

ORBITAL COMPUTING AS THE INTEGRATING NODE OF MULTI-DOMAIN OPERATIONS

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Abstract: *The exponential growth of satellite-borne sensor data has created a structural mismatch between collection capability and the downlink bandwidth available to military communication satellites. This paper examines orbital computing, defined as the processing of sensor data directly aboard satellites or across LEO constellation nodes, as a technical and doctrinal solution to this challenge. The analysis shows that onboard artificial intelligence, region-of-interest extraction, compression, and optimized bandwidth-computing resource allocation can reduce raw-data transmission by up to 100-fold in advanced processing cases, while also lowering dependence on ground-station processing. These effects compress the Observe-Orient phases of Boyd's OODA-loop by shortening the sensor-to-decision chain and accelerating the delivery of decision-relevant information to command nodes. Beyond bandwidth efficiency, the paper argues that military satellites equipped with onboard artificial intelligence constitute the structurally necessary integrating node of multi-domain operations, because they provide persistent cross-domain visibility over land, air, maritime, cyber/electromagnetic, and space activities. This finding aligns with NATO multi-domain operations doctrine and the United States JADC2 strategy, positioning orbital computing as a key enabler of decision superiority in 21st-century warfare.*

Keywords: orbital computing, multi-domain operations, decision superiority, satellite AI, on-orbit processing

1. Introduction

Modern military operations are increasingly defined by information velocity. NATO's formal recognition of space as a fifth operational domain [1] and the doctrine of Multi-Domain Operations (MDO) demand the convergence of effects across land, air, maritime, cyber, and space simultaneously [2]. Yet the sensor data generated by the growing constellation of military and commercial satellites (imagery, signals intelligence, hyperspectral, infrared) exceeds the capacity of conventional satellite downlinks by orders of magnitude. The Wideband Global SATCOM (WGS) system, the United States Department of Defence's primary broadband satellite architecture, provides approximately 2.1-3.6

Gbps per satellite, shared across the entire theatre of operations [3], while a single hyperspectral satellite scene generates approximately 7 GB per image.

Orbital computing, also known as in-orbit computing or space-edge computing, addresses this structural mismatch by executing AI-based data processing directly on the satellite, transmitting only pre-analysed, decision-ready intelligence to ground-based command nodes. This paradigm shift has operational implications beyond bandwidth efficiency: it fundamentally restructures the information flow of Colonel John Boyd's Observe-Orient-Decide-Act (OODA) loop [4], compressing the sensor-to-decision cycle and enabling what Bucăřă and Moro [5]

describe as "decision-making at various levels" inside the adversary's reaction time. This paper argues that orbital computing constitutes the structural bridge linking all five operational domains, because only satellite systems have persistent, simultaneous line-of-sight to activities in all other domains, and onboard artificial intelligence (AI) can fuse these multi-domain data streams before transmission, delivering integrated situational awareness directly to command nodes.

2. Research Questions

Three interconnected research questions guide this study:

RQ1: To what extent does orbital computing reduce the volume of data transmitted from satellite-borne sensors to military command nodes?

RQ2: How does AI-based on-orbit sensor fusion compress the OODA-loop and contribute to decision superiority over adversaries?

RQ3: In what sense can orbital computing be considered the integrating bridge linking the five NATO operational domains (land, air, maritime, cyber, space)?

3. Methodology

3.1 Systematic Literature Review - PRISMA 2020

A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework [6]. The review covered peer-reviewed journals, conference proceedings, technical reports, and official governmental and intergovernmental publications from 2018 to 2025.

- Identification: Database searches were performed across IEEE Xplore, Scopus, Google Scholar, DTIC, ESA Technical Reports, and DARPA program documentation using the Boolean search terms: ("orbital computing" OR "on-orbit computing" OR "space edge computing" OR "onboard AI satellite") AND

("military" OR "multi-domain operations" OR "OODA loop" OR "decision superiority"). A total of 247 candidate records were identified.

