Edgeline and ProLiant systems. Equipped with more than 130 TB of flash storage, it supports machine-learning and other data-intensive workloads ^[32]. Unibap's SpaceCloud iX5-100 computer, launched on D-Orbit's ION SCV-4 in 2022, supports in-orbit edge computing, data storage, and sensor management ^[33]. Lonestar's "Independence" payload reached the Moon on Intuitive Machines' Odysseus Nova-C lander ^[34] and completed a proof-of-concept for Earth-Moon data transfer and lunar data storage. In August 2023, Star.Vision launched its "String" on-board intelligent-processing unit. In November 2025, Starcloud reported deploying an NVIDIA H100 GPU on the Starcloud-1 mission; in December, the company reported running a version of Gemini and training the nanoGPT model in orbit ^[35]. The spaceborne intelligent computing unit from Zhejiang Lab has achieved a performance of 744 TOPS, featuring high-throughput inference optimization, autonomous fault detection, and hardware/software self-healing capabilities ^[36].

2.4 Satellite communication networks

The evolution of satellite communication networks serves as the cornerstone for space computing. In 2021, the Tiansuan Constellation achieved the world's first deployment of a spaceborne 5G core network, completed satellite-ground Quick UDP Internet Connections (QUIC) protocol testing, and conducted in-orbit validation of lightweight 5G core network versions V3 and V4. It also proposed a 6G cognitive service architecture ^[37]. In 2023, Amazon's Project Kuiper achieved a 100 Gbps transmission rate through infrared laser-based optical Inter-Satellite Links (ISLs)^[38]. Meanwhile, Starlink demonstrated satellite-to-ground transmission with peak rates of 350 Mbps for downlink and 40 Mbps for uplink ^[39]. Huawei unveiled its "Space Broadband" initiative, aiming to increase optical interconnection speeds to over 100 Gbps via an interstellar optical network ^[40]. Similarly, Kepler Communications is developing a next-generation space data network to enable real-time connectivity in orbit ^[41].

Table 1 – Comparison of representative space computing practices

Organization / project	Mission objective	Architecture and key features	Validation status	Standardization relevance
NASA/HPE – Spaceborne Computer-2 ^[32]	On-board analysis of ISS experiment data	COTS Linux edge servers, CPU/GPU acceleration, software-based mitigation	Operational on ISS	COTS qualification, workload benchmark, software fault mitigation
Red Hat/NASA – ISS edge platform ^{[14], [15]}	Deploy and manage ground-developed applications in orbit	OpenShift containers and Ansible-based configuration/orchestration	ISS demonstration	Container packaging, lifecycle management, portable orchestration interfaces
DLR – ScOSA ^[17]	Reliable high-performance on-board computing	Distributed heterogeneous nodes with reconfiguration and task migration	In-orbit system tests	Resource abstraction, node interfaces, task migration, fault recovery
BUPT/Huawei – Tiansuan Constellation ^{[19], [28]}	Open research platform for satellite-ground computing	Cloud-native KubeEdge/Sedna framework and edge-cloud collaborative AI	In-orbit experiments	Cloud-native APIs, application distribution, experiment interfaces
Wuhan University – Oriental Smart Eye ^[22]	Flexible in-orbit Earth-observation processing and validation	Open on-board processing platform for reconfigurable intelligent applications	Satellite launched; in-orbit validation platform	Payload interfaces, application packaging, algorithm evaluation

Organi- zation / project	Mission objective	Architecture and key features	Validation status	Standardi- zation relevance
Zhejiang Lab – Three- Body Computing Constellation [23]	Constella- tion-scale computing and intelligent task execution	Distributed operating system with unified computing, storage, networking, and task orchestration	Initial 12- satellite deployment and in-orbit operation	Resource models, distributed system APIs, scheduling, monitoring, fault tolerance
AWS/ D-Orbit/ Unibap [26], [33]	Rapid on-board detection of Earth- observation targets	Cloud and machine- learning software on Unibap space- edge hardware	In-orbit experiment	Cloud-to- orbit deployment, model packaging, data interfaces, performance reporting
LEOcloud/ Axiom Space [16]	Commercial hybrid space-edge cloud services	Integration of space assets with terrestrial cloud and enterprise services	Partnership/ service- develop- ment stage	Service catalogue, SLA, identity, multi- operator interfaces

