

Article

Real-Time Contrail Monitoring and Mitigation Using CubeSat Constellations

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Abstract: Contrails, or condensation trails, left by aircraft, significantly contribute to global warming by trapping heat in the Earth's atmosphere. Despite their critical role in climate dynamics, the environmental impact of contrails remains underexplored. This research addresses this gap by focusing on the use of CubeSats for real-time contrail monitoring, specifically over major air routes such as the Europe–North Atlantic Corridor. The study proposes a 3×3 CubeSat constellation in highly eccentric orbits, designed to maximize coverage and data acquisition efficiency. Simulation results indicate that this configuration can provide nearly continuous monitoring with optimized satellite handovers, reducing blackout periods and ensuring robust multi-satellite visibility. A machine learning-based system integrating space-based humidity and temperature data to predict contrail formation and inform flight path adjustments is proposed, thereby mitigating environmental impact. The findings emphasize the potential of CubeSat constellations to revolutionize atmospheric monitoring practices, offering a cost-effective solution that aligns with global sustainability efforts, particularly the United Nations Sustainable Development Goal 13 (Climate Action). This research represents a significant step forward in understanding aviation's non-CO₂ climate impact and demonstrates the feasibility of real-time contrail mitigation through satellite technology.

Keywords: CubeSats; contrails; constellations; environmental impact; LEO



Citation: Pushparaj, N.; Cormier, L.; Cappelletti, C.; Portapas, V. Real-Time Contrail Monitoring and Mitigation Using CubeSat Constellations.

Atmosphere **2024**, *15*, 1543. <https://doi.org/10.3390/atmos15121543>

Academic Editor: David F. Plusquellic

Received: 15 November 2024

Revised: 16 December 2024

Accepted: 21 December 2024

Published: 23 December 2024



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1. Introduction

The global aviation industry is a vital component of modern society, facilitating international trade, tourism, and cultural exchange on an unprecedented scale. However, the environmental impact of aviation has become a growing concern in the context of global climate change [1]. While the industry has made strides in reducing its carbon dioxide (CO₂) emissions through more efficient engines, alternative fuels, and operational improvements, it has become increasingly clear that the non-CO₂ effects of aviation are also significant contributors to global warming [2].

One of the most pressing non-CO₂ effects is the formation of contrails, or condensation trails, which are ice-crystal clouds that form in the wake of aircraft under specific atmospheric conditions. These contrails, though seemingly innocuous, have a profound impact on the Earth's climate [3]. Under the right conditions, contrails can persist and spread, evolving into cirrus clouds that cover large areas of the sky [4]. These clouds trap heat in the Earth's atmosphere, contributing to a warming effect known as radiative forcing [5]. The contrail formation process begins with jet engine exhaust releasing soot and aerosols into the atmosphere. As the exhaust mixes turbulently with the surrounding air, cooling occurs, leading to supersaturation. When the temperature drops below a critical threshold, droplets form and freeze, creating contrails. In soot-rich exhaust, the ice crystals evolve in the aircraft's wake, where fluid dynamics causes distinct processes: sublimation occurs in

the lower part of the wake, while crystal growth dominates in the upper part. Over a few minutes, the wake disperses, merging the contrail into the ambient air [6].

The environmental impact of contrails is particularly concerning over high-traffic air routes, such as the North Atlantic Corridor, where the frequency and persistence of contrails are highest. In these regions, the cumulative effect of contrail-induced cloudiness can have a significant impact on regional and global climate patterns [7]. Despite their importance, contrails have not been given the same level of attention as CO₂ emissions in climate policy discussions, leaving a critical gap in our understanding and management of aviation's full environmental footprint [8–10].

This research addresses the urgent need to better understand and mitigate the environmental impact of contrails. The primary objective is to explore the potential of CubeSats, miniaturized, low-cost satellites, for real-time monitoring of atmospheric conditions that lead to contrail formation. By deploying constellations of CubeSats with monitoring payloads, it is possible to collect high-resolution data on temperature, humidity, and other relevant atmospheric variables in key flight corridors [11,12]. These data can then be integrated into machine learning algorithms [13,14] to develop predictive models that inform real-time flight management decisions, enabling pilots to adjust flight paths to avoid conditions conducive to contrail formation.

The significance of this research extends beyond its immediate application to contrail mitigation. It represents a broader shift towards integrating real-time environmental data into aviation operations, aligning the industry with global sustainability goals. Specifically, this research supports the United Nations Sustainable Development Goal 13 (Climate Action), which calls for urgent action to combat climate change and its impacts [15].

