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Mission Space – White Paper Environmental Monitoring (EM) RFI Sensing Gap: Space Weather / Upper Atmospheric Activity

Closing the LEO Sensing Gap: Real-Time Multi-Point SW Monitoring

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Executive Summary

The low Earth orbit (LEO) upper atmosphere sensing gap threatens billions of dollars annual losses from unpredicted drag, reentries, proper connectivity issues and radiation damage during Solar Cycle 25 peak (2024-26). Current L1/GEO assets provide coarse global modeling with 6-12hr latency. Current operational LEO in-situ data exhibits major gaps with no global coverage in most parameters.

Mission Space provides in-situ radiation measurement payloads and a combined data-as-a-service (DaaS) offering for operators who need operational awareness of the charged-particle environment affecting spacecraft health, mission performance, and anomaly response. The instrument line is steadily expanding to cover new parameters, enhancing performance and optimizing usability.

Flight heritage: the TLR-9 PL-1/PL-2 instrument family has been operating on orbit since March 2025. Mission Space can supply the instrument set and deliver processed data products via SaaS (API + dashboard) with configurable alerting.

Affordable in-situ measurements enable denser monitoring networks, improving global coverage and reducing latency.

Market addressing: space weather, radiation monitoring, and environmental intelligence for space, defense, and critical infrastructure operations.

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The LEO Sensing Gap

LEO Within the Magnetosphere: Limited External Visibility

LEO orbits (up to 1500-2000 km) remain deep within Earth's magnetosphere, experiencing slower dynamics compared to GEO where disturbances and substorms occur rapidly. Feedback loops between solar wind and inner magnetosphere are delayed, masking direct coupling effects. The polar cusps, primary windows to solar energetic particles (SEPs) and galactic cosmic rays (GCRs), lack dedicated instrumentation despite offering direct access to heliospheric conditions. No operational LEO platforms currently provide SEP/GCR measurements, forcing reliance on distant GEO and L1 monitors with poor time correlation.

Insufficient Low/Medium Energy Particle Coverage

Limited coverage of electrons (10 keV-1 MeV) and protons (1-50 MeV) prevents real-time reconstruction of the radiation environment inside the magnetosphere. Without comprehensive energy spectra and angular distribution of fluxes source localization remains impossible. The density of measurement points from current LEO constellations does not allow separate time-origin vs space-origin events. It requires multi-point in-situ data. Nowcasting lacks both spatial and temporal resolution; forecasting inherits model uncertainties.

GNSS-RO Statistical Mismatch with In-Situ Data

GNSS radio occultation (RO) data from Starlink/Spire/COSMIC-2 and other sources has exploded, providing 10e6 daily density profiles, which is orders of magnitude above sparse in-situ monitoring data. However, remote vs direct measurement timescales differ dramatically: RO integrates over ~1 min paths while particle precipitation varies on sub-sec to seconds scales. Statistical averaging smears localized effects, reducing accuracy during dynamic conditions. In-situ particle spectrometers remain essential for validation and high-time-resolution nowcasting.

Ground-Based Models: Global Indices Ignore Local Structure

Operational models, including atmospheric models such as NRLMSIS 2 and JB2008 rely on Kp/dst/F10.7 indices, inherently averaging geographical and local time asymmetries. Most advanced use solar wind parameters from L1 point, though giving global averages on the output. LEO missions can sample MLT/local structure but current missions prioritize other payloads (no focus on the space weather). Ground magnetometers capture only ionospheric currents, missing the outer loop of the global electric circuit, which is critical for density/chemistry coupling. Local ionospheric disturbances and polar currents require in-situ particle context absent from index-driven simulations.