Table 1 shows a progression from payload-level demonstrations and single platform edge processing toward distributed constellations and service-oriented space-ground infrastructures. However, validation evidence remains heterogeneous: some systems have completed in-orbit experiments, whereas others remain at the partnership, prototype, or staged-demonstration level. Across these cases, standardization gaps include portable application packages, common resource descriptions, workload and model deployment interfaces, comparable in-orbit benchmarks, fault-recovery criteria, and multi-operator service management.

3. KEY TECHNOLOGIES OF SPACE COMPUTING

Currently, space computing primarily manifests in two paradigms: space edge computing and space cloud computing. (1) Space edge computing: Also known as in-orbit edge computing, it refers to the deployment of computing, storage, and sensing hardware at the data source (e.g., satellites). This enables near-source processing, ideal for missions with stringent real-time requirements such as navigation, disaster monitoring, and instant scientific analysis. (2) Space cloud computing: This paradigm involves the centralized or distributed management and scheduling of resources across a constellation. It provides elastic computational resources and cloud services to support complex data analysis and storage, serving near-Earth missions and high-demand tasks like galaxy research and deep space exploration.

The architecture of space computing adopts a three-tier collaborative design comprising the user, ground, and space segments (as shown in Fig. 1) and integrates space-based and terrestrial resources. The user segment consists of developers, research institutions, and general users, who interact with the ground segment through interfaces for application development, task submission, and data retrieval. The ground segment comprises the telemetry, tracking, command, and operations control center, the digital twin platform, and the data service platform, which are responsible for command uplink, state synchronization, and remote-sensing data transmission. At the core of the space segment is a distributed space computing platform that incorporates a distributed space operating system to support the deployment and operation of space-based data-processing systems and large models. Meanwhile, intelligent computing units and on-board routers are interconnected through laser and microwave inter-satellite links to form a space-based intelligent computing cluster. High-speed space-ground links enable closed-loop data flows and coordinated computing across the space and ground segments.