- Screening: After removal of 38 duplicates, 209 records underwent title and abstract screening. Records were excluded if they addressed exclusively non-military space applications (n=67), hardware design without operational analysis (n=44), or pre-2018 publications superseded by more recent work (n=21). This yielded 77 records for full-text assessment.
- Eligibility: Full-text review excluded an additional 34 records: 18 lacked quantitative data on bandwidth reduction or decision-cycle metrics, 9 were conference abstracts without peer-reviewed follow-up, and 7 addressed commercial Earth observation without defense relevance.
- Included: 43 sources were included in the synthesis: 19 peer-reviewed journal articles, 9 conference proceedings papers, 8 official doctrine documents and technical reports, and 7 validated grey literature sources (DARPA, ESA, NATO, SDA official publications). Quality assessment applied three criteria: methodological transparency, data specificity, and institutional credibility.
- Research Gap: The systematic review reveals that while the technical feasibility of onboard AI processing has been demonstrated at the component and mission levels (Phi-Sat-1/2, Blackjack), no peer-reviewed study quantitatively links measured data-reduction ratios directly to operational OODA-loop compression metrics within a unified multi-domain military framework. Furthermore, existing literature treats orbital computing either as a communications engineering problem or as a doctrinal MDO enabler, but no work formally establishes the satellite as the structural convergence node across all five NATO operational domains

simultaneously, integrating sensor streams from land, air, maritime, and cyber environments. This paper addresses both gaps by bridging quantitative bandwidth evidence with OODA-loop analysis and multi-domain doctrinal alignment.

3.2 Mixed Qualitative-Analytical Approach

Following Booth et al. [7] and the framework applied in analogous military technology studies in this proceedings series [5] [8], this study adopts a mixed qualitative-analytical methodology combining three methods:

- doctrinal analysis of NATO Allied Command Transformation MDO doctrine, TRADOC Pamphlet 525-3-1, and the Department of Defense (DoD) Joint All-Domain Command and Control (JADC2) Strategy;
- technology assessment of flight-proven orbital computing platforms for quantitative performance metrics including data reduction ratios, processing latency, and AI accuracy;
- and operational scenario analysis synthesising the Russia-Ukraine conflict (2022-present) to assess real-world decision cycle dynamics and satellite-AI integration effects.

4. Literature Review and Results

4.1 RQ1: Data Volume Reduction Through Orbital Computing

The fundamental driver of orbital computing is the sensor-downlink gap. Furano et al. [9] quantify this precisely, sensor data generation capability grows by a factor of 100 per technology generation, while downlink capacity grows by only 3-5. A single hyperspectral Earth observation scene requires approximately 7 GB, satellite downlink passes at Low Earth Orbit (LEO) last approximately 9 minutes, and the entire WGS system provides only 2.1-3.6 Gbps per satellite shared across all DoD operations. Giuffrida et al. [10] demonstrated on ESA's Phi-Sat-1 that a convolutional neural

network (CloudScout) running on an Intel Movidius Myriad 2 VPU achieved cloud detection with 92% accuracy at approximately 1% false positives, reducing transmitted data by approximately 30%, because roughly one-third of all imagery collected is cloud-contaminated and thus operationally useless. KP Labs [11] reports that more comprehensive onboard segmentation, transmitting only regions of interest (detected vessels, infrastructure changes, fire hotspots), achieves reductions of up to 100-fold versus raw data transmission.

The military implications are direct. During Operation Enduring Freedom, only half of the available UAVs could be operated simultaneously due to limitations on SATCOM bandwidth [12]. Onboard AI processing ensures that only actionable intelligence, rather than raw sensor streams, consumes the critically scarce downlink capacity.

4.2 RQ2: OODA-loop Compression and Decision Superiority

The findings of RQ1 have direct operational consequences for the speed of the military decision cycle. In conventional intelligence, surveillance and reconnaissance (ISR) pipelines, the sequence is: sensor collection → downlink to ground station → ground-based processing → analysis → dissemination to command. This process is latency-sensitive because bandwidth, ground-station availability and processing capacity are sequentially dependent. When raw sensor data volumes exceed available transmission capacity, ground-station queues and processing backlogs delay the delivery of actionable intelligence to commanders. This problem is particularly relevant in military satellite communication environments, where WGS provides only 2.1-3.6 Gbps per satellite shared across an entire theatre [3], and where previous ISR operations have already shown that bandwidth limitations can restrict the simultaneous employment of sensor platforms [12].