This paper is structured to provide a detailed exploration of the challenges and opportunities associated with contrail monitoring and mitigation. It begins with an in-depth examination of the physical and atmospheric mechanisms behind contrail formation, including a discussion of the Schmidt–Appleman criterion and the role of various atmospheric variables. The environmental impact of contrails is then analyzed, with a focus on their contribution to global warming and the broader implications for climate change.

Following this, the paper introduces CubeSat technology as a solution for real-time contrail monitoring. The capabilities of CubeSats, including their sensor payloads, data transmission systems, and potential for integration with machine learning algorithms, are discussed in detail. The paper then explores the concept of a distributed CubeSat system, examining the technical, logistical, and regulatory challenges of deploying such a system globally.

Finally, the paper outlines a future roadmap for implementing CubeSat-based contrail monitoring, including phased deployment strategies, integration with flight management systems, and the potential for international collaboration. The long-term vision for this technology is also discussed, emphasizing its potential to transform the aviation industry and contribute to global climate goals.

2. Contrail Formation and Environmental Impact

2.1. Theoretical Background of Contrail Formation

Contrails are formed when the hot, humid exhaust gases from aircraft engines mix with the cold, low-pressure air at high altitudes, causing the water vapor to condense and freeze into ice crystals that appear as a visible trail behind the aircraft. The Schmidt–Appleman criterion provides the theoretical framework for contrail formation, specifying that ambient temperatures below $-40\text{ }^{\circ}\text{C}$ and high relative humidity with respect to ice are necessary [16]. The exact thresholds depend on factors such as the aircraft's exhaust properties, including water vapor and particulates, and engine efficiency [17,18].

The critical temperature for contrail formation, T_{crit} , is influenced by variables like ambient pressure, the specific heat of air, and the fuel's combustion characteristics. This allows for predictive modeling of contrail formation based on real-time atmospheric data. Other factors, such as fuel type and engine technology, also play significant roles in contrail

formation [18]. While more efficient engines generate fewer soot particles, they may produce more water vapor, increasing the likelihood of contrail formation under certain conditions. These insights are crucial for improving predictive capabilities and devising strategies to minimize contrail-related climate impacts [19].

2.2. Persistence and Evolution of Contrails

Contrails form as narrow trails of ice crystals but can persist and evolve into broader cirrus clouds under specific atmospheric conditions, such as ice supersaturation [20,21]. These persistent contrails significantly contribute to radiative forcing by trapping longwave radiation, creating a warming effect that amplifies aviation's non-CO₂ climate impact [22]. Unlike CO₂ emissions, contrails and their induced cirrus clouds have an immediate warming effect, particularly over regions of heavy air traffic such as the North Atlantic Corridor. Factors like low temperatures, high humidity, and wind patterns contribute to their persistence and spread.

As shown in Figure 1, contrails are most prominent in heavily trafficked air routes, highlighting their localized and cumulative environmental effects. Studies have demonstrated that contrail-induced cirrus clouds can contribute radiative forcing comparable to or exceeding that of aviation's CO₂ emissions. This highlights the urgency of addressing these non-CO₂ effects, as they compound the industry's overall climate impact [23,24]. Targeted monitoring and mitigation strategies, such as real-time atmospheric monitoring, are essential to minimizing contrail formation and persistence, particularly in high-traffic areas [25,26]. For example, research has shown that contrail-induced cloudiness can lead to warmer nights, as the clouds trap heat that would otherwise be lost to space [27]. This can have downstream effects on weather patterns, agricultural practices, and even human health.