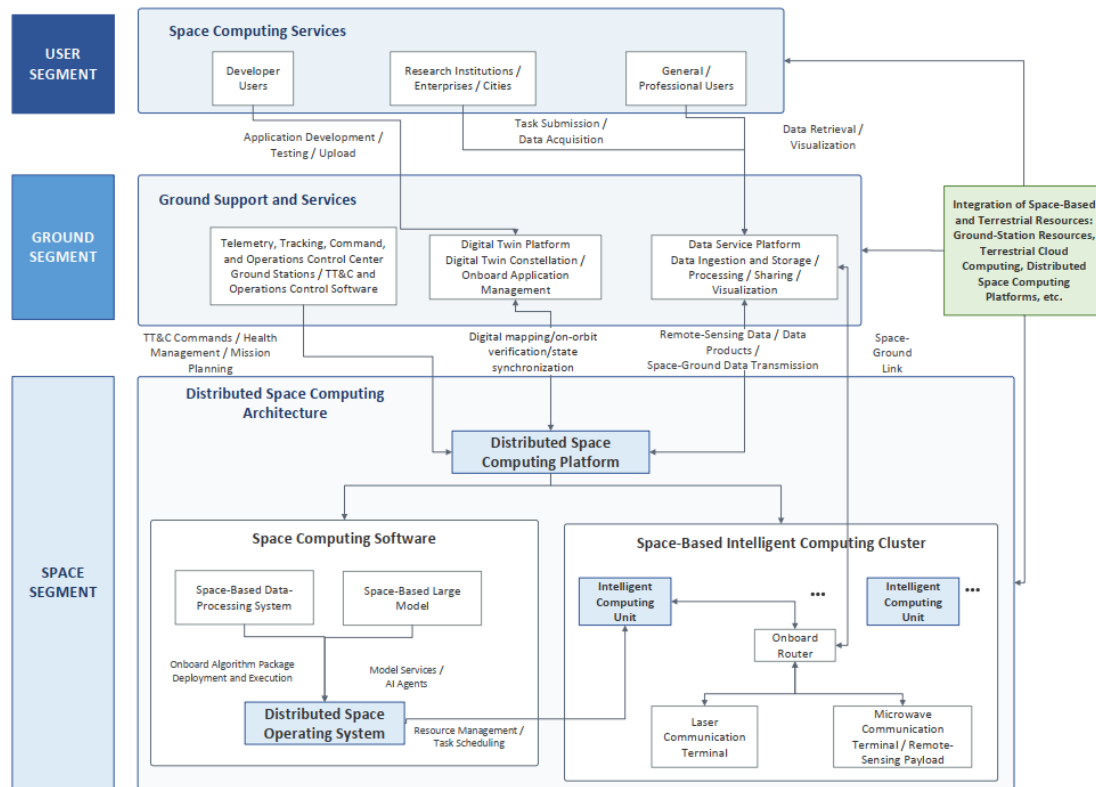


Figure 1 – The architecture of space computing

The development and deployment of space computing systems depend on breakthroughs in the following seven key technological areas:

1. Space distributed computing architecture: This involves organizing dispersed nodes into a collaborative network. Key technologies include architectures adapted to dynamic topologies, high-reliability computing, and security/trustworthiness technologies.
2. Space-based distributed operating system: This manages constellation resources in a unified manner. Key technologies include constellation autonomy, cross-satellite task orchestration, on-demand application distribution, and space-terrestrial collaborative computing.
3. Intelligent computing payload units: These units enable real-time processing of massive datasets. Key technologies include heterogeneous architectures, radiation hardening of COTS components, autonomous fault sensing/self-healing, and efficient thermal management for high-power payloads.
4. Inter-Satellite Link (ISL) technology: Enabled by wireless communication and networking. Key technologies include space-based protocols, high-speed ISL payloads, Acquisition, Pointing, and Tracking (APT) under high dynamics, and dynamic routing.
5. Space computing services: Integrating AI and big data for real-time processing. Key technologies include space-based foundation models, intelligent algorithm libraries, and integrated services.

6. Ground support and services: Managing (telemetry, tracking, and command) networks. Key technologies include integrated TT&C facilities, digital twin support systems, and virtualization of physical resources.

7. Space-terrestrial fusion technology: Achieving deep integration of multi-domain resources. Key technologies include open sharing of station resources and the synergy between terrestrial cloud and space-based platforms.

Technology Readiness Level (TRL) is used here as a nine-level scale ranging from basic principles observed (TRL 1) to an actual system proven through successful mission operations (TRL 9), following ISO 16290 [47]. The ranges in Table 2 are indicative system-level assessments synthesized from publicly reported demonstrations and literature rather than formal certification results.

Table 2 – Technology bottlenecks, maturity, dependencies, and standardization priorities

Technology area	Bottlenecks	Dependencies	Indicative system-level maturity	Priority standardization need	Potential standardization organization
Space Distributed Computing Architecture	Dynamic topology, intermittent links, node reliability/stability, cluster scale	Reliable networking and resource abstraction	Early in-orbit validation; TRL 5-6	Reference architecture, resource description, node discovery, trust and fault models	ITU-T SG13; CCSDS; IEEE