Valente, et al. [10] provide a more precise technical basis for this argument than simple onboard filtering. Their study shows that in LEO Earth Observation constellations, processing tasks can be allocated dynamically among the source satellite, other satellites in the constellation and the ground segment, depending on available bandwidth and computing resources. This changes the ISR model from a ground-centred processing chain into a distributed orbital edge-computing architecture. The operational significance is that decision-relevant data can be processed, prioritised or transformed before transmission, reducing unnecessary downlink traffic and accelerating the Observe and Orient phases of the OODA-loop.

This logic is reinforced by more advanced onboard processing concepts. KP Labs [11] reports that transmitting only relevant regions of interest, such as detected vessels, infrastructure changes or fire hotspots, can reduce transmitted data volumes by up to 100-fold compared with raw-data transmission. The causal chain is therefore: orbital edge processing and optimized resource allocation → reduced dependence on raw-data downlink → lower ground-station and processing bottlenecks → faster Observe/Orient transition → OODA-loop compression inside the adversary's reaction time → decision superiority.

Boyd's OODA framework defines decision speed as a systemic source of advantage, because an adversary operating inside a slower loop faces growing uncertainty, confusion and loss of initiative [4]. The Russia-Ukraine conflict illustrates this principle: Ukraine's AI-enabled GIS Arta system, supported by commercial satellite intelligence and resilient connectivity, enabled decision cycles described as one to three orders of magnitude faster than Russian equivalents [13] [14]. Russia's centralized command structure, by contrast, has been assessed as limiting its utilization of information from space [15]. The UK Ministry of Defence's reported 95%

reduction in AI-assisted satellite imagery processing time [16] and the JADC2 Sense-Make Sense-Act logic [17] further confirm that orbital computing contributes to decision superiority by accelerating the transformation of sensor data into command-relevant knowledge.

4.3 RQ3: Orbital Computing as the Bridge Between Five Domains

The argument that orbital computing constitutes the structural bridge linking all five NATO operational domains rests on three intersecting foundations.

First, geometric universality: satellites in low- and medium-Earth orbit have persistent, simultaneous line-of-sight access to activities across all other domains. No ground-based, maritime, or airborne platform possesses this cross-domain visibility at a global scale. The Space Development Agency's Proliferated Warfighter Space Architecture (PWSA) exploits this. Its Transport Layer provides Link-16 data relay connecting sensors in all domains to command nodes, while its Tracking Layer fuses missile data from land, air, and sea sensors [18].

Second, AI-enabled sensor fusion: orbital computing enables the integration of heterogeneous sensor streams, electro-optical and infrared imagery (land/maritime), signal intelligence (SIGINT – cyber/electromagnetic spectrum), weather data (air), and precision navigation (all domains), aboard the satellite itself. This is the operational definition of MDO convergence. DARPA's Blackjack Pit Boss system demonstrated precisely this, integrating third-party sensor data from HawkEye 360 (RF/maritime), Kitware (computer vision/land), and Raytheon BBN (decision support) aboard a commercial host satellite [19].

In the cyber/electromagnetic domain, this integration is not limited to passive signal collection. Onboard AI can perform real-time classification and anomaly detection on radio-frequency and electromagnetic-spectrum data before downlink. For

example, a satellite collecting SIGINT or RF emissions over a contested theatre may use lightweight sequence models, autoencoders, or transformer-based anomaly detectors to distinguish routine communication patterns from spoofing attempts, jamming signatures, abnormal emitter behaviour, or deceptive navigation-signal activity. Instead of transmitting the full raw electromagnetic stream, the onboard system can filter encrypted or non-actionable signal noise, extract metadata such as emitter location, frequency behaviour, signal persistence, modulation anomalies, and temporal correlation with kinetic activity, and transmit only a compressed alert or confidence-ranked event package to the ground station. In practical MDO terms, this means that orbital computing links the cyber/electromagnetic domain to the kinetic domains: a suspicious RF anomaly detected

from space can be correlated onboard with maritime vessel movement, land-based missile activity, air-defence radar activation, or GNSS spoofing indicators, thereby transforming cyber/electromagnetic sensing into decision-relevant cross-domain intelligence rather than a separate technical data stream.