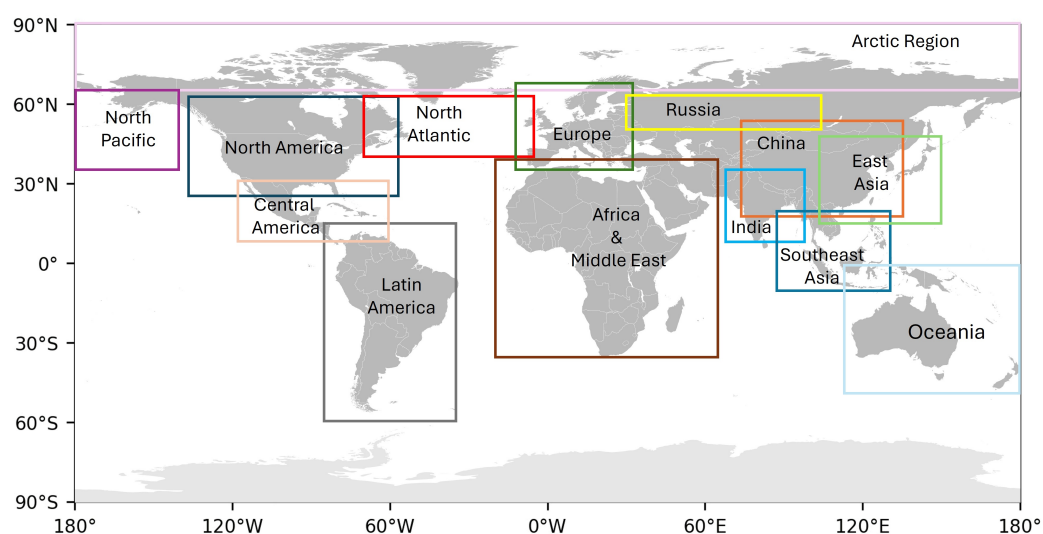


Figure 1. Spatial bounding boxes to highlight the regional air traffic zones.

2.3. Environmental Impact and Climate Implications

Contrails, particularly those that persist and evolve into cirrus clouds, contribute significantly to aviation's non-CO₂ climate impacts by trapping longwave radiation and altering the Earth's radiative balance. The extent of their radiative forcing depends on factors such as altitude, atmospheric humidity, and the time of day, with nighttime contrails exerting a stronger warming effect due to the absence of counteracting solar radiation. Studies show that contrails can have an immediate and pronounced impact on regional and global climate, often comparable to or exceeding the radiative forcing of CO₂ emissions on a per-flight basis [28].

As aviation activity grows, particularly in emerging markets, the frequency and persistence of contrails are expected to increase, exacerbating their short-term warming

effects. Addressing these impacts requires both real-time monitoring and mitigation strategies to minimize contrail formation. By integrating technologies such as CubeSats into contrail monitoring systems, aviation can reduce these non-CO₂ effects and contribute more effectively to global climate goals, including those outlined in the Paris Agreement [29].

3. Mitigation Strategies Through Real-Time Monitoring

3.1. Advancements in Contrail Monitoring Technologies

The challenge of monitoring contrails has long been a topic of interest within the atmospheric science and aviation communities. Traditional methods, such as ground-based radar systems, pilot observations, and imagery from large satellites, have provided the foundational data necessary to understand contrail formation [30–32]. However, these methods often fall short in several key areas, particularly in their ability to offer the high temporal and spatial resolution needed for real-time monitoring and predictive modeling.

Ground-based radar, while effective at capturing large-scale cloud formations and precipitation, lacks the vertical resolution necessary to accurately monitor contrails, which form at altitudes of approximately 26,000 to 40,000 feet. These radar systems are also limited by their fixed locations, which means they can only monitor specific areas and cannot provide the global coverage required for comprehensive contrail tracking.

Satellite imagery has been a valuable tool in observing contrail formations and their evolution over time. Large satellites, such as those in the Geostationary Operational Environmental Satellite (GOES) series [33], offer broad coverage and have been used extensively to monitor weather patterns and cloud formations, including contrails. However, these satellites are often designed for multiple purposes, and their sensors may not be optimized specifically for detecting the fine-scale ice crystals that characterize contrails. Additionally, the temporal resolution of these satellites and how frequently they pass over the same point on Earth can be too low to capture the dynamic processes involved in contrail formation and dissipation.

Pilot reports and visual observations have also contributed to our understanding of contrails, particularly in identifying areas where contrails are frequently observed. However, these methods are inherently subjective and limited by the pilot's ability to observe and report contrails while managing the complexities of flight operations [34,35].

In contrast to these traditional methods, the advent of CubeSat technology represents a significant leap forward in contrail monitoring. CubeSats are miniaturized satellites, typically measuring as small as $10 \times 10 \times 10$ cm per unit, which can be deployed in smaller to larger constellations to provide high-resolution data on atmospheric conditions. These satellites are particularly well suited to the task of monitoring contrails due to their ability to carry specialized sensors designed to detect the specific environmental conditions that lead to contrail formation. CubeSats offer several key advantages over traditional monitoring methods. First, they can be deployed in constellations, meaning multiple CubeSats can work together to provide continuous, global coverage. This capability is particularly valuable for monitoring high-traffic air routes, where the frequency and persistence of contrails are of greatest concern. Second, CubeSats can be equipped with state-of-the-art sensors, including infrared and hyperspectral imagers, that are specifically tuned to detect the presence of ice crystals and water vapor in the upper atmosphere [36]. In particular, the use of high-resolution sensors in the thermal infrared band to detect contrail formation has been demonstrated [37], with different bands used to differentiate contrails from water and ice clouds.