Technology area	Bottlenecks	Dependencies	Indicative system-level maturity	Priority standardization need	Potential standardization organization
Space-based Distributed Operating System	Heterogeneous and constrained resources, task migration, autonomy; multi-objective task orchestration; container isolation and reliability	Distributed architecture and platform APIs	No mature precedent; constellation autonomy and cross-satellite orchestration at TRL 4-5	OS service model, scheduling APIs, recovery	ITU-T SG13; CCSDS; IEEE
Intelligent computing payload units	Radiation, thermal and power limits, COTS reliability	Platform interfaces and environmental qualification, multilevel fault detection and recovery	TRL 5-6	Compute/energy benchmarks, accelerator interfaces, radiation-aware tests, payload-platform interfaces	ISO/TC 20/SC 14; CCSDS; IEEE
Inter-satellite links	Acquisition/tracking, topology dynamics, routing and link availability	High precision attitude determination and pointing control; on-board routers	TRL 6-7	Link/service interfaces, routing support, performance testing, cross-vendor interoperability	CCSDS; ITU-R; IEEE
Space computing services	Limited on-board memory and computing capacity; compression – accuracy trade-off; constrained uplink bandwidth; model compression, limited training data, runtime compatibility, secure update	Payload computing power and orchestration	TRL 3-6	Model/package formats, operator APIs, update and rollback, accuracy/latency/energy evaluation	ITU-T; ISO/IEC JTC 1/SC 42; IEEE
Ground support and services	Model fidelity, synchronization delay, scenario coverage, limited cross-domain sharing	Telemetry and common information models, digital twin platform	Foundational ground capabilities at TRL 6-7; digital twin platform at TRL 4-6	Information models, synchronization interfaces, fidelity metrics, benchmark (data, metrics, scenarios)	ITU-T SG13; ISO/IEC JTC 1/SC 41

Technology area	Bottlenecks	Dependencies	Indicative system-level maturity	Priority standardization need	Potential standardization organization
Space-terrestrial fusion technology	Administrative boundaries, security policies, service continuity, commercial confidentiality	High-speed space-ground links; ground-station networks; cloud-native technologies; data service platform, common APIs and governance	Preliminary integrated applications; collaborative computing architecture at TRL 3-4	Federated resource/service interfaces, SLA, portability, cross-domain conformance	ITU-T SG13; CCSDS; ISO; IEEE

4. STANDARDIZATION OF SPACE COMPUTING

The key technologies of space computing encompass space distributed computing, Inter-Satellite Links (ISLs), spaceborne intelligent computing units, and integrated space-ground services. Focusing on these critical areas, this section identifies relevant standardization organizations and channels, constructs a comprehensive space computing standardization framework, defines priority directions, and proposes strategic paths for standardization.

4.1 Relevant standardization organizations

ISO TC20, ITU-T SG13, CCSDS, and IEEE SA are actively conducting standardization work in space data transmission, future networks, cloud computing, and satellite/space communications. ISO/TC 20 develops standards for aircraft and space vehicles. Within this committee, SC 13 focuses on space data and information transfer systems and currently lists 87 published standards, while SC 14 covers space systems and operations and lists 201 published standards. These portfolios provide mature foundations for reference architectures, communication and data exchange, components, testing, and mission operations, but they are not organized around shared space computing resources and services^[42].

ITU-T SG13 focuses on future networks, including cloud computing and next-generation systems. Specifically, questions Q17, Q18, and Q19 define requirements for computing capabilities, architecture, and management, while Q23 standardizes network capabilities for the convergence of fixed, mobile, and satellite systems. This work is directly relevant to network-computing integration, APIs, cloud capabilities, orchestration, data handling, and security, but it does not yet constitute an end-to-end standard suite for distributed in-orbit computing^[43].

CCSDS provides widely adopted recommendations for space links, networking, delay-tolerant communications, on-board interfaces, cross-support services, and mission operations. Its Cloud Data Delivery Standards Working Group (CSS-CLOUD), under the cross support services area, is developing cloud-oriented data delivery specifications. These activities strongly support data transport and service access but workload placement, runtime portability, heterogeneous accelerator management, and the lifecycle of on-board AI models remain outside their main scope ^[44].

