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RADIO OCCULTATION ARCHITECTURE ANALYSIS OF ALTERNATIVES

Phase 1 Executive Summary

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Table of Contents

Table of Figures

Table of Tables

1. Summary

The Office of Systems Architecture and Engineering (SAE) conducted Phase 1 of a Radio Occultation (RO) Analysis of Alternatives (AoA) study to evaluate mission concepts capable of sustaining RO data needs as the COSMIC-2 constellation degrades. The study assessed hybrid future RO architectures, which include commercial, international, and independent satellite systems, to determine how they can collectively meet NOAA's observational requirements. The RO criteria for this study were based on current NOAA needs and do not address the 2024 ROMEX study recommendations. Phase 2 of the AoA will refine study criteria based on insights from ROMEX studies and model impact analyses.

Findings indicate that, to efficiently meet observational needs, space mission architecture designs must incorporate a diverse range of coordinated orbits that provide coverage both geographically and by local time of observation. The observation refresh rate, or how often the entire globe can be covered within a given time frame, presents a more significant challenge than simply achieving the required number of observations. Architectures that include spacecraft in low-inclination orbits (where spacecraft do not fly over latitudes exceeding approximately ±30º) are particularly effective at meeting data requirements in the tropics (-23º to 23º) and mid-latitudes (23ºN/S to 66ºN/S). These architectures are significantly more efficient compared to constellations composed solely of polar, sun-synchronous orbit (SSO) satellites, which primarily cross the equator at the same local time each orbit and concentrate coverage at high latitudes. While SSO satellites remain essential for global coverage, they alone are insufficient for addressing data gaps in lower latitudes.

The study finds that supplementing the baseline constellation with commercial data enables NOAA to meet the six-hour refresh criteria in the tropics, largely due to COSMIC-2's low-inclination design. However, existing international and commercial RO missions do not fully meet all NOAA requirements, particularly as COSMIC-2 continues to degrade.

To mitigate near-term degradation and ensure future performance, the study recommends:

1. Expand commercial data acquisition to address immediate observation gaps.
2. Prioritize observation distribution, orbit coordination, and latency improvements in future commercial data acquisitions.
3. Explore RO constellations in low-inclination orbits to improve tropical and mid-latitude coverage. Current commercial observations from high-inclination orbits do not meet the needs.

2. Introduction

SAE conducted a preliminary AoA to evaluate potential mission concepts that can sustain RO observational needs beyond COSMIC-2. The study aimed to identify viable RO architectures, assess their performance against NOAA's study criteria, and estimate associated costs. This effort was conducted in collaboration with the Office of Low Earth Orbit Observations (LEO) and the Office of Space Weather Observations (SWO).

RO measurements are crucial for both terrestrial and space weather applications, providing valuable atmospheric and ionospheric data. For terrestrial weather forecasting, they enhance numerical weather prediction forecasts by improving temperature, pressure, and moisture profiles. In space weather, they support monitoring of ionospheric disturbances that can impact satellite communications, GPS accuracy, and power grid stability. Ensuring the continuity of RO observations beyond COSMIC-2 is vital for maintaining and advancing these capabilities.

3. Study Scope

The study examined the potential contributions of Commercial Data-as-a-Service (CDaaS) providers, international partner satellites, and other independent missions to the global RO architecture. While the primary focus was on neutral atmosphere (NA) soundings, the findings also provide insights relevant to space weather applications.

Performance was evaluated based on coverage, refresh rate, and latency criteria. Orbits were assessed for feasibility, and preliminary cost and risk analyses were conducted (though specific cost details are omitted due to proprietary considerations). Assumptions made in modeling future RO constellations are documented in the appendix.

4. Study Criteria

Candidate constellations were assessed against NOAA's defined RO study criteria, summarized below. The criteria included a total number of neutral atmosphere (NA) profiles per day by latitude band, a metric for refresh rates, and a metric for latency (the time from data collection to product delivery).