Third, doctrinal alignment: NATO's MDO concept demands “converging effects at the speed of relevance” [20]. The JADC2 Strategy requires connecting sensors to shooters across all domains with AI-enabled fusion at every layer. Orbital computing is the only architecture that can provide the persistent, latency-minimised, AI-fused situational picture across all five domains simultaneously, making it not merely a communications enabler but the operational centre of gravity of MDO.

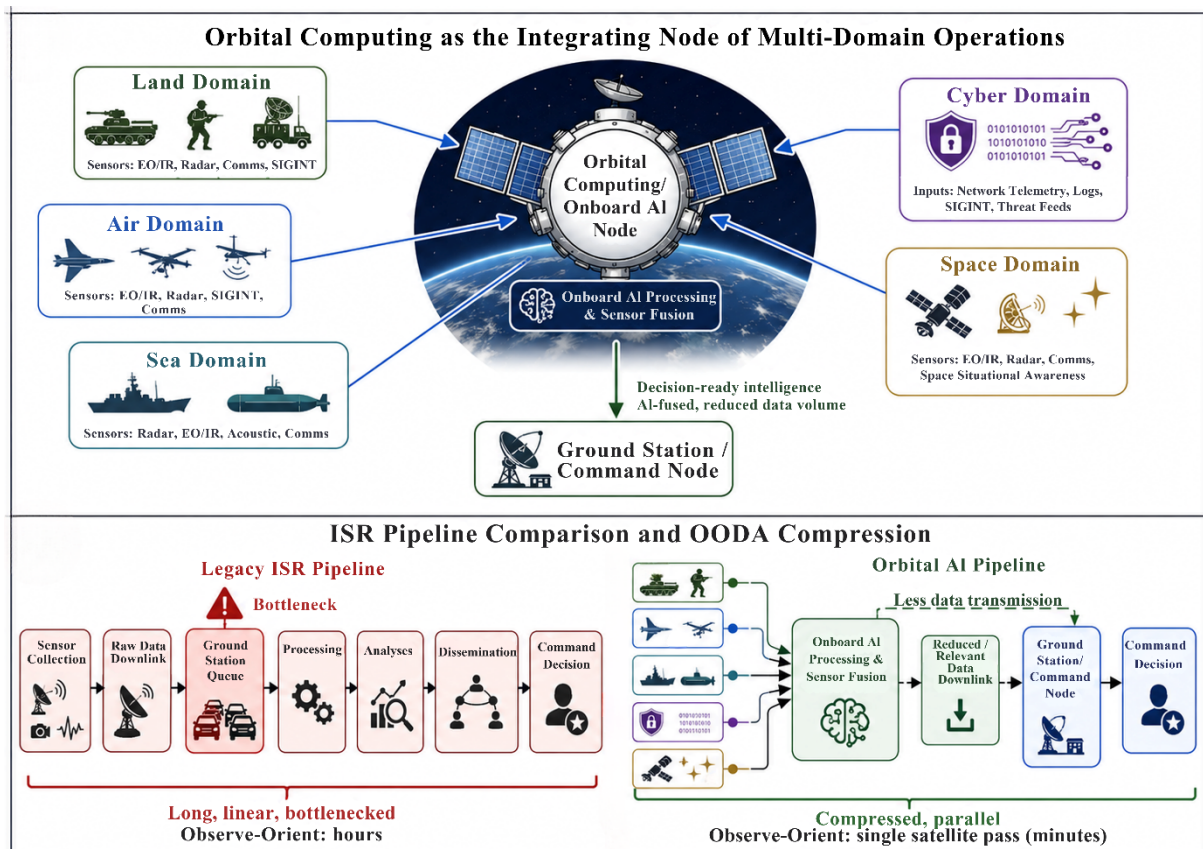


Figure 1: Orbital computing architecture for multi-domain sensor fusion and OODA-loop compression

Source: Edited by the author.

