

Terrestrial-space interconnected collaborative computing: Architecture, scientific challenges, and application scenarios

Yongwei Li¹, Ruming Liu¹, Yu Cai¹, Wei Li¹

¹*Institute of Cloud Computing and Digitization, China Academy of Information and Communications Technology, Beijing, China*

Corresponding author: Wei Li, liweil3@caict.ac.cn

With the rapid development of satellite constellations, space-based edge computing, and terrestrial computing networks, Terrestrial-Space Interconnected Collaborative Computing (TSICC) has attracted increasing research attention in the fields of space computing and space artificial intelligence. Computing resources across terrestrial and space domains exhibit distinctive characteristics. Conventional terrestrial-centric computing architectures may face challenges in efficiently supporting global-scale applications involving Earth observation and the intelligent processing of massive spatial data. This paper proposes a working definition and establishes explicit conceptual boundaries for Terrestrial-Space Interconnected Collaborative Computing (TSICC), based on a structured comparison with closely related paradigms including satellite edge computing, satellite-terrestrial integrated computing, space-air-ground integrated networks, space data centers, satellite computing networks, and cloud-edge-end collaboration. It then presents a five-layer TSICC architecture and three representative operation paradigms, and analyzes key scientific challenges for the development of TSICC from the perspectives of scheduling algorithms, network protocols, operating systems, and AI models. In addition, representative application scenarios, including emergency communication, environmental monitoring, remote sensing, and global information services, are discussed. Finally, several future research directions are outlined to support the interconnection and collaborative utilization of terrestrial and space computing resources, the development of terrestrial-space collaborative intelligence, and related standardization efforts.

Keywords – Computing network, satellite-terrestrial integration, space artificial intelligence, space computing.

1. INTRODUCTION

The deep integration of the global digital economy with aerospace information technologies is reshaping existing computing paradigms. As a result, computing systems are evolving from terrestrial-centric centralized cloud architectures toward distributed collaborative computing across integrated space-air-ground-sea infrastructures [1-3]. The deployment of mega-constellations in Low Earth Orbit (LEO), such as Starlink, has demonstrated the capability of space-based nodes to provide near-global coverage and wide area service capability [4, 5]. Simultaneously, performance enhancements in radiation-hardened computing chips, Field Programmable Gate Arrays (FPGAs), and lightweight AI processors have provided the hardware foundation for space-based edge computing. Furthermore, the maturation of terrestrial computing networks has established high-density, high-reliability, and low-cost large-scale parallel computing capabilities.

In recent years, substantial research efforts have been devoted to satellite-terrestrial integrated computing and related space computing paradigms. Existing research can be broadly categorized into five research streams: architecture, networking, resource scheduling, computing systems, and Artificial Intelligence (AI).

Regarding architecture, existing research has evolved from satellite-assisted edge computing toward multilayer and heterogeneous space-terrestrial computing architectures. Early studies integrated satellite and terrestrial resources to support cooperative computation offloading [6], followed by architectures that coordinate computing resources across satellites and terrestrial edge nodes [7, 8]. More recent work has explored cloud-edge collaboration and hierarchical computing for space-ground integrated networks [9, 10], while satellite computing has emerged as a broader paradigm for extending cloud and edge capabilities into space [11].

Experimental platforms such as ComEdge have further demonstrated cloud-native integration of computing and communication functions across satellite-terrestrial networks [12], and space-ground fluid AI has investigated adaptive migration of AI tasks across heterogeneous resources [13, 14]. These studies establish important architectural foundations, but most remain focused on specific network configurations, service deployment, or resource coordination rather than unified resource abstraction and cross-domain orchestration.

From the networking perspective, research has focused on dynamic topology, intermittent connectivity, routing, and resource coordination in satellite networks. LEO constellations have motivated studies on topology, routing, and link dynamics [15, 16], supported by measurements of operational satellite networks [4]. Recent work has investigated adaptive routing [17-19] and computing-aware routing that jointly considers transmission and computation [20, 21]. Meanwhile, space-air-ground integrated networking has addressed heterogeneous connectivity and coverage [22, 23]. However, the coupling of network states with heterogeneous computing resources and application-level task requirements remains insufficiently explored.

Regarding resource scheduling, research has progressively shifted from static resource allocation toward dynamic task offloading and joint communication-computation optimization. The high mobility of LEO satellites, heterogeneous resources, time-varying channels, stochastic task arrivals, and limited onboard energy introduce substantial scheduling dynamics [24-26]. Existing studies have investigated task offloading and resource allocation under latency, energy, security, and deployment objectives [24-27], with satellite mobility and orbital information increasingly incorporated into scheduling decisions [28, 29]. Deep and multi-agent reinforcement learning have further been applied to dynamic offloading and cooperative decision making [15, 30-32], including dependent task offloading under time-space-varying resources [33]. However, a unified framework jointly considering heterogeneous resources, dynamic topology, orbital visibility, energy availability, task dependencies, and service requirements remains lacking.