Table 1: RO AoA study criteria

Criteria	Threshold Performance
Daily NA Profiles (Global)	6,000
Daily NA Profiles (23ºS – 23ºN)	2,400
Daily NA Profiles (23º – 66º N/S)	3,100
Daily NA Profiles (66º – 90º N/S)	500
Geographic Refresh Time	90% of grid cells covered over 6 hours on a 500x500 km equal area grid
Observation-to-Product-Latency	<60 min

5. Results

A baseline constellation consisting of COSMIC-2 and existing international partner missions initially meets the daily profile criteria. However, the loss of five COSMIC-2 spacecraft, estimated by 2035, leads to insufficient tropical and mid-latitude coverage (see Figure 1).

Augmenting the baseline constellation with an additional 4,000 profiles per day from current CDaaS providers allows daily count criteria to be met throughout the assessed period (see Figure 2). However, even with this augmentation, the system does not meet the six-hour global refresh requirement[1] (see Figure 3).

Notably, the six-hour refresh criteria is met in the tropics when the baseline constellation is supplemented with commercial data, largely due to COSMIC-2's design, which includes six satellites in low-inclination/equatorial orbits. Polar-orbiting satellites alone cannot efficiently provide adequate coverage in the tropics and mid-latitudes. To fully satisfy the refresh requirement, existing international partner missions must be supplemented by an

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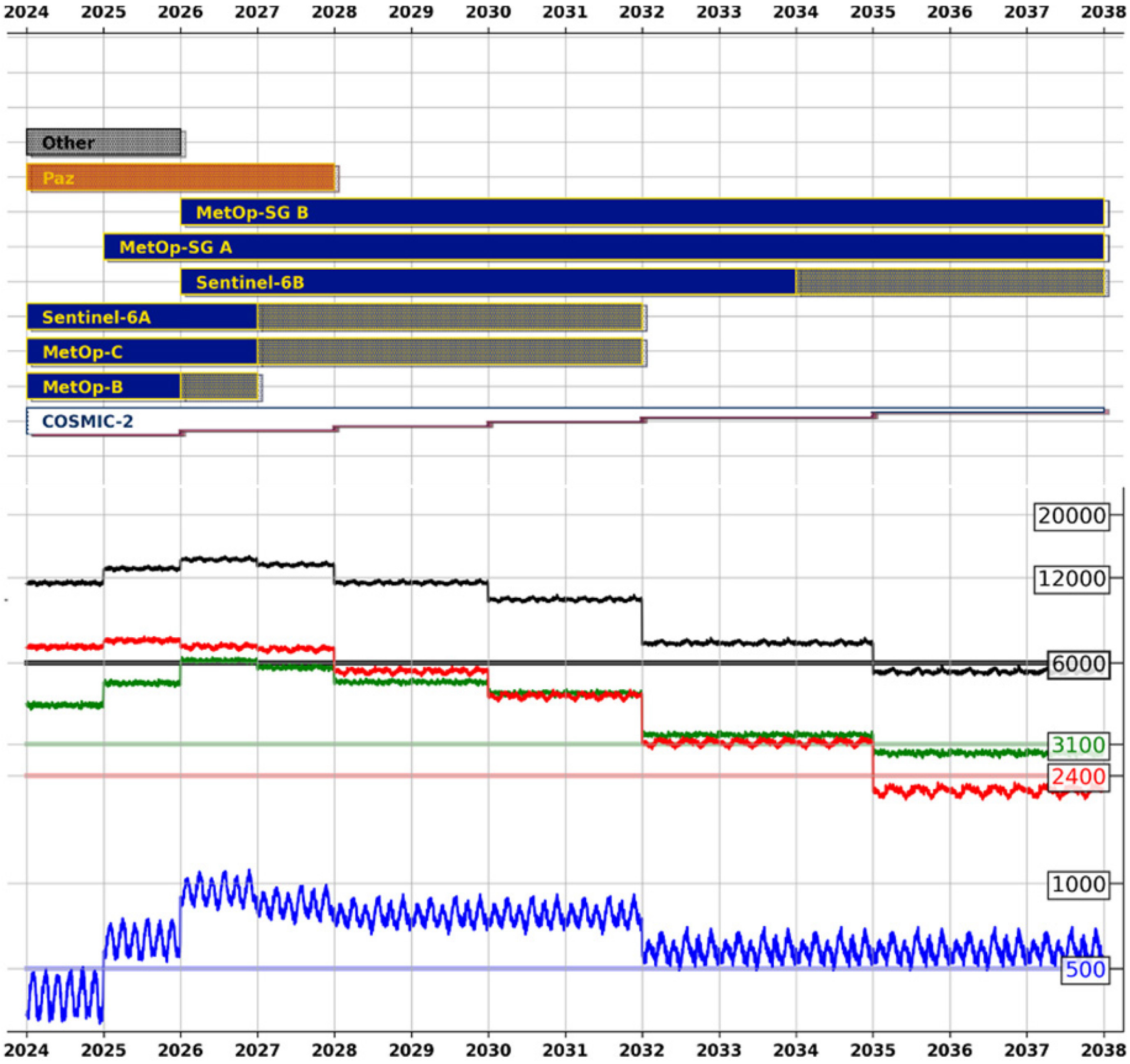
[1] Global numerical weather prediction models are executed on a six-hour cadence.