IEEE standards projects complement these activities in selected domains. For example, IEEE P3349 is an active project defining cybersecurity controls across the ground system, space vehicle, link segment, and integration layer. Such work provides an important security baseline, but it does not by itself address distributed operating systems, computing-resource orchestration, model portability, or digital twin validation ^[45].

Existing standards therefore provide indispensable but fragmented foundations. Standards concerning communication protocols, data formats, reference architectures, service access, and baseline security offer valuable guidance, whereas computing-resource abstraction, cross-platform task execution, AI-model lifecycle management, and compute-oriented conformance verification are only partially covered or not explicitly standardized.

Table 3 – Coverage and gaps analysis of standardization activities

Dimensions to consider for standardization	Existing coverage and representative activities	Status	Main Space Computing gaps
General foundation	ISO/TC 20/SC 13 reference architectures and data-system standards; ITU-T SG13 computing/network concepts and APIs	Partial	Unified Space Computing terminology, use cases, reference architecture, and cross-domain conformance model
Intelligent computing payload	ISO/TC 20/SC 14 spacecraft engineering and test standards; CCSDS on-board interface services	Partial	Compute/energy benchmarks, heterogeneous accelerator interfaces, radiation-aware validation, and payload-platform computing interfaces

Dimensions to consider for standardization	Existing coverage and representative activities	Status	Main Space Computing gaps
Computing system	ITU-T SG13 Q17-Q19 computing/cloud architecture and management; Q23 satellite convergence; CCSDS networking, DTN, and on-board services	Partial	Constellation-wide resource abstraction, distributed operating-system services, workload orchestration, task portability, and compute-oriented fault recovery
Space-based models	General AI and cybersecurity work in ISO/IEC JTC1 SC42; selected ITU-T AI/network activities and IEEE security projects	Limited	Model packaging and update, operator/runtime portability, radiation- and power-aware evaluation, provenance, and trustworthy on-board deployment
Ground digital twin	ITU-T and ISO/IEC JTC1 SC41 work on digital twin networks; ISO/CCSDS architecture and mission-operation practices	Early/partial	Fidelity metrics, space-ground state synchronization, scenario coverage, and benchmark methods for on-board algorithms
Application/service management	CCSDS cross-support and service-management activities; CSS-CLOUD data delivery; ITU-T cloud management/security; IEEE cybersecurity	Partial	Multi-operator service catalogues, identity and authorization, service-level metrics, application lifecycle, certification, and cross-border governance

The distinction between inherited and computing-specific requirements is central to this gap analysis. Space computing inherits physical and data-link transmission, coding, routing, delay-tolerant networking, data formats, cross-support services, and baseline link-layer security, including the CCSDS Space Data Link Security Protocol ^[46]. It adds requirements that arise from treating spacecraft as programmable computing nodes: heterogeneous resource abstraction, distributed operating-system services, task packaging and migration, cross-node scheduling, AI-model deployment and update, compute-state fault recovery, digital twin fidelity, and service-level conformance testing. Consequently, the proposed framework extends rather than replaces existing communication standards.

4.2 Space computing standardization Framework

The scope of space computing standardization covers intelligent computing payloads, computing systems, space-based models, ground digital twins, and related applications and management, encompassing design, testing, operation, and maintenance. In constructing the framework, existing

mature standards for network transmission, data exchange, and communication protocols should be reused wherever possible to reduce development cost and improve compatibility. The resulting standard system comprises six dimensions: general foundation, intelligent computing payload, computing system, space-based model, ground digital twin, and application service and management, as shown in Fig. 2.