The small size and relatively low cost of CubeSats also allow for more flexible and frequent deployments compared to larger satellites. This means that new CubeSats can be launched regularly to replace or supplement existing constellations, ensuring that the monitoring network remains up to date with the latest technological advancements. Moreover, CubeSats can be deployed in low Earth orbit (LEO), providing them with the proximity to the atmosphere necessary to capture detailed, high-resolution data.

3.2. Detailed Role of CubeSats in Contrail Monitoring

The role of CubeSats in contrail monitoring is multifaceted, encompassing data collection, real-time analysis, and the integration of these data into broader predictive models. Each CubeSat in a constellation can be equipped with a variety of sensors designed to measure different aspects of the atmosphere, providing a comprehensive picture of the conditions that lead to contrail formation.

One of the primary sensors used on CubeSats for contrail monitoring is the infrared spectrometer. Infrared sensors are capable of detecting thermal emissions from the Earth's surface and atmosphere, allowing them to measure temperature profiles at various altitudes. This is particularly important for contrail monitoring, as the formation of contrails is highly sensitive to temperature variations in the upper troposphere. By measuring these temperatures in real time, CubeSats can provide critical data on whether the conditions are right for contrail formation. Such sensors have been integrated into CubeSats to directly observe similar climate variables [38–41], and instruments can be developed to target frequencies of interest to individual missions. More specifically to this mission, through analysis of several spectral bands it is possible to identify contrails among naturally occurring water and ice clouds [37], while post-processing using high-resolution RGB imagery can enable geolocation of the spectrometer data [42].

In addition to temperature, humidity is another crucial factor in contrail formation. CubeSats can be equipped with microwave radiometers, which measure the amount of water vapor present in the atmosphere. High levels of humidity, especially when the air is supersaturated with respect to ice, increase the likelihood that contrails will form and persist. By continuously monitoring atmospheric humidity, CubeSats can help predict when and where contrails are likely to form, allowing for proactive mitigation measures.

Another important tool in the CubeSat arsenal is the hyperspectral imager. Hyperspectral imaging involves capturing data across a wide range of wavelengths, beyond the visible spectrum, which can be used to identify the specific types of particles present in the atmosphere. This capability is particularly useful for detecting the ice crystals that make up contrails, as well as distinguishing between natural cirrus clouds and contrail-induced clouds. By analyzing the spectral signatures of these particles, CubeSats can provide detailed information on the composition and extent of contrails, contributing to more accurate predictions of their environmental impact.

Data from CubeSats are transmitted to ground stations, where they are processed and integrated into predictive models. These models use machine learning algorithms to analyze the data and identify patterns that precede contrail formation. For example, a deep neural network might be trained to recognize the combination of temperature, humidity, and particle data that typically leads to the formation of persistent contrails. By continuously updating these models with new data from the CubeSats, it is possible to improve their accuracy over time, providing more reliable predictions [43].

These predictions can then be fed into flight management systems (FMSs), which can suggest adjustments to flight paths in real time. For instance, if the CubeSat data indicate that contrail formation is likely at the aircraft's current altitude, the FMS might recommend climbing or descending to an altitude where the air is drier or warmer, reducing the likelihood of contrail formation [44]. This capability represents a significant step forward in contrail mitigation, as it allows for dynamic, real-time adjustments based on the latest atmospheric data.

3.3. Case Studies and Validation of the Technology

To demonstrate the effectiveness of CubeSats in contrail monitoring, it is helpful to examine specific case studies where this technology could have been or has been applied. One such case study is the North Atlantic Corridor, which is one of the most heavily trafficked airspaces in the world. This region is known for its frequent contrail formation due to the high volume of long-haul flights that operate at altitudes where the atmospheric conditions are conducive to contrail development. In this case study, we simulate the

deployment of a CubeSat constellation over the region of high-air-traffic routes to enable real-time data from the CubeSats.

Another relevant case study is the collaboration between Delta Airlines and the Massachusetts Institute of Technology (MIT), which has focused on predicting contrail-prone areas and adjusting flight paths accordingly [45]. While this project has relied on predictive models based on historical data, it has not yet fully integrated real-time atmospheric data, which could limit the accuracy of its predictions. The introduction of CubeSat technology into this framework would enhance the precision of the models by providing up-to-the-minute data on atmospheric conditions, allowing for more accurate and responsive flight path adjustments [46].