additional six satellites in low-inclination orbit (similar to COSMIC-2) and two in high-inclination, sun-synchronous orbits are required (see Figure 4).

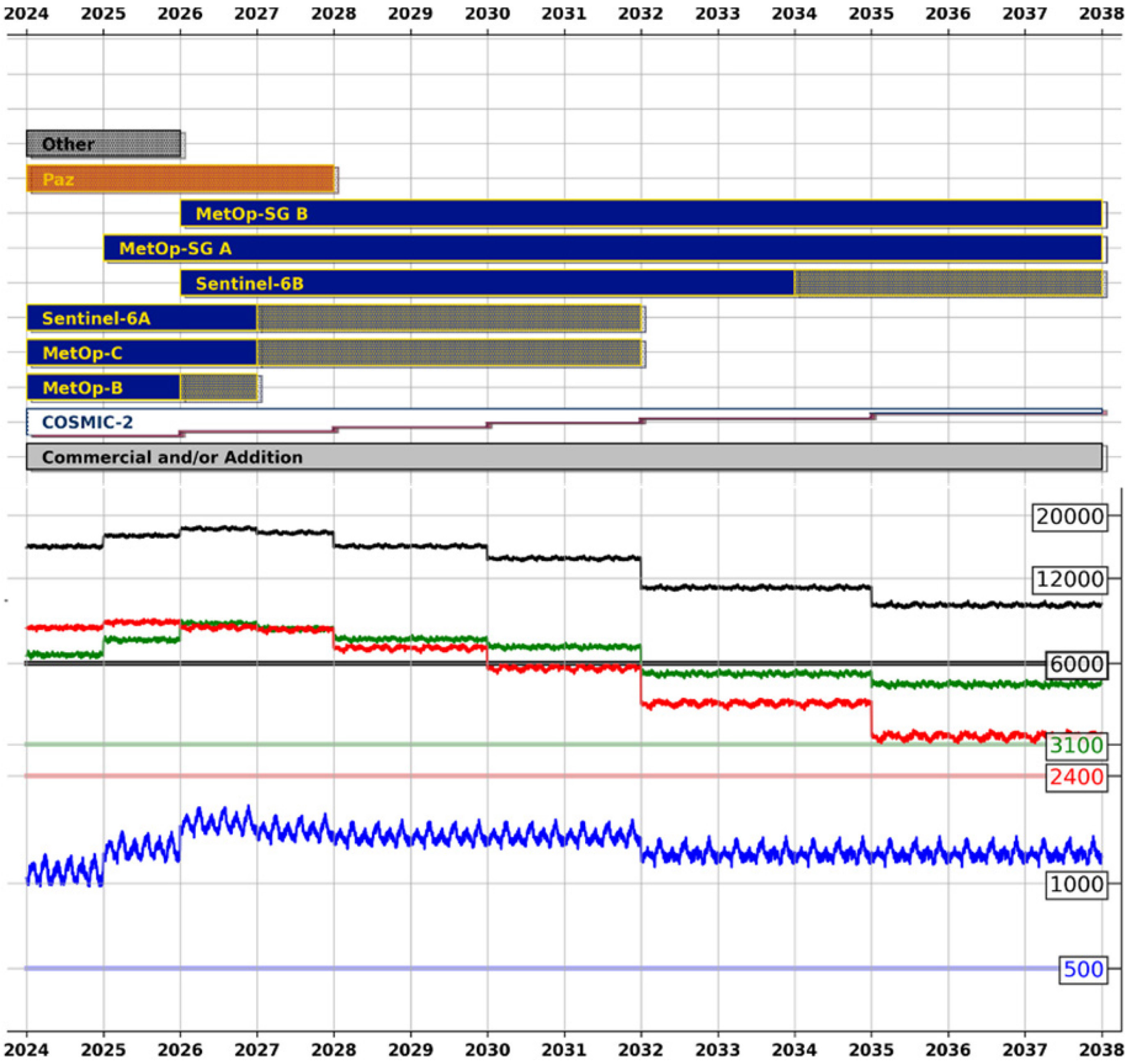
The study evaluated over 100 architecture configurations. The optimal solution minimizes complexity by leveraging coordinated and diverse orbits, achieving necessary coverage without excessive redundancy.