5. Discussion and Conclusions

This section explicitly answers each research question based on the evidence assembled through the three methodological components, PRISMA 2020 systematic review, technology assessment of flight-

proven platforms, and operational scenario analysis, before synthesizing the findings into a central conclusion. Table 1 provides a consolidated mapping of research questions, methodologies, key evidence, and answers.

Table 1 Summary of research questions, methodologies, key evidence, and findings

Research Question	Methodology	Key Evidence	Answer / Finding
RQ1 Data volume reduction	Technology assessment of orbital edge/cloud computing architectures; PRISMA review of bandwidth, onboard processing and LEO constellation resource-allocation studies	Optimal bandwidth and computing resource allocation in LEO EO constellations; KP Labs: up to 100× reduction through onboard region-of-interest processing; SAR BAQ: ~100× data reduction; WGS capacity: 2.1–3.6 Gbps shared across theatre-level users	Orbital computing reduces the transmission burden by shifting selected processing tasks from the ground segment to the satellite constellation. Depending on processing depth, onboard prioritisation, compression and region-of-interest extraction can reduce raw-data downlink requirements and convert bandwidth scarcity from a hard operational constraint into a manageable resource-allocation problem.
RQ2 OODA-loop compression	Operational scenario analysis (Russia-Ukraine 2022-present); Boyd OODA framework applied to RQ1 bandwidth findings; JADC2 doctrinal analysis	UK MoD: 95% processing time reduction, +30% accuracy; GIS Arta: 1-3 orders faster decisions; RAND: Russian pipeline limited by space data underutilisation	Orbital computing compresses the Observe-Orient phases from hours to ~9 minutes (one satellite pass), operating inside adversary decision cycles and achieving qualitative decision superiority.
RQ3 Five-domain bridge	Doctrinal analysis (NATO MDO, JADC2, TRADOC 525-3-1); technology assessment of multi-domain fusion architectures (DARPA Blackjack, SDA PWSA)	DARPA Pit Boss: on-orbit fusion of RF, EO and decision-support data; SDA PWSA: Link-16 relay across all domains; NATO APSS: IOC achieved Dec. 2025	Satellites are the only node with simultaneous cross-domain visibility; onboard AI makes them the structurally necessary convergence point of MDO, the bridge without which multi-domain integration remains aspirational.

5.1 Answer to RQ1: Data Volume Reduction

RQ1 asked: To what extent does orbital computing reduce the volume of data transmitted from satellite-borne sensors to military command nodes?

Answer: Orbital computing reduces transmitted data volumes and bandwidth pressure by moving selected processing functions closer to the point of collection. In LEO Earth Observation (EO) constellations, data can be processed on the source satellite, on another constellation node, or in the ground segment, depending on available bandwidth and computing capacity. Valente, et al. show that optimal resource allocation is therefore central to reducing transmission load and latency [10]. The strongest reductions occur when satellites transmit only mission-relevant outputs instead of raw sensor streams. Onboard region-of-interest processing may reduce transmitted data by up to 100-fold [11], while SAR block-adaptive quantization can achieve comparable reductions [21]. Against the limited theatre-level bandwidth of systems such as WGS [3], this is operationally significant. Orbital computing therefore converts bandwidth scarcity from a fixed constraint into a manageable architectural and resource-allocation problem.

5.2 Answer to RQ2: OODA-loop Compression

RQ2 asked: How does AI-based on-orbit sensor fusion compress the OODA-loop and contribute to decision superiority over adversaries?

Answer: Orbital computing compresses the OODA-loop by eliminating the ground-station processing queue, the dominant latency source in conventional ISR pipelines, and reduces the combined Observe-Orient phase from hours to the duration of a single satellite overpass (approximately 9 minutes for LEO). This is a direct and quantifiable consequence of the RQ1 data reductions: when transmitted data volume is reduced significantly, downlink queues that previously spanned hours are

cleared in minutes, and ground processing workloads that required hours of analyst time are replaced by sub-second onboard inference. The United Kingdom Ministry of Defence (UK MoD) reports that AI-assisted satellite imagery analysis reduces processing time by 95% and increases accuracy by 30% [16]. The Ukraine conflict provides operational validation: Ukraine's AI-enabled GIS Arta system achieved decision cycles "one to three orders of magnitude faster" than Russian counterparts [13, 14], while Russia's centralized, non-AI pipeline "limits its utilization of information from space" [15]. Applying Boyd's framework, an adversary whose OODA-loop spans hours while the orbital-computing-enabled force operates in minutes is structurally disoriented: it cannot complete a decision cycle before the next satellite pass invalidates its initial assumptions. Decision superiority is therefore not a marginal improvement but a qualitative shift like the engagement.