At the computing-system level, research has increasingly explored the adaptation of cloud and edge computing to heterogeneous and resource-constrained space environments. Satellite edge computing has been investigated for source-side data processing, including Earth observation and computing-aware routing [34, 20], while cloud-native technologies have enabled flexible computing and communication services across satellite-terrestrial nodes [13]. Recent studies have further examined constellation-level computing resource design [35] and space-based data centers [36]. These efforts indicate a transition toward distributed and service-oriented space computing, but unified resource abstraction, cross-domain portability, lifecycle management, and coordinated execution remain insufficiently addressed.

AI constitutes another important research stream in space computing, encompassing onboard inference, distributed learning, federated learning, and AI-enabled network and resource management. AI models have increasingly been deployed onboard satellites for Earth observation and autonomous data processing [37, 38]. Federated learning has further enabled collaborative training across satellite clusters and heterogeneous LEO networks under computing and communication constraints [39-41], with communication-efficient mechanisms based on model quantization and asynchronous aggregation also investigated [42, 43]. At the network level, AI-enabled optimization and distributed intelligence have been studied over space-air-ground networks [44], while space-ground fluid AI has explored dynamic task and model migration [14]. However, AI is still largely treated as an application or local optimization tool rather than an integrated intelligence layer coordinating resources, network states, tasks, and service requirements across terrestrial and space domains.

Despite these advances, a cross-domain synthesis reveals three remaining gaps. First, terminology and conceptual boundaries remain heterogeneous across satellite edge computing, satellite-terrestrial integrated computing, space-air-ground integrated networks, and satellite computing, making it difficult to identify the necessary conditions for a genuinely cross-domain computing system. Second, existing studies are often focused on isolated components, such as task offloading, networking, learning, or satellite-side processing, while fewer studies provide a unified system-level view spanning resource abstraction, networking, orchestration, computing services, and applications. Third, existing analyses tend to optimize individual technical objectives, whereas the joint coupling between computing state, network state, orbital topology, energy availability, and service requirements remains insufficiently synthesized. The comparison in Table 1 provides the basis for these observations.

To address these issues, the contributions of this paper are summarized as follows:

- We formalize the concept, core characteristics, and application scenarios of TSICC, thereby clarifying its research scope and boundaries.
- We propose a TSICC architecture comprising the heterogeneous resource layer, the global networking layer, the collaborative orchestration layer, the cloud service layer, and the application layer, and further elucidate three representative operation paradigms.
- We analyze key scientific challenges in TSICC development from the perspectives of scheduling algorithms, network protocols, operating systems, and AI models, and outline promising future research directions.

The remainder of this paper is organized as follows: Section 2 presents TSICC definition, characteristics, and differentiation; Section 3 describes architecture and operation paradigms; Section 4 discusses scientific challenges; Section 5 presents application scenarios; and Section 6 concludes the paper with future directions.

2. DEFINITION AND CHARACTERISTICS

2.1 Definition

Terrestrial-Space Interconnected Collaborative Computing (TSICC) is a novel computing paradigm emerging from the deep integration of space computing and terrestrial computing networks. As shown in Fig. 1, it integrates large-scale terrestrial computing facilities with distributed space-based nodes. By leveraging satellite-terrestrial integrated communication networks, TSICC enables cross-domain resource interoperability and service orchestration. It provides a globally integrated logical framework for computing services to meet global demands for real-time analysis of massive spatial data, high-precision inference, and high-reliability intelligent services. It is worth mentioning that the unified resource abstraction is logical rather than physical: it provides a common representation of heterogeneous space and terrestrial resources for resource discovery, orchestration, and service scheduling, while the underlying resources remain physically distributed.

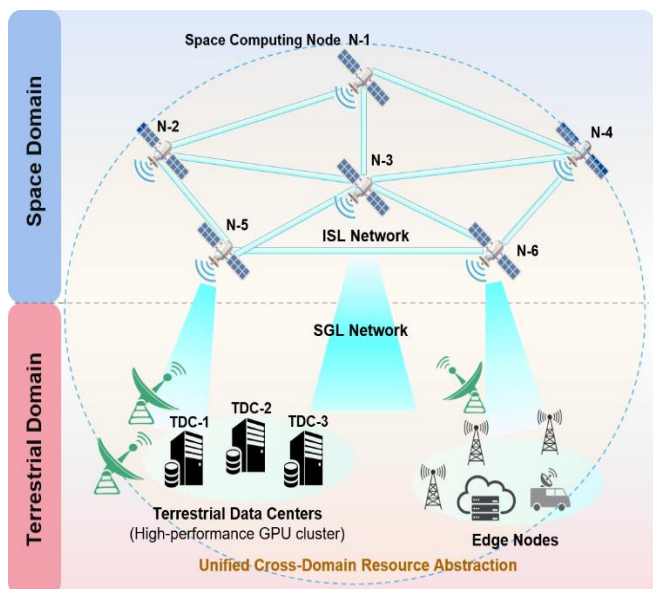


Figure 1 – Conceptual illustration of Terrestrial-Space Interconnected Collaborative Computing (TSICC).