Figure 1: Performance of the baseline constellation (shown as a flyout) without commercial data buy contributions. Gradual COSMIC-2 degradation modeled.



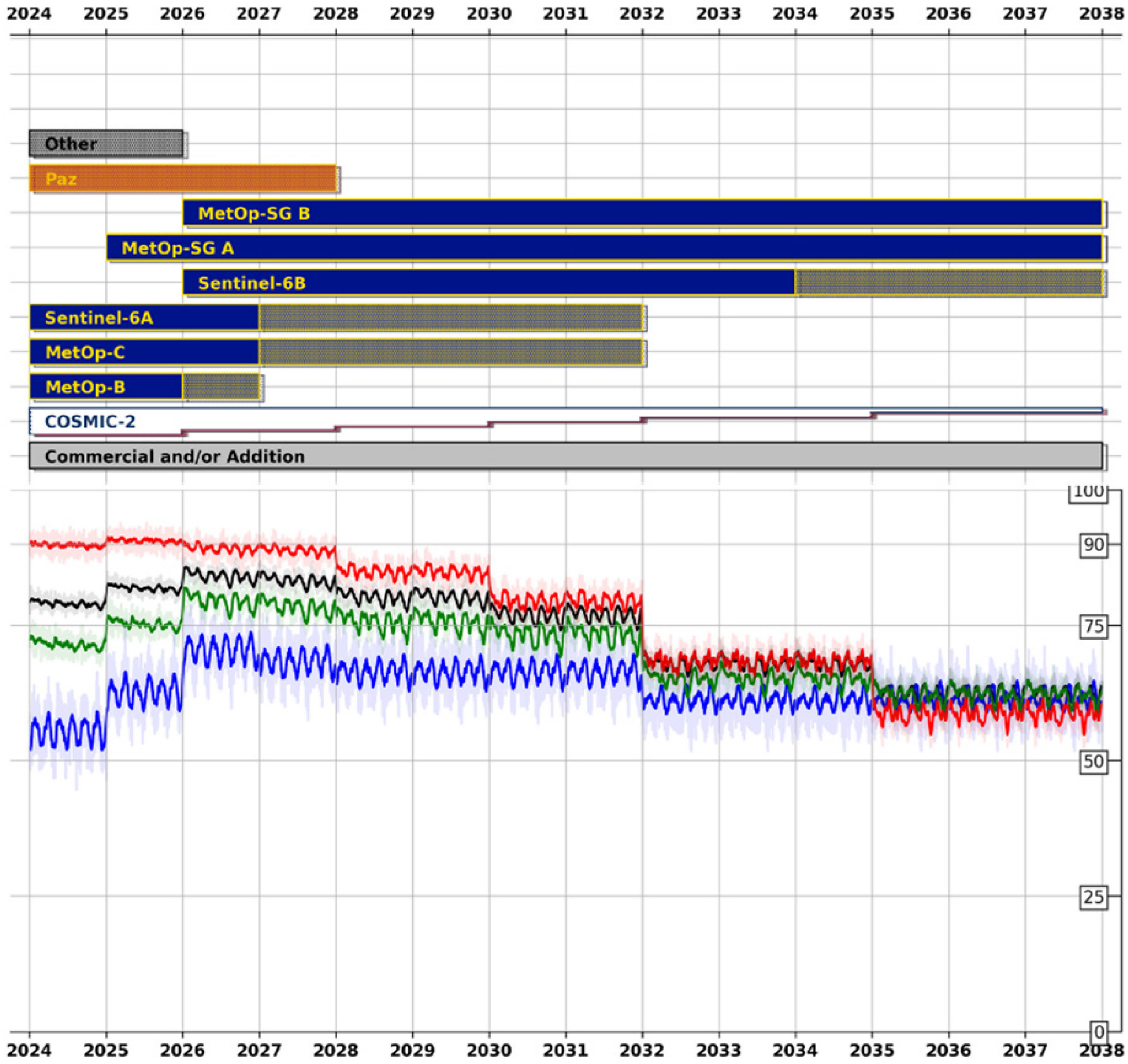
Key: Color-coded daily count criteria: black=global; green=mid-latitude; red=tropics; blue=polar. Partner mission flyouts depict estimated mission extensions.