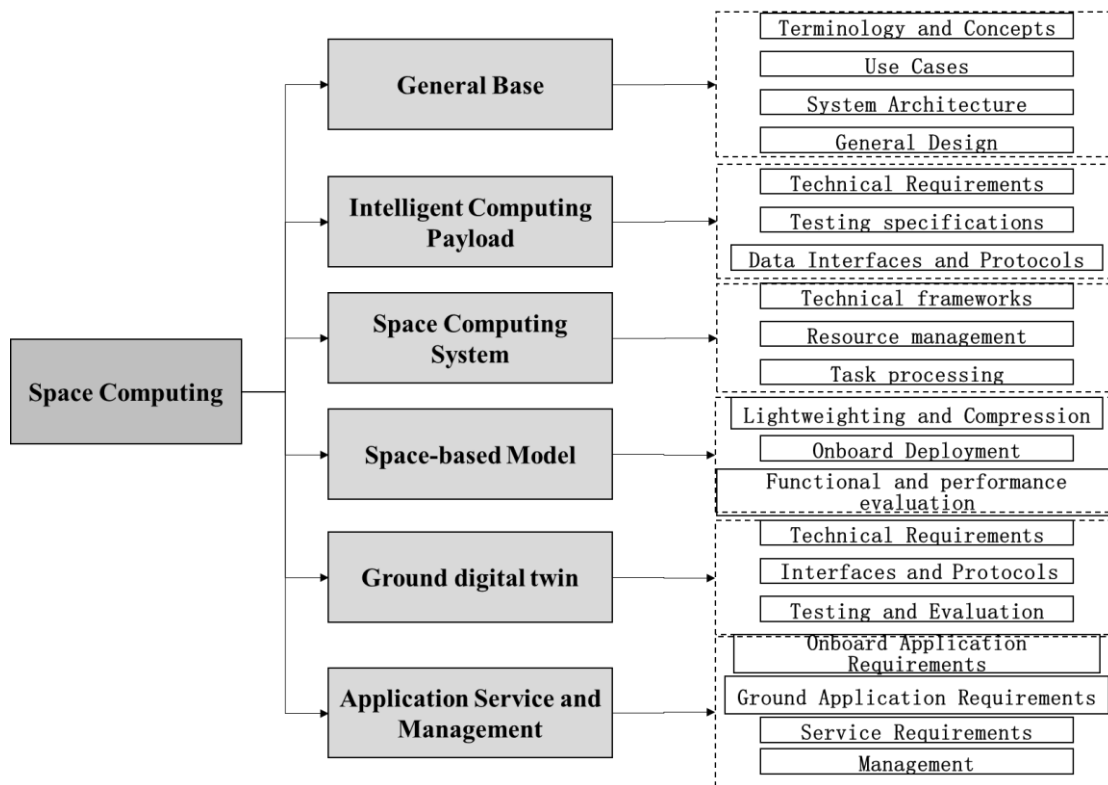


Figure 2 – Framework of space computing standardization

General base standards: Covering terminology, use cases, general architecture, and design. (1) Terminology and concepts: Unifying technical definitions to support other sub-standards. (2) Use cases: compiling application scenarios to define service types and attract stakeholders; (3) System architecture: Specifying technical logical relationships and interactions; (4) General design: defining specifications for constellation configurations.

Intelligent computing payload standards: including technical requirements, testing specifications, and interfaces. (1) Technical requirements: Regulating design architectures, physical dimensions, performance metrics (compute/storage), electromagnetic compatibility (e.g., radiation hardening), and thermal management; (2) performance testing: defining testing requirements for computational power, energy efficiency, and scalability under various environmental conditions (vibration, thermal vacuum, aging); (3) data interfaces and protocols: standardizing connections between payloads, satellite platforms, and nodes to ensure hardware-level interoperability.

Space computing system standards: focusing on technical frameworks, resource management, and task processing. (1) Technical frameworks: defining hierarchical frameworks and functional modules for integrated space-terrestrial systems and space edge clouds; (2) resource management: regulating in-orbit storage, distributed computing resources, file systems, data compression, codecs, and security; (3) task execution and processing: specifying requirements for task orchestration, multi-node coordination, fault tolerance, and recovery to ensure reliable execution and scheduling.