5.3 Answer to RQ3: Orbital Computing as the Five-Domain Bridge

RQ3 asked: In what sense can orbital computing be considered the integrating bridge linking the five NATO operational domains?

Answer: Orbital computing constitutes the five-domain bridge on three simultaneously valid grounds. Geometrically, satellites are the only military platforms with persistent, simultaneous line-of-sight over activities across all five domains at the global scale; no ground, maritime, or airborne node shares this cross-domain coverage. Onboard AI enables the real-time fusion of heterogeneous sensor streams from all domains, electro-optical and infrared imagery (land/maritime), SIGINT (cyber/electromagnetic), weather (air), and positioning, navigation, and timing (all domains), before transmission, producing an integrated operational picture that no ground-based fusion centre can replicate at comparable latency. DARPA's Blackjack Pit Boss demonstrated this concretely by

integrating third-party sensor data from RF-maritime, computer vision, and decision-support vendors aboard a single satellite [19], and the SDA PWSA Transport Layer operationalizes it at constellation scale with Link-16 relay connecting all-domain sensors to command nodes [18]. Doctrinally, NATO MDO requires "converging effects at the speed of relevance" [20], and JADC2 demands AI-fused sensor-to-shooter connectivity across all domains [17]. Orbital computing is the only architecture that satisfies both requirements simultaneously. The conclusion is therefore not only that orbital computing can serve as a domain bridge, but that it is the structurally necessary bridge. Without it, multi-domain convergence is a doctrinal aspiration; with it, convergence becomes an engineering reality.

5.4 Central Conclusion

The three research questions converge on a single overarching finding: orbital computing is not merely a capability enhancement within the space domain, but an enabling architecture for multi-domain operations. The evidence for RQ1 shows that orbital computing reduces the burden of raw-data transmission by combining onboard processing, region-of-interest extraction, compression, and optimized bandwidth-computing resource allocation across LEO constellation nodes. The evidence for RQ2 shows that this architectural shift shortens the sensor-to-decision chain by reducing dependence on ground-station processing and accelerating the Observe-Orient phases of the OODA-loop. The evidence for RQ3 demonstrates that satellites provide the only persistent cross-domain vantage point from which land, air, maritime, cyber/electromagnetic, and space activities can be observed, fused, and linked to command structures.

This conclusion depends on matching artificial intelligence model types to mission functions. Convolutional Neural Network-based (CNN) models remain central for

electro-optical, infrared, hyperspectral, and SAR imagery, particularly for object detection, change detection, target recognition, and region-of-interest segmentation. Recurrent Neural Network (RNN), Long Short-Term Memory (LSTM), and transformer-based models are more relevant to SIGINT, radio-frequency pattern analysis, electronic-order-of-battle reconstruction, and time-series anomaly detection. Lightweight autoencoders and compression-oriented models may support onboard feature extraction where full raw-data transmission is operationally impractical.

The decisive limitation is no longer algorithmic performance alone, but deployable computing under space-environment constraints. Orbital artificial intelligence must operate within strict power, mass, volume, and thermal limits while tolerating radiation, single-event effects, limited heat dissipation, and restricted maintenance opportunities. Practical orbital computing therefore requires model compression, quantisation, pruning, radiation-tolerant processors, low-power Vision Processing Units (VPUs), Field-Programmable Gate Arrays (FPGAs), and mission-specific artificial intelligence accelerators.

Future research should address radiation-hardening for high-performance artificial intelligence accelerators, power- and thermal-aware model optimisation, adversarial robustness against spoofing and electronic warfare, integration into allied JADC2 and multi-domain operations architectures under NATO's Commercial Space Strategy [22], and the legal-ethical governance of autonomous artificial intelligence decision-support from orbit.

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