4. Distributed Systems with CubeSats

4.1. System Design and Technical Specifications

The concept of a distributed system using CubeSats for contrail monitoring leverages the strengths of these small satellites to provide comprehensive, real-time coverage of the Earth's atmosphere. Such a system would involve the deployment of multiple CubeSats in low Earth orbit (LEO), each equipped with sensors designed to monitor specific atmospheric parameters related to contrail formation. The design of this system would address several key technical challenges, including satellite configuration, sensor payloads, data processing capabilities, and communication protocols. Each CubeSat would need to be designed with a specific set of sensors tailored to its mission objectives. For example, some CubeSats might be equipped primarily with infrared sensors to monitor temperature profiles, while others might carry hyperspectral imagers to detect ice crystals and water vapor. This specialization allows each CubeSat to contribute specific types of data to the overall monitoring network, enhancing the resolution and accuracy of the system as a whole.

In terms of configuration, the CubeSats would be deployed in a constellation, with each satellite occupying a specific position in an orbit to ensure complete coverage of the target airspace. The constellation design would need to consider factors such as orbital altitude, inclination, and spacing between satellites. A low-Earth-orbit (LEO) configuration, typically at altitudes between 500 and 2000 km, would be ideal for this mission, as it would allow the CubeSats to maintain close proximity to the atmosphere, providing high-resolution data while minimizing signal latency.

The sensor payloads on each CubeSat would need to be carefully selected and calibrated to provide accurate, high-quality data. Infrared sensors, for example, must be sensitive enough to detect subtle variations in temperature that could indicate the potential for contrail formation [47–49]. Infrared imagers on nanosatellite constellations are gaining prominence for their ability to monitor thermal phenomena and environmental changes with high precision. Companies like OroraTech [50] and Yunyao Yuhang are leading this effort, with OroraTech's FOREST constellation deploying infrared sensors for wildfire detection and thermal monitoring, while Yunyao Yuhang's Yunyao-1 satellites are scaling toward 80 planned spacecraft [51]. Similarly, missions like SatVu [52] further demonstrate the viability of nanosatellites in the infrared domain, with SatVu focusing on high-resolution thermal imagery, contributing to regional monitoring needs. Leveraging such advanced infrared capabilities, these constellations provide persistent and cost-effective monitoring solutions for critical applications, such as environmental hazard detection, energy efficiency analysis, and atmospheric studies, further solidifying nanosatellites as a valuable tool for addressing global challenges.

Similarly, hyperspectral imagers must be capable of distinguishing between different types of particles in the atmosphere, such as ice crystals, water droplets, and aerosols, which are critical for identifying contrails and assessing their impact [51,53]. Hyperspectral payloads on nanosatellite constellations are transforming Earth observation by providing high-resolution spectral data for environmental and atmospheric monitoring. Nanosatellite constellation missions such as Planet and Carbon Mapper's Tanager-1 [54], Kuva Space's Hyperfield-1 [49], Pixxel [55], and Zhuhai Orbita's constellation [56] systems demonstrate

the growing capability of small satellites equipped with multi-band hyperspectral imagers to detect trace gases, pollutants, and other atmospheric phenomena. Adapting this technology for contrail mitigation offers significant potential, as it enables the precise detection and characterization of contrails, including their composition, persistence, and optical properties. Deploying nanosatellite constellations with hyperspectral sensors across critical aviation regions, like the North Atlantic Corridor, can provide continuous, real-time data to optimize flight routes and reduce contrail formation.

Data processing capabilities are another critical aspect of the system design. Each CubeSat would have onboard processing power sufficient to handle the raw data collected by its sensors, performing initial analysis and compression before transmitting the data to ground stations. This approach reduces the amount of data that needs to be transmitted, conserving bandwidth and allowing for more efficient use of the satellite's communication systems.

Communication protocols would also be a key consideration, as the CubeSats would need to maintain continuous contact with ground stations to relay their data in real time. This could be achieved through a network of ground stations strategically located around the globe, ensuring that at least one ground station is always within range of the CubeSat constellation. Alternatively, the CubeSats could be equipped with inter-satellite communication links, allowing them to relay data between each other until they can be transmitted to a ground station.

4.2. Feasibility Studies and Deployment Scenarios

Before deploying a full-scale CubeSat constellation for contrail monitoring, it would be necessary to conduct a series of feasibility studies to assess the system's viability. These studies would involve simulations of the CubeSat constellation in various deployment scenarios, evaluating factors such as coverage area, data resolution, and system reliability. One possible deployment scenario could involve a small-scale pilot project focused on a high-priority region, such as the North Atlantic Corridor. This region, with its high volume of air traffic and frequent contrail formation, would serve as an ideal testbed for the CubeSat system. By deploying a small number of CubeSats in this region, researchers could collect valuable data on the system's performance, identify any technical challenges, and refine the design before scaling up to a global deployment.