Figure 2: Performance of the baseline constellation (shown as a flyout) augmented by 4,000 commercial data buy contributions. Gradual COSMIC-2 degradation modeled.



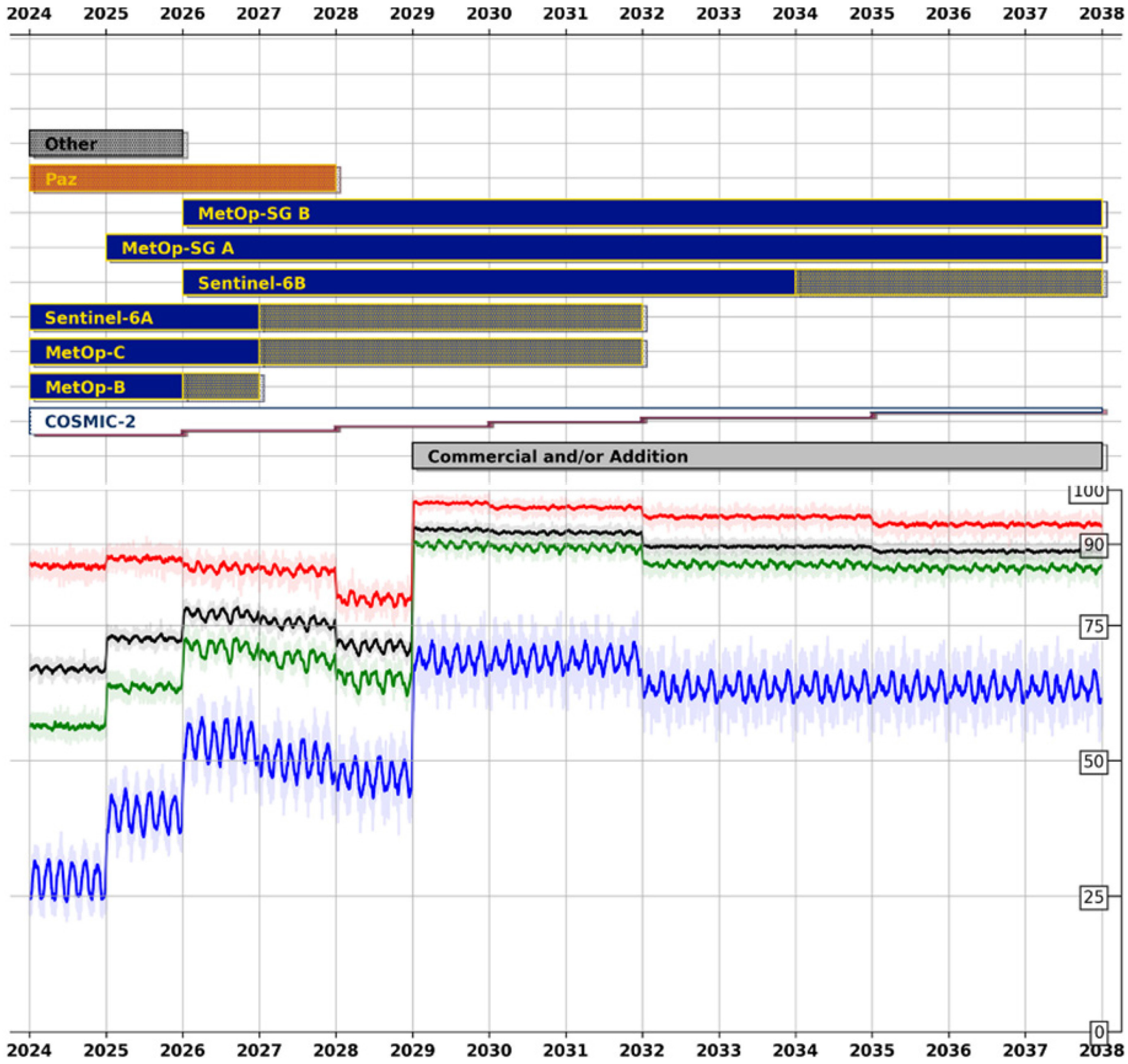
Key: Color-coded daily count criteria: black=global; green=mid-latitude; red=tropics; blue=polar. Partner mission flyouts depict estimated mission extensions.