Unlike satellite edge computing, which focuses on localized processing within individual satellites without deep integration with terrestrial resources, TSICC coordinates heterogeneous computing resources across terrestrial and space domains to support large-scale cross-domain collaborative tasks. Similarly, unlike space data centers, which emphasize persistent storage and computing in orbit, TSICC leverages complementary advantages between terrestrial and space resources to balance deployment cost and global service capability.

Terrestrial computing offers high density, high performance, and low cost, focusing on computationally-intensive scenarios like large-scale model training and long-cycle complex tasks. Conversely, space computing provides broad geographic coverage, distributed processing capabilities, and

strong resilience, particularly for tasks requiring in-orbit or near-source processing. The core logic of TSICC lies in unified resource awareness, dynamic interconnection, collaborative scheduling, and coordination of terrestrial and space resources to achieve localized processing, on-demand scheduling, and global coverage.

2.2 Conceptual boundaries

To distinguish TSICC from existing paradigms, this paper defines TSICC according to four necessary conditions. First, computing resources in both terrestrial and space domains are treated as first-class schedulable resources rather than merely communication end-points or data sources. Second, cross-domain task partitioning, offloading, migration, or execution is explicitly supported, such that a service workflow may span space and terrestrial computing nodes. Third, resource orchestration jointly considers computing, communication, and space-specific operational states, including computing capacity, link availability, energy status, and satellite topology. Fourth, the collaboration is closed-loop at the service or task level, meaning that resource allocation and processing decisions in one domain can affect or trigger subsequent computation, communication, or model operations in the other domain.

Accordingly, a system should not be categorized as TSICC merely because it combines satellite communication with terrestrial cloud computing. A satellite edge-computing system that performs only local processing, a space data center that operates primarily as an autonomous orbital computing facility, or a satellite-terrestrial network that provides connectivity without cross-domain computing orchestration does not necessarily constitute TSICC. In this paper, TSICC refers specifically to a computing paradigm in which heterogeneous terrestrial and space resources are jointly exposed, dynamically orchestrated, and cooperatively utilized to complete service-level tasks.

As shown in Table 1, TSICC overlaps with existing paradigms at the component level, but differs in its integration goals at the system level. Satellite edge computing emphasizes computation pushed toward individual satellites; satellite-terrestrial integrated computing focuses on joint resource allocation and task offloading; space-air-ground integrated networks primarily address multilayer connectivity and service provisioning; space data centers emphasize persistent storage and computation in orbit; satellite computing networks focus on distributed computing among satellite nodes; and cloud-edge-end collaboration mainly assumes a terrestrial computing continuum. TSICC instead emphasizes the joint orchestration of terrestrial and space computing resources as a unified, dynamically changing computing system, with communication state, computing state, energy state, and orbital topology jointly incorporated into task-level decisions.

2.3 Characteristics

Constrained by multiple conditions such as differences in terrestrial and space resource architectures, the laws of in-orbit spacecraft operation, and the complex spatial

Table 1 – Comparison of TSICC with related computing and networking paradigms.

Paradigm	Terrestrial-space resource integration	Unified resource abstraction	Cross-domain orchestration	Dynamic task migration	Computing-centric
Satellite edge computing [6]	○	–	–	○	√
Satellite computing networks [11]	√	○	○	√	√
Space data centers [36]	○	√	○	–	√
Satellite-terrestrial integrated computing [7]	√	○	○	√	√
Cloud-edge-end collaboration [56]	–	○	√	√	√
TSICC	√	√	√	√	√

√ indicates that the capability is an intrinsic or defining feature of the paradigm; ○ indicates that the capability may be supported but is not a primary design focus; – indicates that the capability is generally outside the paradigm's primary scope.

transmission environment, TSICC exhibits three core characteristics: cross-domain heterogeneity, spatio-temporal dynamicity, and time-varying weak link connectivity.

Cross-domain heterogeneity is the most fundamental characteristic of TSICC, manifested at three levels: computing heterogeneity, network heterogeneity, and system heterogeneity. First, terrestrial computing platforms encompass heterogeneous CPU architectures and accelerators, including x86 and ARM-based processors, GPUs, FPGAs, and domain-specific accelerators. Space computing platforms are likewise becoming increasingly heterogeneous, incorporating radiation-tolerant CPUs, FPGAs, GPUs, and specialized AI accelerators depending on mission requirements. Second, the terrestrial domain relies on fiber-optic backbone networks and 5G/6G wireless communication networking, whereas satellite-terrestrial communication primarily utilizes microwave and laser links, differing in bandwidth scale and transmission latency. Third, terrestrial servers generally run general-purpose operating systems, predominantly Linux-based in cloud and high-performance computing environments, while space-borne devices mostly deploy lightweight real-time operating systems such as VxWorks [45] and RTEMS [46], leading to significant challenges in cross-platform adaptation.