This feasibility study considers the cost effectiveness of the CubeSat system compared to traditional satellite systems. While CubeSats are generally less expensive to build and launch than larger satellites, the cost of deploying and maintaining a large constellation could be significant. Another important aspect of the feasibility studies would be the assessment of the system's scalability. As air traffic continues to grow, particularly in emerging markets, the demand for contrail monitoring and mitigation is likely to increase. The CubeSat system would need to be designed with scalability in mind, allowing for the addition of new satellites to the constellation as needed. This could involve designing the system with modular components that can be easily upgraded or replaced, as well as ensuring that the data processing and communication infrastructure can handle the increased data volume.

4.3. Preliminary Constellation Simulations

Satellite constellation design for contrail monitoring in the North Atlantic Corridor demands a strategic balance between satellite availability and coverage continuity. Based on a preliminary analysis, the optimal configuration consists of three orbital planes, each populated by three satellites, denoted as a 3×3 configuration. This architecture achieves an effective trade-off between coverage performance and system complexity. A moderately high eccentric orbit is proposed, with a perigee of 500 km and an apogee extending to 10,000 km. Table 1 presents the orbital parameters of the proposed CubeSat constellation designed for contrail monitoring within the North Atlantic Corridor. The constellation comprises three orbital planes (P1, P2, and P3), each hosting three satellites, identified

as CS-1 to CS-9. Each orbital plane is configured with a semi-major axis of 11,628 km, supporting a highly eccentric orbit with an eccentricity of 0.40850 and an inclination of 60.0 degrees to maximize coverage over the target region.

The right ascension of the ascending node (Ω) for each plane is separated by 120 degrees to provide an optimal distribution of coverage across the corridor. Each satellite is positioned with an argument of perigee (ω) fixed at 270.0 degrees, with specific true anomalies (ν) allocated to each satellite to ensure even spacing within the orbit. This configuration, with a perigee of approximately 500 km and an apogee extending to around 10,000 km, is tailored to balance continuous area coverage with efficient system complexity.

The parameters specified in Table 1 highlight the planned orbital characteristics that allow for extended visibility over the North Atlantic Corridor, thereby enhancing monitoring of aviation-induced contrails. This configuration supports prolonged satellite passes over the region while minimizing the number of satellites required, striking a balance between system cost and performance.

Table 1. Orbital parameters of the CubeSat constellation for contrail monitoring in the North Atlantic Corridor.

Plane	Satellite IDs	Semi-Major Axis [km]	Eccentricity	Inclination [deg]	Ω [deg]	ω [deg]	ν [deg]
P1	CS-1, CS-2, CS-3	11628	0.40850	60.0	0	270.0	0.87, 150.99, 209.37
P2	CS-4, CS-5, CS-6	11628	0.40850	60.0	120	270.0	0.87, 150.99, 209.37
P3	CS-7, CS-8, CS-9	11628	0.40850	60.0	240	270.0	0.87, 150.99, 209.37

Ω is the right ascension of the ascending node; ω is the argument of perigee; and ν is the true anomaly.

This configuration ensures prolonged satellite visibility over the target region, thereby enhancing monitoring capabilities with a reduced number of satellites. However, the increased orbital eccentricity presents challenges in signal transmission, which may necessitate more advanced communication systems to maintain reliable data links.

Figures 2–5 provide an analysis of the performance metrics for various satellite constellation configurations over the North Atlantic Corridor. Figure 2 presents the availability of satellites over the region, with a single satellite providing 20.3% availability over the target region. This rises to 96.6% availability for two planes each containing two satellites, with 100% coverage being achieved with a total of nine satellites spread evenly over three planes. Figure 3 examines the contact duration between satellites and ground stations, showing the minimum, average, and maximum durations for different configurations. As the number of orbital planes and satellites per plane increases, contact duration improves, as indicated by the darker shades in the heatmap: the average contact duration ranges from 73 min for a single satellite to an unlimited duration achieved with nine satellites. Figure 4 illustrates the minimum, average, and maximum number of visible satellites across the region. The results indicate that increasing both the number of planes and satellites per plane results in a higher number of satellites being visible at any given time. This increased satellite visibility enhances network redundancy, ensuring consistent data collection and minimizing potential coverage gaps. Notably, the proposed 3×3 configuration is shown to have a minimum of two satellites of signal at any given time, providing full redundancy against failure, which cannot be achieved in a six-satellite configuration.