Density Measurement Shortfall Drives Drag Uncertainty

In-situ neutral density measurements remain scarce because the highest-fidelity approaches have historically dependance on specialized spacecraft configurations and/or complex instrument chains, including precision accelerometry, drag-compensation architectures, and ion/neutral analyzers. As a result, neutral-density truth data are still sparse, and operational drag models continue to rely heavily on proxies and assimilative/statistical methods rather than dense local measurements. Indirect methods (e.g. accelerometer-derived drag acceleration) suffer 1-2 day latency and station-keeping bias. GNSS-only orbit determination conflates accelerometer noise with true density variations. During Solar Cycle 25 peaks (2024-26) atmospheric density became 2–3 times higher than expected from earlier forecasts. It leads to times higher than expected orbital decay rates during active solar conditions. It occurred without adequate density precursors, which means that direct neutral / ion density sensors needed at scale.

Latency Bottleneck: Hours vs Seconds

Current mainstream data pipeline: LEO particle detectors → S-band dump → ground ingest → model update gives 6-12 hour forecast cycles. Substorm timescales (minutes) and auroral precipitation (seconds) demand sub-minute latency via LEO/MEO swarms/constellations (e.g. Starlink) or direct-to-the-cloud. No operational LEO radiation suite leverages commercial constellations for continuous global nowcasting, leaving operators blind during critical windows.

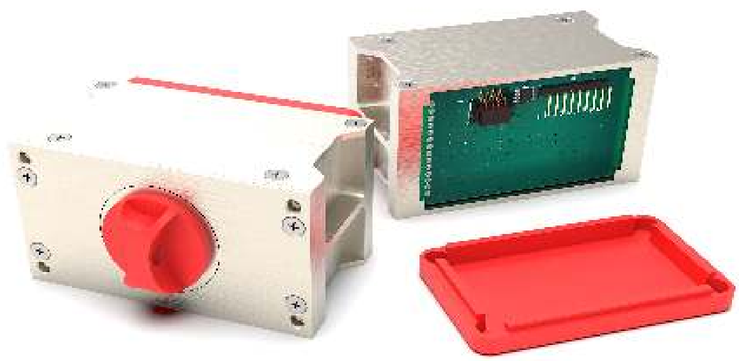
Result: up to $1B+ annual LEO risk *(rough estimation on previous years data)* exposure from unpredicted drag, reentries, and radiation degradation during Solar Cycle 25 peak. Real-time, multi-point in-situ particle + density measurements from commercial LEO networks represent the missing capability.

Technical Solution: LEO Radiation & Density Suite

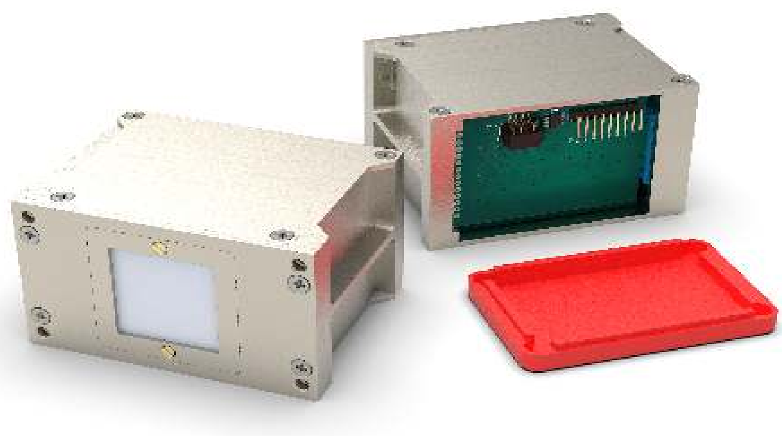
Flight-proven series

Instruments described below stay on TRL 9 having flight heritage since March, 2025.

PL-1 (available in variants **PL-1b**, **PL-1f**, **PL-1g**, **PL-1m**) is a semiconductor spectrometer designed to measure medium-to-high energy charged particles, primarily those found in the Earth's radiation belts. It operates on the classic silicon telescope principle, using a series of coaxially aligned silicon sensors to register transiting charged particles. These configurations are tailored to suit different installation and operational environments. **PL-1g** is designed for TunaCan extra volume under CubeSat specifications. Other designs have a rectangular shape with maximum dimension 85 mm. **PL-1m** is a multipixel detector for precise determination of the income direction of the particles (the average FOV of a single synthetic pixel is ~ 5 degrees).