Figure 3: Refresh performance of the baseline constellation (shown as a flyout) augmented by 4,000 commercial data buy contributions. Gradual COSMIC-2 degradation modeled.



Key: Color-coded 6-hourly 500x500 km equal area grid refresh percentage: black=global; green=mid-latitude; red=tropics; blue=polar. Partner mission flyouts depict estimated mission extensions.

Figure 4: Refresh performance of the baseline constellation (shown as a flyout) replenished by a six-satellite equatorial constellation and two polar orbiters. Gradual COSMIC-2 degradation modeled.



Key: Color-coded 6-hourly 500x500 km equal area grid refresh percentage: black=global; green=mid-latitude; red=tropics; blue=polar. Partner mission flyouts depict estimated mission extensions.

In Phase 1, the RO AoA performed a preliminary evaluation of multiple approaches for deploying spacecraft into key orbits to achieve the necessary observational coverage. These approaches include commercial data-as-a-service systems, commercially operated systems, hosted payloads on independent platforms, and commercially hosted payloads.

CDaaS is a well-established method for acquiring RO data and has demonstrated the capability to meet the required daily profile count. However, due to its reliance on rideshare launches, CDaaS has historically concentrated observations in SSOs, particularly the MetOp plane. This results in a high degree of data redundancy at specific local times, limiting geographic distribution during six-hour numerical weather prediction (NWP) ingest cycles. Furthermore, no CDaaS spacecraft to date have been deployed into low-inclination orbits (<30º), and there are no projected rideshare opportunities into this domain. Without targeted deployment strategies, CDaaS alone cannot provide the global coverage necessary to fully meet NESDIS RO requirements with SSOs.

Expanding beyond the current reliance on equatorial orbiting constellations to incorporate a more diversified approach would significantly improve observational efficiency. Low-inclination orbits are particularly valuable for addressing gaps in equatorial and mid-latitude regions, which are underserved by polar-only architectures. To ensure optimal data distribution, a strategic combination of orbit types is required.

Commercial-hosted RO payloads, where RO instruments are integrated onto commercial spacecraft, present another potential avenue for data acquisition. These payloads may be deployed as part of broader commercial partnerships or through DaaS models.