Figure 5 presents the blackout duration, or periods without satellite coverage, revealing that configurations with a higher number of planes and satellites per plane effectively reduce these blackout times. Darker shades correspond to longer blackout periods, highlighting that sparse constellations are more prone to interruptions in coverage. Overall, these figures collectively demonstrate that increasing constellation density through more planes and satellites is crucial for minimizing blackout durations, maximizing visibility, and extending contact periods, thereby optimizing the network's performance for contrail monitoring in the North Atlantic Corridor. In particular, it can be seen that a single satellite configuration would result in blackout periods between 73 and 353 min, which reduces to less than 23 min for a 2×2 constellation. These initial simulations suggest that a constella-

tion composed of three planes with three satellites, each in highly eccentric orbits, presents a robust and practical solution for continuous contrail monitoring over the North Atlantic Corridor by ensuring continued, fully redundant satellite availability while minimizing constellation complexity.

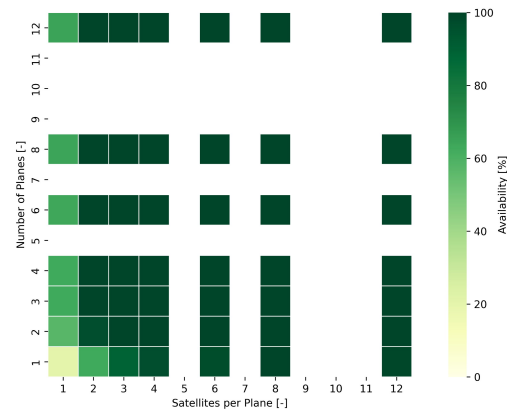


Figure 2. Percentage availability of satellites in the North Atlantic Corridor.

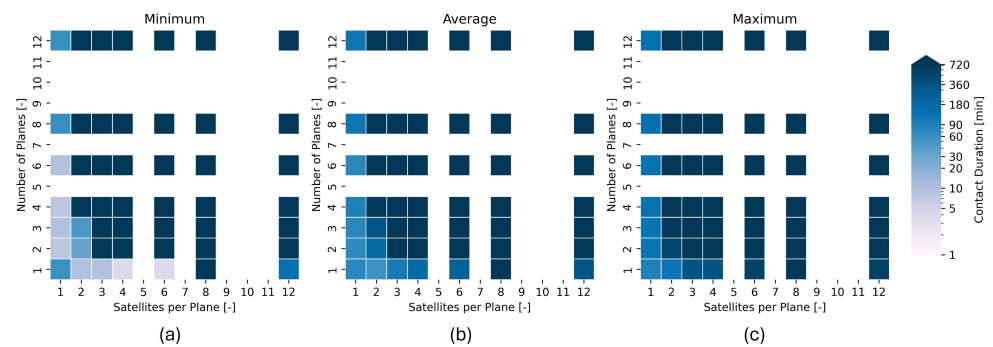


Figure 3. Minimum (a), average (b), and maximum (c) contact duration over the North Atlantic Corridor region for various highly elliptic orbit configurations. Subfigure (a) highlights the lowest contact durations, (b) shows typical contact durations, and (c) demonstrates the highest contact durations. The color bar represents the contact duration in minutes.

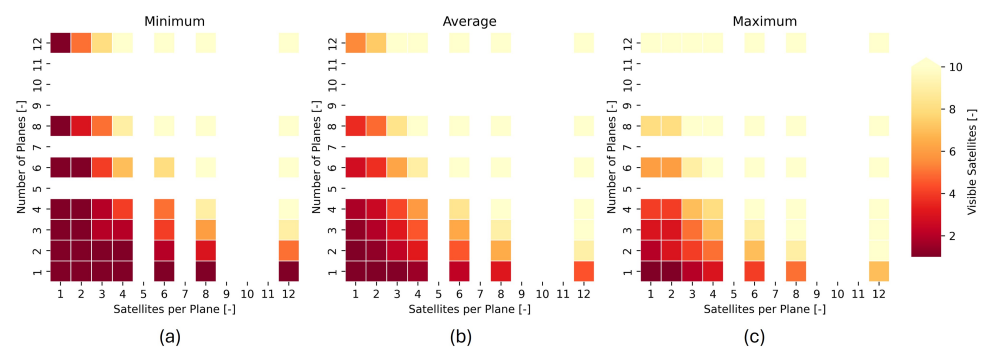


Figure 4. Minimum (a), average (b), and maximum (c) number of visible satellites over the North Atlantic Corridor region for various highly elliptic orbit configurations. Subfigure (a) shows the lowest number of visible satellites, (b) depicts the typical number of visible satellites, and (c) highlights the highest number of visible satellites. The color bar represents the number of visible satellites.