PL-1b



PL-1f

Figure 1 – Different designs of silicon telescopes: the smallest PL-1b, first gen. vs PL-1f, second gen.

PL-2 is a Cherenkov detector consisting of two identical units, each featuring transparent crystals coupled with Silicon Photomultipliers (SiPMs). These components detect Cherenkov radiation flashes generated by relativistic particles, predominantly protons and electrons. The combined active detection area of the crystals is 100 cm². There is an option to fit the unit in a 10 x 10 cm-size (CubeSat size) with corresponding decrease of the total sensitive area.

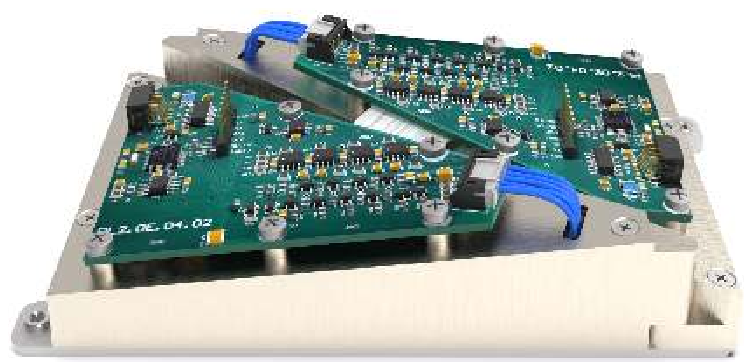


Figure 2 – Cherenkov monitor, PL-2, gen. 2.

The specifications of the product line are described in the table below. Values may be modified to align with the objectives, preferred operating modes, and configurations.

Table 1 – Mission Space’s hardware line specifications.

Parameters	**PL-1b**	**PL-1g**	**PL-1f**	**PL-1m**	**PL-2**	**PL-2s**
Type	Silicon telescope				Cherenkov detector	
Dimension l x w x d, mm	85 x 50 x 50	95 x 95 x 55	85 x 50 x 70	85 x 50 x 75	147 x 95 x 30	90 x 95 x 30
Mass, no more than, kg	0.3	0.5	0.6	0.6	0.7	0.5
Power consumption, W	< 0.5	< 0.5	< 0.5	< 1	< 0.5	< 0.5
Power supply, V	Default: 5 VDC regulated. Optional: up to 36 VDC unregulated.					
Charged particles, MeV: electrons protons	0.1 … 5 1 … 120	0.1 … 5 1 … 120	0.06 … 10 1 … 250	0.06 … 10 1 … 250	> 5 > 450	> 5 > 450
Auxiliary parameters	- 9-axis sensor (magnetometer, accelerometer, gyroscope) - Temperature					
FoV, °	30…65	30…65	25…50	90 … 110 ~5° per pixel	Omni	Omni
Data produced, MiB/day	1…70	1…70	1…75	10 … 250	0.5…50	0.5…50
Digital interface	Under the agreement with the developer of the spacecraft Options available: UART, RS232, RS422, RS485, USB, CAN					

Pipeline of Instruments

PL-3 – surface charge monitor

Mission Space is currently leading an R&D initiative to develop a new surface charge measurement device, the **PL-3**. This instrument is fully compatible with the **PL-1b**, sharing both mechanical and electrical interfaces, and is suitable for a wide range of applications, including spacecraft service operations and scientific research tasks. The instrument is based on the flat Langmuir probes and measures accumulated charge and extra potential on the local surface of the spacecraft. The instrument is on TRL 3, heading TRL 4.

Figure 3 – Surface charge monitor outlook.

PL-4 – Solar X-ray Monitor

Prerequisites for the instrument: optimal observations of solar X-rays require a Low Earth Orbit (LEO) platform.

The **PL-4** will share a design compatible with **PL-1f**/**PL-1m** units and is intended for measuring solar X-ray emissions from LEO in one or two spectral lines. It combines small SWaP and high sensitivity to solar radiation. The optimal constellation requires 2-6 units depending on orbital parameters and mission specifications. The development of the **PL-4** monitor is currently in low TRL stages, though its unification level with the existing products is high.