If incorporated into a commercial constellation with globally distributed orbits, hosted RO payloads could help address data distribution challenges. However, securing hosted payload opportunities remains a significant hurdle. To date, no major commercial constellation has indicated a willingness to accommodate additional RO instruments, and available slots are highly competitive. Even if such opportunities arose, RO payloads would need to compete with numerous other instruments, making selection uncertain.

Ad-hoc hosting of RO payloads offers a limited alternative. While some payloads have been successfully flown on commercial spacecraft, these opportunities have been sporadic and lack long-term sustainability. Additionally, the ad-hoc nature of such missions does not inherently support a globally coordinated and diversified architecture. While commercial hosting should be explored when feasible, it is unlikely to provide the consistent, structured coverage required for global RO needs.

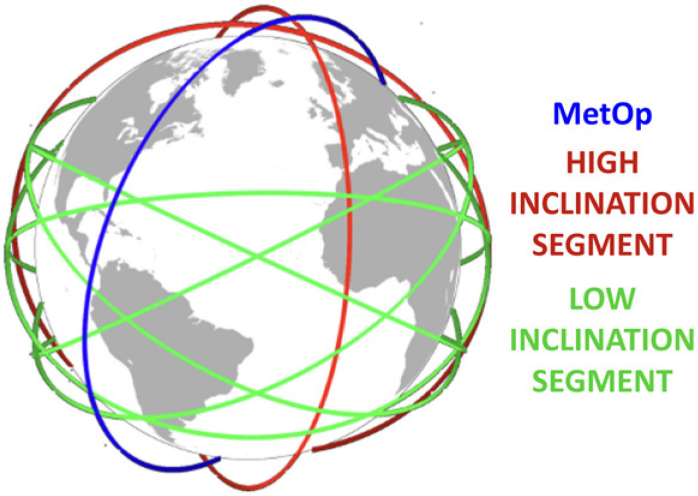
Achieving a truly global RO system—including robust coverage in equatorial and mid-latitude regions—requires targeted deployments into diverse orbital regimes. While existing methods provide valuable data, they are not optimized for global distribution. Future approaches should prioritize diversification of orbit inclinations to maximize observational utility and ensure data availability where it is needed most.

6. Conclusions and Recommendations

A primary finding of the study is that the loss of COSMIC-2 significantly degrades tropical and mid-latitude coverage. Attempting to replace this coverage using only high-inclination orbits cannot provide the necessary coverage.

The study also finds that while international partnerships and commercial data purchases can sustain the required observation count, they cannot fully meet the global refresh criteria. To ensure long-term continuity, investment is required in spacecraft deployed in coordinated and diversified orbits—including low-inclination/equatorial orbits—to maintain COSMIC-2's capabilities.

Figure 5: Orbits of the recommended radio occultation architecture



Recommended Actions

- Increase commercial data acquisitions to address immediate observation gaps, regardless of orbit.
- Continue commercial data purchases, with a focus on improving orbital diversity and latency, particularly data in low inclination orbit.
- Explore additional RO constellations in low-inclination orbits to enhance tropical and mid-latitude coverage, in line with the recommendations outlined in the Summary.

7. Next Steps

The study recommends a Phase 2 analysis to expand scope and refine results, with the following objectives:

- Refine study criteria through model impact analyses
    - Use Observing System Simulation Experiments (OSSEs) and Observing System Experiments (OSEs) to evaluate model sensitivities.
    - Leverage ROMEX findings for neutral atmosphere applications.
- Expand analysis to include space weather applications, incorporating ionospheric total electron content and scintillation.
- Engage with commercial providers to assess feasibility of diverse orbital deployments and understand the cost model.
- Optimize constellation design through trade space analysis, considering ownership models and associated risks.

Appendix A: Methodology and Assumptions

The RO AoA assessed architectures composed of partner missions, commercial data, and various satellite constellations. The performance of each alternative was evaluated based on coverage, refresh rate, and latency criteria. While costs and risks were also assessed, specific financial details are not included in this report due to proprietary considerations.