Spatio-temporal dynamicity originates from the high-speed motion of satellites and the periodic changes in the space environment, reflected in both spatial distribution dynamics and temporal state dynamics. From a spatial perspective, LEO satellites operate at speeds of approximately 7-8 km/s. During their orbital operation, their ground coverage areas shift continuously, causing the topological relationships of inter-satellite and satellite-terrestrial communication links to switch dynamically. This imparts a strong time-varying attribute to the spatial distribution pattern and networking structure of space computing resources. Temporally, influenced by factors such as occultation and changes in the spatial thermal environment, satellite power supply capabilities and in-orbit operating conditions exhibit periodic fluctuations. Coupled with the fact that application demands, such as disaster

emergency response and global monitoring, constantly change with the scenario, this creates a pronounced spatio-temporal imbalance between the supply of global computing resources and actual demands.

Time-varying weak link connectivity refers to the characteristic where satellite-terrestrial or inter-satellite links, disturbed by multiple factors such as atmospheric turbulence, rain attenuation, space radiation, and satellite occlusion, exhibit weak connection features including high bit error rates, low stability, intermittent connectivity, and bandwidth fluctuations. This weak connectivity leads to high packet loss rates and low efficiency in satellite-terrestrial data transmission. Consequently, protocol mechanisms in conventional IP-based networking, particularly end-to-end transport mechanisms that rely on relatively stable connectivity, timely feedback, and persistent paths, may experience degraded performance under intermittent, asymmetric, and highly variable space links.

3. TSICC ARCHITECTURE

3.1 Architecture overview

This section proposes an integrated TSICC architecture. Drawing on the design philosophies of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) [47-49], and deeply customized for the space environment, this architecture aims to break the "space-based silo" effect.

As illustrated in Fig. 2, the TSICC architecture is logically divided from bottom to top into: the heterogeneous resource layer, global networking layer, collaborative orchestration

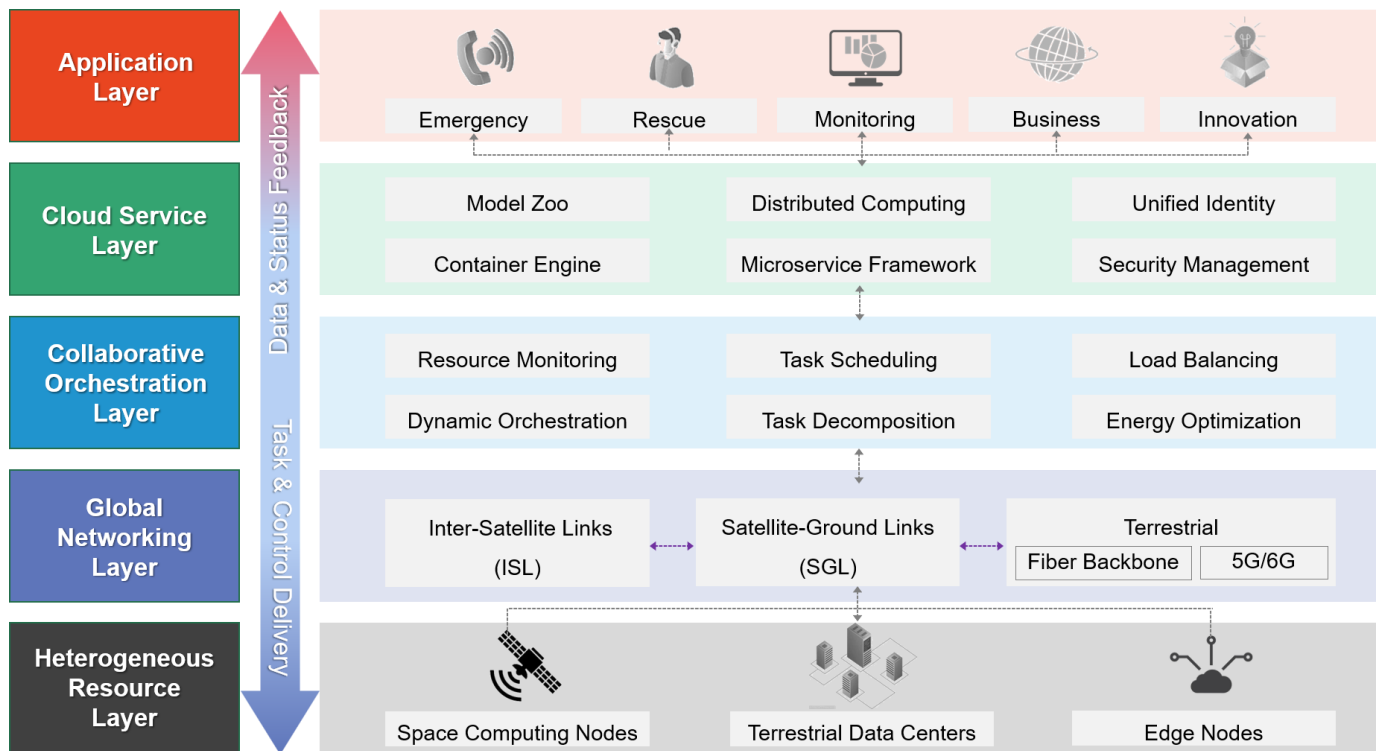


Figure 2 – Layered architecture of the proposed TSICC.

layer, cloud service layer, and application layer. Each layer performs signaling interaction and data transmission through conceptual logical interfaces, collectively forming a closed-loop collaborative computing system. Its TSICC-specific contribution lies in the cross-layer coupling between heterogeneous computing resources, time-varying space-terrestrial connectivity, and collaborative orchestration.