Figure 4 – Solar X-ray Monitor preliminary outlook.

PL-5 – X-ray and Gamma-ray Spectrometer

The **PL-5** spectrometer is expected to be compatible with the **PL-1f/PL-1m** design framework, having slightly lower mass. The unit has a high grade of unification with other items in Mission Space's product line. It is based on the phoswich scintillator detector and is sensitive to the direction of incoming radiation. It is optimal for service and technical purposes, especially in monitoring of internal sources of ionizing radiation onboard the spacecraft. Multiple **PL-5** units can be combined into arrays, allowing synchronised measurements from various directions. The instrument is currently in low TRL stages.

Instrument suites

We offer configurable instrument suites optimized for common LEO monitoring tasks:

- **Complete Magnetospheric Monitoring Suite**, 4 or more units including:
    - Surface charge monitor (low energies).
    - Two or more silicon telescopes (directional mid-energy particles).
    - Omnidirectional Cherenkov detector (high energies).
- **Basic Suite**: Single unit of each type above.
- **Minimal Suite**:
    - The smallest silicon telescope (TID monitoring).
    - Surface charge monitor (surface charge).
- **Sunshine Suite** for solar activity tracking:
    - Solar X-ray Monitor.
    - Cherenkov detector.
- **Custom configurations** tailored to specific mission objectives.

Figure 5 – The Complete Magnetospheric Monitoring Suit consists of minimum 4 units and covers all energy ranges from plasma to relativistic.

Architecture, integration

Mission Space can support two integration paths:

a. Hosted payload or dedicated payload accommodation on a commercial spacecraft bus.
b. Customer-owned spacecraft integration using the PL-series IDD-defined interfaces, with an ICD agreed per mission.

Demonstration opportunities and mission operations approach

Mission Space’s PL units can be integrated as hosted payloads or as part of a small satellite mission. A representative demonstration path is:

- **Phase A** – Definition, Initial Integration: ICD finalization, interface selection (RS422/RS485 by default), data product definition, design updates as required, and mission CONOPS.

- **Phase B** – Spacecraft Integration: mechanical accommodation, harnessing to Harwin Datamate series connector (default), functional testing up to full-stack system-level testing.

- **Phase C** – Launch and Early Operations: functional verification, calibration and configuration adjustments as required, optimisation of operational modes, etc.

- **Phase D** – Operations till the End of Life: monitoring mode or session mode; regular data flow; optional near-real-time data drop for operational alerting, scheduled maintenance.

Lifecycle sustainment and resiliency

Instruments are designed for LEO operation with an estimated lifetime not less than 3 years. Firmware may be updated via the regular communications interface, with multiple redundant firmware images stored in memory.

Data buffering supports operations with intermittent downlink. Default buffer options include FRAM (256 KiB) or NAND flash (128 MiB), configurable before manufacturing.

Mission Space is also expanding its product portfolio to include radiation-tolerant designs for operation in harsh environments and compliance with higher sustainability requirements. The estimated readiness of the new hardware line is 2028-2029.

Scalability, affordability, and tailoring

Scalability is achieved by deploying multiple identical sensors on multiple orbits, enabling multi-point sampling for improved spatial/temporal coverage. Tailoring options include selection among PL-1 variants (b, g, f, m) or PL-2 (s) to fit spacecraft accommodation constraints and interface selection among supported digital buses. Additional adjustments can be made by request.

ROM pricing framework

The ROM items below reflect a combined DaaS offer where Mission Space supplies the instrument set and provides SaaS access for data delivery.

a. SaaS subscription (combined DaaS): starting from 3,500 USD per month per customer account for API + dashboard access and standard alerts based on measured particle environment. Higher-volume API usage, custom alert thresholds, and mission-unique reporting are priced separately.

b. Hardware: starting from 300,000 USD per instrument set (baseline set: 2 × PL-1 + 1 × PL-2, per the current IDD default set). Mission-unique integration engineering, ICD adaptations above standard options, and acceptance testing support are priced separately.