Space-based model standards: governing adaptation, deployment, and evaluation. (1) Lightweighting and compression: Defining distillation, quantization, and pruning standards to match model scale with SWaP-C (Size, Weight, Power, and Cost) constraints; (2) model packaging and in-orbit deployment: standardizing packaging formats, operator library interfaces, and on-board update requirements for dynamic loading; (3) evaluation: establishing metrics for inference stability, latency, and energy efficiency within unique space environments (e.g., radiation-induced bit flips).

Ground digital twin standards: covering digital twin requirements, interfaces, and evaluation. (1) Technical requirements: regulating modeling and simulation for satellites, payloads, and networks, alongside requirements for data synchronization and state prediction; (2) interfaces and protocols: defining connectivity between ground digital twin, distributed computing systems, and TT&C platforms; (3) testing and evaluation: assessing digital twin fidelity, data latency, and prediction reliability, while defining ground-based benchmarking methods for on-board algorithms.

Application service and management: covering application requirements, services, and governance. (1) On-board application requirements: specifying functional metrics and uplink procedures; (2) ground application requirements: defining development frameworks, constellation maintenance, and data synchronization performance; (3) service requirements: regulating data exchange interfaces between space systems, ground stations, and end users; (4) management: defining multi-user permission management, risk mitigation, and system security protocols.

4.3 Core standards development recommendations

The fundamental goals of space computing standardization are to foster secure global collaboration and interoperability while ensuring high quality and reliability. Furthermore, standardization should empower commercial innovation through digital and intelligent technologies, enabling AI-to-orbit deployment. Accordingly, we recommend prioritizing core standards in the following three areas:

1. Interoperability standards: Unlike static terrestrial nodes, space nodes face challenges like dynamic topologies, intermittent links, and long latencies. While utilizing existing communication standards, focus should shift toward cross-medium data transfer and payload-platform interconnects. This ensures stable transmission across multi-orbit constellations and supports system-level interoperability between diverse nations and commercial entities.

Emphasis must be placed on aligning technical standards with international space regulations to facilitate cross-border operations. Additionally, standards for data encryption and integrity verification for relay satellites and ground terminals should be established to protect against unauthorized tampering and cyberattacks.

2. Hardware and software validation specifications: Unlike the stable thermal and spatial environments on Earth, space computing faces severe heat dissipation, power efficiency constraints, and single event effects (e.g., SEU). Hardware: Standards must define technical requirements for computing payloads (processing power, storage, power consumption, and thermal limits) and communication loads (data rates, bit error rates, and link-establishment time).

Software: Testing methodologies for space-based distributed operating systems, virtualization technologies, and software components must be established to ensure seamless multi-task scheduling and resource sharing.

Furthermore, certification standards for applications and services, defining functional performance and entry criteria, are essential to ensure that space-based services meet industry-wide quality benchmarks.

3. AI data and space-based models: Space computing involves multi-satellite, multi-band, and multi-modal data fusion. Standardization for heterogeneous data access and format conversion is necessary to ensure cross-platform compatibility. For massive datasets, efficient and persistent storage solutions and resource scheduling standards must be developed to enable flexible allocation across on-board nodes and terrestrial data centers.

Algorithm/model evaluation: Priority should be given to establishing performance metrics for AI algorithms and Large Language Models (LLMs) in space, assessing their inference speed, accuracy, data adaptability, autonomous learning, and decision efficiency. Additionally, quality assessment and preprocessing standards for training datasets are vital to support the continuous evolution of space-based intelligent models.