Heterogeneous resource layer. This layer serves as the physical foundation of TSICC, enabling unified logical management of terrestrial and space computing facilities. The heterogeneous resource layer comprises three categories of computing resources: space computing nodes, terrestrial data centers, and terrestrial or mobile edge nodes. Space computing nodes include satellite-borne processors and accelerators; terrestrial data centers include centralized cloud and high-performance computing facilities; and edge nodes refer to geographically distributed terrestrial computing resources such as mobile edge servers, gateway computing nodes, ground stations with computing capability, and other localized service nodes. The layer provides a common resource abstraction that represents not only computing and storage capacity but also energy availability, orbital position, link visibility, and communication capacity.

Global networking layer. As the link for data circulation, this layer is responsible for constructing resilient and adaptive interconnection paths across space and time to support timely access to distributed computing resources. The global networking layer includes not only horizontal Inter-Satellite Links (ISLs) using laser or microwave to support inter-satellite task offloading, but also vertical Satellite-Ground Links (SGLs) connecting the two domains

to enable data backhaul and command delivery. Crucially, this layer also covers high-speed fiber backbone networks between terrestrial data centers and terrestrial mobile communication networks, forming an integrated "inter-satellite, satellite-ground, and terrestrial" transmission matrix. This provides resilient connectivity and supports latency-aware cross-domain collaboration under time-varying network conditions.

Collaborative orchestration layer. The collaborative orchestration layer acts as the control and decision-making plane of TSICC. Because continuous global state synchronization is generally infeasible under intermittent and heterogeneous connectivity, the orchestration mechanism does not assume a perfectly consistent global resource view. Instead, it maintains hierarchical and partially observable resource states, including satellite position and visibility, residual energy, computing load, link quality, and estimated resource availability. Based on these potentially delayed or stale observations, the orchestrator performs task decomposition, resource selection, routing, migration, and load balancing across space and terrestrial nodes. The resulting decisions jointly consider task latency requirements, computing capacity, communication availability, energy constraints, topology evolution, and service priorities.

Cloud service layer. The cloud-native service layer adopts cloud-native design principles to perform standardized encapsulation and abstraction of underlying heterogeneous resources and scheduling logic. Through microservices and containerization technologies, this layer provides users and developers with readily deployable computing, storage, and AI services. Its functional components include a model zoo,

a spatial distributed computing framework, and a cross-domain unified identity authentication interface. It shields the underlying hardware heterogeneity and complex space communication protocols, allowing developers to access space computing resources.

Application layer. This layer directly faces the end-users and supports the deployment of intelligent services across various vertical industries by invoking the standardized capabilities provided by the cloud service layer. Its application scope covers global emergency disaster rescue, large-scale maritime environmental monitoring and illegal activity surveillance and enforcement, inclusive broadband communication services for remote areas, high-efficiency remote sensing image processing, and dynamic situational awareness of aerospace targets. The application layer drives adaptive resource adjustment and algorithm evolution of the underlying architecture by feeding back actual business flow characteristics.

3.2 Operation paradigms

To adapt to diverse task requirements, time-varying link states, and service quality, the proposed TSICC architecture can flexibly adopt three typical operation paradigms tailored to specific application scenarios, as illustrated in Fig. 3.

In-situ pre-processing. For applications with extreme real-time requirements, raw data undergoes feature extraction and dimensionality reduction directly at the space-based edge nodes. Only extracted high-value information is transmitted to the ground, which significantly alleviates the bandwidth pressure on the satellite-ground link.

Terrestrial-space pipeline collaboration. For compute-intensive tasks, a chained processing flow is adopted, consisting of coarse spatial identification followed by fine-grained ground-based analysis. Space-based nodes are responsible for the preliminary screening of Regions of Interest (ROI) [50], while terrestrial centers handle the

inversion of complex physical parameters and long-term sequence comparisons.

Iterative optimization. Terrestrial centers train large-scale foundation models based on massive historical data and push lightweight, distilled models to satellites via satellite-ground links. Satellite nodes perform online or incremental model adaptation based on newly acquired samples and periodically transmit model updates or compressed gradient information to the ground for global model evolution, achieving the co-evolution of terrestrial and space intelligence.