GNSS Constellation

The analysis assumed that the GNSS constellation used for RO measurements remained constant over time, consisting of 30 GPS, 24 GLONASS, 24 Galileo, and 26 BeiDou satellites. The orbits of each GNSS satellite were modeled as idealized Keplerian orbits, using orbital parameters from the most recent configuration handbooks and two-line element (TLE) data.

Receiver Performance Assumptions

Non-Commercial Receiver Performance

The number of useful profiles collected includes a scaling factor that is assigned per mission and is designed to incorporate quality control observed in operations and other inefficiencies such as sensor tasking algorithms. Existing on-orbit receivers were modeled based on demonstrated performance, while future receivers were modeled using advertised capabilities with a 5% reduction applied to account for uncertainty in performance projections.

Receivers were assumed to produce data immediately after launch without degradation over time, maintain 100% system availability, and operate in either 550 km or 830 km altitude orbits. COSMIC-2 was assumed to achieve Galileo tracking within the next 12 months, and all future missions were assumed to support all four GNSS constellations. The projected lifespan of partner satellite missions was estimated based on published information and heritage performance. The degradation of COSMIC-2 followed Aerospace reliability analyses at 50% confidence, with additional evaluations conducted using a more conservative 90% confidence reliability analysis.

Commercial Receiver Performance

All commercial data service providers were assumed to have the capability to track all four GNSS constellations, with a field of view (FOV) of 90 degrees. A scaling factor was applied to simulate the potential range of purchased commercial data, varying from zero to 12,000 profiles per day. The geographic and temporal distribution of commercial data was modeled based on current provider orbits, with additional projections exploring the impact of deploying commercial constellations into new orbits. While future commercial launch opportunities into different orbital regimes remain possible, uncertainties exist in predicting the geographic and temporal distribution of these data sources.

Ground Segment

To assess space-to-ground communications latency, the analysis assumed a distribution of ground stations available for direct-to-Earth contacts. Existing missions were modeled using their current ground stations. Future missions with well-defined ground segments were assumed to use their advertised infrastructure, while others were modeled using a notional ground network.

For latency modeling, an 8-minute data processing and delivery time was applied to all missions, with an additional 10-minute penalty for McMurdo/Troll contacts to account for bandwidth limitations in Antarctica. Commercial providers were assumed to have access to Ground Station as a Service (GSaaS) globally, but a 10-minute penalty was applied to account for real-world performance variability. This latency assessment represents potential capability rather than a prediction of actual performance, which will depend on contract terms and operational constraints.

Cost Estimates

Cost estimates were generated as part of this study but are not included in the Executive Summary to allow for wider report distribution. The cost assessment methodology included flight segment expenses (payload and bus), ground segment expenses (GSaaS, satellite operations, and data processing), and launch costs.

Flight segment costs include the payload and bus with associated programmatic wraps for: systems engineering and program management (SEPM), integration assembly and test (IAT), aerospace ground equipment (AGE), fee, and additional expenses incurred beyond direct spacecraft development and operations, including oversight, compliance, personnel, security, facilities, and contingency reserves.

Payload costs were estimated using the SEER for Space tool (Galorath Corporation) for both three-year and five-year design life options, while bus costs were derived using the Small Spacecraft Cost Model (SSCM, version 2019) and the SSCM Microsat cost-estimating relationship (The Aerospace Corporation). Estimates were built using a bottom-up approach from design and development stages and did not assume pre-existing payloads or bus platforms.

Ground segment costs, including GSaaS, satellite operations, and data processing, were estimated by analogy to similar programs, incorporating costs associated with downlink time and data delivery for processing. Launch costs varied based on satellite quantity, size, and whether the launch was dedicated or a rideshare. In this study, launches to polar orbits were assumed to utilize rideshares where feasible.

The cost of maintaining existing partnerships was estimated based on historical expenses related to algorithm development, data processing, and storage. Commercial data service costs were based on actual expenditures incurred through NOAA’s Commercial Data Program.

These cost-estimating tools provide rough order of magnitude (ROM) estimates intended for comparative analysis within the AoA. However, they are not intended as independent cost assessments or program budget estimates, as actual costs will vary based on procurement strategies, satellite design choices, and mission execution.

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