Science & Operations Value

Comprehensive LEO Radiation Environment Characterization and key gaps closed

Our PL-series modular instruments provide complete coverage across the LEO radiation spectrum, from plasma energies to relativistic particles, enabling both scientific discovery and operational nowcasting. Complementary instrumentation can significantly upgrade the scientific value of the measurements.

Table 2 – Scientific capabilities of instruments.

Item	Energy Range	Key Capability	LEO Science Value
PL-1	~60 keV … 10 MeV (electrons) ~1 … 250 (protons)	Mid-energy particles directional spectra	Radiation belt dynamics, substorm injections, ionizing impact, Ionosphere-magnetosphere coupling
PL-2	>3 MeV (electrons) >450 MeV (protons)	High-energy particles omnidirectional	GCR modulation, SEP penetration, CME prediction
PL-3	<100 keV (plasma e/p)	Plasma-related data	Local health of sensitive elements
PL-4	~1…100 keV in one or several lines (solar X-ray)	Solar flare nowcasting	SEP onset warning, connectivity situation monitoring
PL-5	Soft component including secondaries, scattered (electrons, X- and gamma-rays)	Bremsstrahlung + albedo X-rays, ionising sources monitoring	Spacecraft charging precursors, X-/gamma-ray sources monitoring, soft component of TID
Auxiliary sensors			
Digital compass: magnetic field fluctuations		LF magnetic field variations	Trapped radiation dynamics, waves propagation
Digital compass: acceleration mapping		Residual atmosphere density	Atmospheric drag
Other complementary instruments and data			

GNSS RO sensor	TEC, sporadic ionospheric events	Complementary data for connectivity mapping and atmospheric drag
Low-energy spectrometer	Plasma behaviour mapping	Magnetospheric dynamics, couplings
Direct neutrals monitor	Residual atmosphere parameters	Atmospheric drag
High-sensitive magnetic field sensors	Magnetic field variations and mapping	Magnetosphere and ionosphere physics fundamental studies, model verification and polishing

The instrument advances addressing the main data gaps listed above include:

- Hardware capabilities enabling the measurement of relativistic particles that can penetrate down to LEO altitudes in polar regions. These observations can both provide alerts about recent high-intensity solar events and offer insight into the dynamics of the outer magnetosphere from within the lower regions of it.
- Instrument affordability, which enables a denser and more uniform distribution of measurement points in the lower magnetosphere. This improves statistical coverage for extrapolation, forecasting, and modeling, while also allowing the identification of local variations in environmental conditions.
- High flexibility in data flow and onboard processing, providing additional options to reduce latency for both raw data and derived data products such as forecasts and alerts.

Operational Impact

The integration of compact space-environment monitoring instruments across multiple spacecraft platforms enables a distributed sensing architecture capable of providing continuous measurements of the near-Earth environment. Such a network significantly improves situational awareness of the space environment and its operational impact on spacecraft systems. By combining in-situ measurements with onboard processing and ground-based analysis, the instrument network supports both operational decision-making and the long-term improvement of space environment models.

Satellite Health

Spacecraft operating in low Earth orbit and within the magnetosphere are continuously exposed to variable radiation and plasma environments. Energetic particles and associated space weather effects can induce single-event upsets, degradation of electronic components, charging effects, and long-term material damage.

The proposed instruments provide in-situ measurements of energetic particle fluxes and related environmental parameters directly within the spacecraft's operational environment. These measurements enable correlation between spacecraft anomalies and external environmental conditions, allowing operators to distinguish between internal subsystem failures and externally driven effects. The availability of local environmental diagnostics supports more informed anomaly resolution, improved fault attribution, and the implementation of mitigation strategies such as temporary configuration changes, payload protection modes, or operational scheduling adjustments during periods of elevated radiation activity.

Over the long term, the accumulation of environmental and spacecraft telemetry data can also contribute to improved radiation risk characterization and reliability assessments for spacecraft components.