4. SCIENTIFIC CHALLENGES

The challenges of TSICC can be organized into six interdependent dimensions: resource orchestration, network and protocol adaptation, cross-domain computing systems, AI model deployment, security and trust, and reliability and sustainability. The present paper focuses on the first four dimensions because they constitute the core mechanisms directly required for cross-domain computing orchestration. Security, trust, and long-term reliability are treated as cross-cutting requirements that influence all four dimensions rather than as independent architectural layers.

4.1 Distributed collaborative scheduling under spatiotemporally dynamic environments

High-speed orbital motion, periodic fluctuations in on-board energy, and the time-varying characteristics of satellite-ground links cause the available space computing resources to remain in a state of dynamic evolution. Coupled with the significant spatiotemporal non-equilibrium distribution of global application demands, this further increases the difficulty of precise matching between terrestrial and space computing supply and demand. Traditional static scheduling strategies and single-objective optimization algorithms cannot adapt to the partially stochastic and multi-constraint

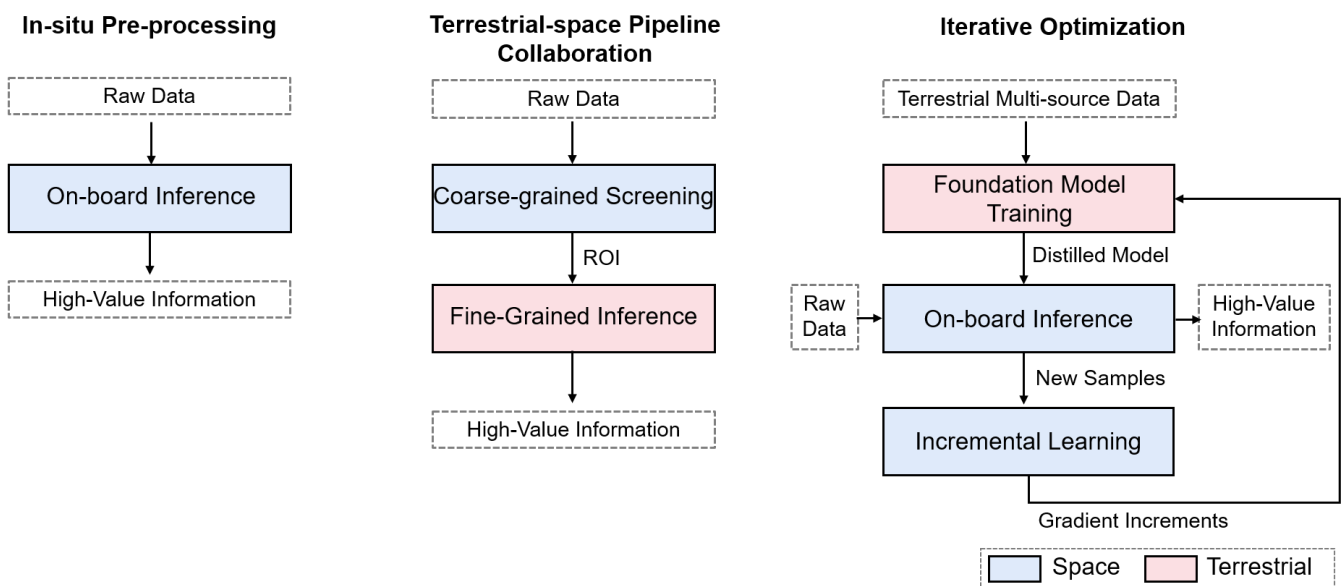


Figure 3 – Three operation paradigms of TSICC: in-situ preprocessing, terrestrial–space pipeline collaboration, and iterative optimization.

coupling characteristics of integrated satellite-ground scenarios, easily leading to fragmented and idle computing resources, drastic fluctuations in service transmission latency, and low overall system energy efficiency [51-53]. Constructing multi-dimensional spatiotemporal joint computing resource prediction models to accurately characterize global resource evolution, and developing intelligent collaborative scheduling algorithms with environment-aware and self-optimizing capabilities to support timely and adaptive matching between cross-domain heterogeneous resources and multi-type tasks, is the primary scientific challenge that TSICC needs to resolve.

4.2 Reliable transmission protocols for time-varying weakly connected satellite-terrestrial networks

Satellite-ground and inter-satellite links are affected by multiple interferences such as atmospheric turbulence, rain attenuation, space radiation, and satellite occlusion, exhibiting typical weak connectivity characteristics of high bit error rates, long feedback cycles, and intermittent links. When conventional TCP/IP protocols are applied to space channels, they often exhibit limited adaptability. For example, conventional TCP congestion-control and retransmission mechanisms may interpret delay or packet loss caused by channel conditions and route changes as congestion, leading to unnecessary rate reduction and degraded throughput. At the network layer, rapidly changing topology can invalidate routing states, while at the cross-domain service layer, intermittent connectivity may interrupt long-running task offloading and data synchronization. Therefore, TSICC requires protocol mechanisms that jointly consider link-state prediction, scheduled or opportunistic connectivity, store-and-forward operation, and application-level task priorities. Delay Tolerant Networking (DTN) [54,55], including bundle protocol mechanisms, provides an important reference for this direction, although additional adaptation is required for computation-aware task orchestration.