4.4 Phased standardization roadmap

Standard development should follow technical maturity and functional dependencies rather than attempt to standardize all six dimensions simultaneously. As summarized in Fig. 3, near-term work should establish terminology, use cases, reference architecture, resource descriptions, interfaces, payload test methods, and baseline security profiles. Medium-term work can then address distributed operating-system and orchestration APIs, task packaging and recovery, AI-model deployment and evaluation, and digital-twin validation. Long-term work should support multi-operator coordination services, autonomous cross-constellation coordination, international certification or mutual recognition, and adaptation for application missions.

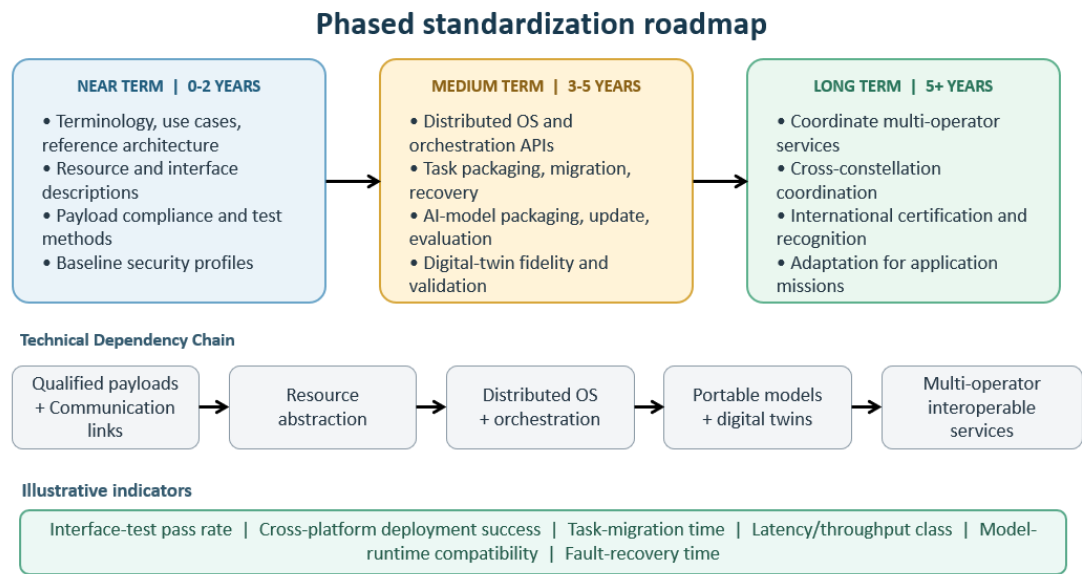


Figure 3 – The phased standardization roadmap

The upper part of the figure organizes standardization priorities into near, medium, and long-term stages; the middle presents the dependency chain of "basic connectivity and links–resource abstraction–distributed operating systems and orchestration–portable models and digital twins–multi-operator interoperable services"; and the lower part provides illustrative metrics. Indicators include interface-conformance pass rate, cross-platform deployment success rate, task-migration and fault-recovery time, end-to-end latency and throughput against a declared service class, and model-runtime compatibility.

5. CONCLUSION

The paradigm of space mission processing is undergoing an essential shift from "data relay" to "in-orbit intelligent computing." This paper has reviewed representative global practices, discussed the key technologies of space computing infrastructure, and developed an integrated standardization framework encompassing six dimensions: general foundation, intelligent computing payload, computing system, space-based models, ground digital twin, and application and service management. By relating these dimensions to existing standardization activities and outstanding gaps, the framework is intended to serve as a strategic reference for organizations such as ITU-T and for stakeholders developing interoperable space computing systems.

The formulation of space computing standards is essential for ensuring system-level interoperability and achieving synergy across heterogeneous resources. In the future, as engineering practices such as the Three-Body Space Computing Constellation continue to mature, standardization efforts should prioritize inter-satellite laser interconnects, spaceborne hardware and software specifications, and the performance evaluation of space-based models. By establishing open and unified standards, we can foster global collaborative innovation in space technology, providing a robust quality assurance foundation for the sustainable development of Earth observation and deep space exploration.

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