Environmental Conditions: Nowcasting and Forecasting

A distributed network of environmental sensors hosted on multiple spacecraft provides an opportunity to obtain spatially distributed measurements of the near-Earth space environment. Such measurements are particularly valuable for characterizing the dynamics of the lower magnetosphere and the radiation environment in LEO.

Near-real-time access to these measurements enables operational nowcasting of environmental conditions. The system can detect increases in energetic particle fluxes associated with solar energetic particle events, geomagnetic disturbances, and magnetospheric dynamics. This capability allows operators to track the evolution of potentially hazardous conditions as they propagate through the near-Earth environment.

When integrated with physics-based models and external observational data sources, the distributed measurement network can also contribute to improved forecasting of space weather conditions. Enhanced observational coverage improves model validation and data assimilation, ultimately leading to more reliable predictions of environmental disturbances that may affect spacecraft operations.

Drag Forecasting & Lifetime Extension

Atmospheric drag represents a major driver of orbital decay for satellites operating in low Earth orbit. Variations in thermospheric density, driven largely by solar and geomagnetic activity, introduce significant uncertainty in drag estimation and long-term orbital lifetime predictions.

The distributed measurement infrastructure offers the potential to improve drag estimation by combining in-situ environmental measurements with spacecraft orbital and attitude data. Future implementations may include onboard data processing capabilities capable of estimating local atmospheric conditions and their effect on drag forces in near real time.

Such capabilities could enable predictive assessments of orbital decay rates and support improved orbit maintenance strategies. Operators could optimize propulsion usage for orbit maintenance maneuvers, better anticipate periods of increased drag during geomagnetic activity, and refine mission lifetime planning. At the network level, aggregated measurements from multiple spacecraft could also contribute to improved thermospheric models, enhancing the accuracy of drag forecasts and re-entry predictions for the broader space operations community.

Quantitative Improvements and Risk Quantification

The deployment of distributed in-situ measurements enables a transition from qualitative assessments to quantitative evaluation of space environment impacts and associated risks. **Increased spatial and temporal coverage** improves the accuracy of environmental characterization and reduces uncertainties in key parameters, including radiation exposure and thermospheric density. The accuracy of extrapolation is directly dependent on data coverage.

Co-located environmental measurements allow for direct correlation between spacecraft anomalies and external conditions, reducing ambiguity in fault attribution and supporting the probabilistic risk models for radiation-induced effects. This enhances the ability to assess and manage spacecraft health in a data-driven manner.

Improved observational inputs also strengthen nowcasting and forecasting capabilities. **Data assimilation** into physics-based models reduces prediction uncertainties and increases lead times for anticipating adverse space weather conditions, enabling more effective operational responses.

For LEO missions, incorporating **in-situ measurements** into **drag estimation** workflows reduces uncertainty in orbital decay predictions and lifetime assessments. This supports more accurate propellant budgeting, optimized maneuver planning, and improved mission lifetime management.

Overall, **the availability of real-time and historical environmental data** enables risk-informed operational decision-making, allowing operators to quantify the likelihood and impact of hazardous conditions and implement targeted mitigation strategies at both spacecraft and system levels.

Data Products

Data products and formats

Mission Space can package delivered products into *netCDF* or *HDF5* containers and deliver via API and/or file-based transfer. Final product specification (variables, metadata, cadence, quality flags) is mission-dependent and would be defined in the ICD and data product specification.

Mission Space proposes three deliverable data tiers:

- Tier 1 – Raw/packet-derived: time-tagged instrument frames with minimal processing and decoding.
- Tier 2 – Calibrated: calibrated differential fluxes and integral fluxes in defined energy bins with quality flags and housekeeping.
- Tier 3 – Value-added: assimilated or model-ready products and alerts suitable for operator workflows (latency and thresholds defined with the Government).

Data product structure:

- **Radiation alerts:** On-orbit and Aviation, crew exposure, specific criteria
- **Anomaly attribution:** Particle flux signatures vs solar activity
- **Drag nowcasts:** Updated time grid with specified cadency of mixed/separated direct and model parameters
- **Reentry warnings (for VLEO):** ETAs for uncontrolled objects and/or associated data
- **Indices and inputs for modelling:** Global and local key parameters, cross-calibrations, data validation, etc.
- **Customized data products:** formats, latency, aggregation windows, customer-specific alert logic, and support tiers.