4.3 Cross-domain integrated intelligent computing system

Terrestrial and space nodes differ significantly in hardware architecture, operating system ecosystems, and resource configurations. Moreover, space-based nodes are exposed to high-radiation environments for long periods, facing extremely high risks of hardware single-event upsets and physical failures. Existing operating systems lack a unified management paradigm for cross-domain collaboration, and in distributed environments, they are prone to stability hazards such as data inconsistency, scheduling command conflicts, and service disruption or system-wide failures caused by single points of failure. Constructing a lightweight, modular, and cross-platform compatible cross-domain computing system software stack, and designing efficient distributed consistency protocols and satellite-ground redundancy fault-tolerance mechanisms to achieve unified management, task collaborative scheduling, resource sharing, and security control of nodes, ensuring smooth system

operation under resource-constrained and unreliable node conditions, is a fundamental scientific challenge for the development of TSICC.

4.4 Lightweight AI models and collaborative inference under resource constraints

On-board computing platforms are constrained by limited computing capacity, power availability, and on-board storage capacity, making it difficult to deploy terrestrial AI models with large parameter counts. Meanwhile, the dynamic fluctuations of satellite-ground links also limit the efficiency of in-orbit iterative updates and cross-domain collaborative inference for intelligent models. Existing mainstream lightweight methods struggle to achieve an effective balance between model compression ratios and inference accuracy for space-based tasks, and there is currently a lack of mature and complete satellite-ground joint inference architectures and incremental learning iteration paradigms for spatial scenarios. Breaking through dedicated on-board AI model design methods that account for both high compression ratios and high inference accuracy, constructing an integrated collaborative inference framework of space-based in-orbit front-end processing and terrestrial back-end deep analysis, and establishing an in-orbit dynamic adaptation and autonomous iterative evolution mechanism for spatial models to achieve real-time deployment and high-precision intelligent services, is an important open research problem.

5. APPLICATION SCENARIOS

5.1 Emergency communication and rescue

In scenarios of sudden major disasters such as earthquakes and forest fires, terrestrial communication networks are highly vulnerable to physical damage or power outages, causing disaster areas to fall into communication blackouts. Rescue operations urgently need to obtain real-time remote sensing imagery and personnel distribution information covering the entire area within an extremely short time, posing severe challenges to the survivability, response speed, and massive data processing capabilities of communication systems.

TSICC can support an emergency communication network with rapidly deployable coverage through satellite constellations and utilize lightweight on-board AI models to perform in-situ analysis of captured images to extract key features, such as fire points and flooded areas. The pre-processed data is then transmitted by space-based nodes to terrestrial emergency command vehicles and core computing centers, where rescue route planning and dynamic resource configuration are completed through satellite-ground collaborative task scheduling.

This application has the potential to improve communication availability in disaster areas by combining satellite coverage with rapidly deployable terrestrial emergency nodes. In addition, in-situ preprocessing and cross-domain task scheduling may reduce the amount of raw data that needs to be transmitted and shorten the processing path between

observation and emergency decision-making. The actual reduction in response time and the achievable coverage depend on constellation configuration, gateway availability, link conditions, computing resources, and disaster characteristics, and therefore require quantitative evaluation in specific deployment scenarios.

5.2 Environmental and maritime monitoring

Operations such as global climate change monitoring, maritime oil spill detection, and illegal fishing regulation are characterized by wide geographical coverage, long monitoring cycles, and strong coupling of multi-source data. Traditional monitoring methods are limited by geographical accessibility, making it difficult to achieve continuous dynamic monitoring in remote regions such as the poles and open oceans. A single satellite payload may provide only a partial view of complex environmental conditions. Multi-sensor and multi-satellite data fusion can therefore provide complementary spatial, spectral, and temporal information for more comprehensive environmental assessment.

Relying on the TSICC architecture, optical, SAR, and hyperspectral satellite constellations collaboratively collect multidimensional global remote sensing data and complete preliminary feature extraction and data cleaning at the space-based edge. Terrestrial core computing centers then integrate the feature information returned from space, ground monitoring station data, and historical meteorological models to perform long-term situational assessment and trend prediction of anomalous events.

This application enables monitoring of global extreme regions and enhances data interaction efficiency through joint satellite-ground processing, reducing expensive satellite bandwidth overhead. Its potential for near-real-time warning and long-term trend analysis may provide additional technical support for ecological monitoring and maritime resource management.

5.3 Remote sensing and meteorological prediction

Extreme weather warning and high-value target tracking have extremely stringent requirements for the timeliness of remote sensing data. Faced with massive remote sensing data streams, the traditional terrestrial centralized paradigm of "backhaul first, process later" often leads to delayed meteorological predictions due to transmission bandwidth bottlenecks and terrestrial processing latency, making it difficult to meet the real-time requirements of services such as nowcasting.

TSICC shifts meteorological analysis models and target detection algorithms forward to on-board computing platforms, enabling real-time in-orbit cloud detection, precipitation intensity estimation, and high-value target detection. Space-based nodes achieve rapid delivery of computing results through inter-satellite links and collaborate with high-performance terrestrial meteorological computing clusters to dynamically adjust satellite sampling strategies in real time, achieving closed-loop tracking and processing of extreme weather events.

This integrated satellite-ground intelligent perception mode can potentially improve the timeliness of short-term meteorological analysis by reducing the amount of raw data that must be transmitted before initial processing. This can provide additional response time for disaster prevention and agricultural precision scheduling, driving the transition of traditional remote sensing toward an active and intelligent perception paradigm.

5.4 Global inclusive business and information services

Currently, hundreds of millions of people worldwide still live in remote areas lacking broadband coverage, facing a severe "digital divide." These regions have an urgent demand for low-cost, wide-coverage online education, telemedicine, and inclusive financial services; however, constrained by terrestrial infrastructure construction costs and geographical environmental limitations, traditional telecommunications services are difficult to reach effectively.

TSICC utilizes LEO satellite constellations to provide low-latency global interconnected access and relies on space computing nodes to deploy lightweight inclusive AI applications, achieving rapid response for localized services. The terrestrial computing center acts as a resource hub responsible for the on-demand delivery and content caching of public service resources, completing the optimal distribution and task scheduling of cross-domain resources through satellite-ground collaboration.

This application can help mitigate the geographic constraints on access to information and digital services, potentially extending computing-enabled services to geographically-underserved areas. By potentially extending computing-enabled digital services to geographically-underserved areas, this architecture may contribute to broader access to basic digital services.

5.5 Near-Earth space activities

As commercial aerospace technology matures, innovative applications, such as space tourism, in-orbit manufacturing, and space laboratories, are gradually becoming a reality. These scenarios generate large volumes of scientific experimental data with frequent interactions, and space tourists' demands for low-latency immersive experiences, in-orbit health monitoring, and instant social networking pose new requirements for computing and connectivity in near-Earth space.

Under the TSICC architecture, a near-Earth orbit computing platform can provide localized computing support for space stations and tourist cabins, enabling real-time high-definition video encoding/decoding and preliminary cleansing of scientific experimental data. Terrestrial computing networks then undertake complex experimental modeling and long-cycle data storage tasks, ensuring high-quality interaction between astronauts, tourists, and ground control centers through close satellite-terrestrial collaboration.

In the longer term, TSICC may provide a conceptual basis for integrating orbital computing resources with terrestrial

computing infrastructure for near-Earth space activities. However, the technical and economic feasibility of such applications remains subject to advances in launch cost, radiation-tolerant computing, thermal management, in-orbit maintenance, communication capacity, and space infrastructure deployment.

6. CONCLUSION

Terrestrial-Space Interconnected Collaborative Computing (TSICC) is conceptualized in this paper as a cross-domain computing paradigm in which heterogeneous terrestrial and space computing resources are jointly exposed, dynamically orchestrated, and cooperatively utilized to complete service-level tasks. Through comparison with satellite edge computing, satellite-terrestrial integrated computing, space-air-ground integrated networks, space data centers, satellite computing networks, and cloud-edge-end collaboration, this paper identifies the necessary characteristics and conceptual boundaries of TSICC.

On this basis, a five layer architecture and three representative operation paradigms are presented. The analysis further identifies key challenges in collaborative scheduling and discusses research challenges associated with spatiotemporally dynamic resource orchestration, adaptive networking, cross-domain computing systems, and lightweight collaborative AI. The application scenarios discussed in this paper should be regarded as potential use cases rather than quantitatively-validated performance outcomes. Future work should therefore focus on benchmark construction, formal optimization, simulation and prototype validation, interoperable interfaces, security and trust mechanisms, and quantitative evaluation of TSICC under representative orbital and terrestrial network conditions.

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AUTHORS



YONGWEI LI received the Ph.D. degree from the School of Transportation Science and Engineering, Beihang University, Beijing, China, in 2025. He is currently an engineer with the China Academy of Information and Communications Technology (CAICT). His research interests include cloud computing, the Internet of Compute (IoC), spatiotemporal prediction, robotics, and space AI.



RUMING LIU, engineer at the China Academy of Information and Communications Technology (CAICT). He is responsible for advancing initiatives in Internet of Compute (IoC), cloud-native computing, satellite computing, and space artificial intelligence.



YU CAI, engineer at the China Academy of Information and Communications Technology (CAICT). She is responsible for advancing initiatives in Internet of Compute (IoC), cloud-edge-device collaborative computing, and space artificial intelligence.



WEI LI, professor of engineering. She currently works at the China Academy of Information and Communications Technology (CAICT), where she has been engaged in research on cloud computing, artificial intelligence, making significant contributions to the establishment of internet of compute (IoC) architecture. She has published more than ten academic papers and holds more than 20 invention patents.