Data Synergy

Mission Space implements an advanced data architecture designed to maximize synergy between proprietary and publicly available measurements, models, and value-added products. The data structure, spanning from raw data to highly processed products, enables seamless integration across all processing levels. This approach ensures full traceability from measurement to application, while supporting both scientific analysis and operational use cases.

Synergy is achieved through the integration of heterogeneous data sources into unified products. Calibrated measurements, environmental parameters and indices, and model inputs are combined to generate higher-level outputs such as radiation alerts, anomaly attribution indicators, drag nowcasts, and re-entry warnings. These products leverage both direct observations and assimilated data, enabling consistent and cross-validated information streams, particularly in regions where neither measurements nor models alone provide sufficient coverage.

The resulting data ecosystem supports a wide range of operational domains, including radiation health monitoring and aviation to spacecraft operations, environmental awareness, including orbit prediction. By combining global indices with localized measurements and validated model inputs, the system enhances the reliability, accuracy, consistency, and overall usability of space environment information for end users.

Cybersecurity and access controls

Cybersecurity controls and the hosting environment, including cloud provider selection, authorization boundaries, logging, and key management, are fully configurable in accordance with Government requirements. Mission Space will align its delivery and operational approach with the specified security control baseline, ensuring compliance with applicable standards and accreditation processes.

The architecture supports secure data handling across the entire processing chain, including access control, encryption in transit and at rest, audit logging, targeted anonymisation, and key lifecycle management. In addition, the system ensures end-to-end traceability of all data products, enabling each output to be linked back to its original source data, processing steps, and applied models. This traceability enhances transparency, supports validation and auditing, and enables reproducibility of results across both operational and analytical use cases.

Conclusion

The current lack of high-resolution, low-latency in-situ measurements in low Earth orbit represents a critical limitation for both operational and scientific applications. Existing gaps, ranging from insufficient particle coverage and limited visibility within the magnetosphere to mismatches between modeled and observed atmospheric density, translate directly into increased uncertainty in drag prediction, radiation risk, and overall mission performance. These limitations contribute to substantial economic and operational risks, including premature re-entries, degraded service continuity, and avoidable spacecraft anomalies.

Mission Space addresses these challenges through a scalable and flight-proven portfolio of mid- to high-energy radiation monitoring instruments, complemented by an expanding pipeline of sensors, including surface charge monitors and X-ray and gamma-ray spectrometers. These instruments can be deployed individually or as integrated suites, enabling flexible mission configurations tailored to specific objectives. Their modular design and full life-cycle support ensure seamless integration across a wide range of platforms at a cost level compatible with large-scale deployment.

By enabling distributed in-situ measurements, the proposed approach directly targets the identified sensing gaps. Enhanced spatial and temporal coverage improves the characterization of local environmental conditions within the lower magnetosphere and LEO, while reducing reliance on global indices that fail to capture fine-scale variability. The integration of multi-source data into structured data tiers and value-added products further amplifies this capability, creating a synergistic data ecosystem that supports both real-time operations and advanced modeling.

This data synergy enables a transition from reactive to predictive operations. Improved nowcasting and forecasting of radiation and atmospheric conditions support timely mitigation actions, while more accurate drag estimation contributes to optimized orbit maintenance and extended mission lifetimes. At the same time, reduced latency (from hours to near real time) enhances responsiveness to rapidly evolving space weather events.

All capabilities are delivered within a secure and configurable framework, aligned with Government requirements for cybersecurity, data governance, and operational control. End-to-end traceability and standardized data interfaces ensure transparency, reliability, and ease of integration into existing infrastructures.

In summary, Mission Space provides a comprehensive, flexible, and cost-effective solution to close critical sensing gaps in LEO. By combining advanced instrumentation, distributed deployment, and synergistic data products within a secure architecture, the approach significantly enhances situational awareness, reduces operational risk, and enables more efficient and resilient space mission operations.