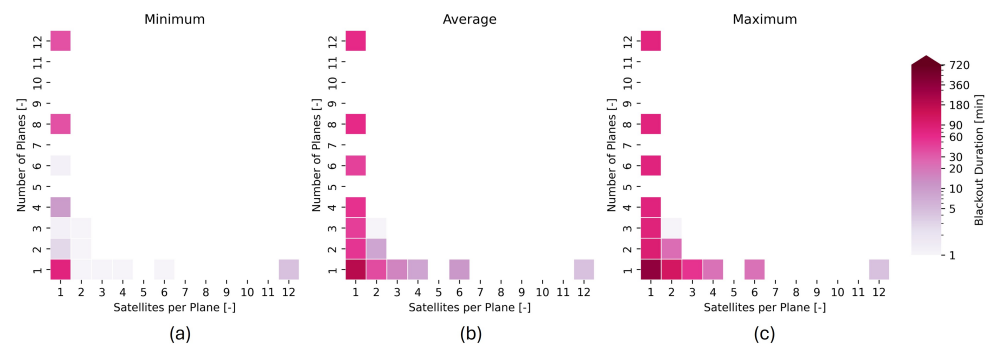


Figure 5. Minimum (a), average (b), and maximum (c) blackout duration over the North Atlantic Corridor region for various highly elliptic orbit configurations. Subfigure (a) shows the shortest blackout durations, (b) depicts the average blackout durations, and (c) highlights the longest blackout durations. The color bar represents the blackout duration in minutes.

Figures 6–8 illustrate the global coverage performance of the proposed 3×3 satellite constellation system, specifically designed for operations in the northern hemisphere. Figure 6 shows the availability of at least one satellite across the hemisphere, where the darker green regions signify near-100% coverage. Notably, the coverage is most consistent at higher latitudes, including the North Atlantic Corridor, emphasizing the constellation's capability to ensure continuous access to satellite data in these critical regions. Figure 7 highlights regions where at least three satellites are simultaneously visible, with brighter areas indicating the strongest overlapping coverage. This redundancy is crucial for operational reliability, as it reduces the risk of data gaps during satellite handovers. The results in Figure 7 confirm that the constellation provides robust multi-satellite visibility in the northern hemisphere, which is essential for applications requiring high-frequency data collection.

Figure 8 further illustrates the average contact duration between the satellites and the targeted regions of observation. The longer contact times, depicted by darker blue regions, are concentrated at mid-to-high latitudes, suggesting that the constellation can maintain extended communication periods in these areas. This extended duration is advantageous for continuous monitoring missions, providing ample time for data acquisition and reducing the likelihood of data loss.

Simulation results from comparable scenarios suggest that while circular orbits with numerous satellites distributed across multiple planes can achieve over 90% availability, the operational and financial burden of deploying and maintaining such a large constellation makes this approach less feasible, with over 150 such satellites required to achieve the minimum viable coverage required for initial operations. By contrast, a constellation with fewer satellites in highly eccentric orbits offers a viable alternative, with fewer than ten satellites potentially sufficient to satisfy mission requirements. An essential aspect of this design is the optimization of handover timing between satellites to minimize data loss and ensure seamless coverage. Such a highly eccentric constellation is uncommon, with almost all nanosatellites launched to date orbiting in near-circular orbits below 1000 km in altitude [57]. As such, the configuration proposed above will occupy a rarely used region of near-Earth space to increase both the performance and operational efficiency of the constellation.

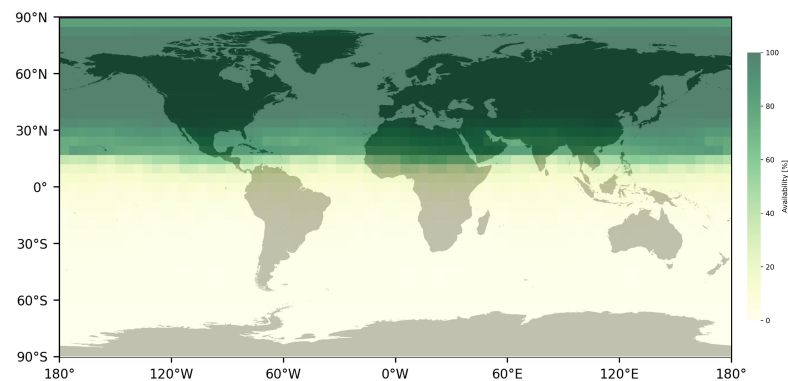


Figure 6. Global coverage of 3×3 satellite constellation system over the northern hemisphere. Note that there is almost 100% availability of at least one of the satellites in the constellation.

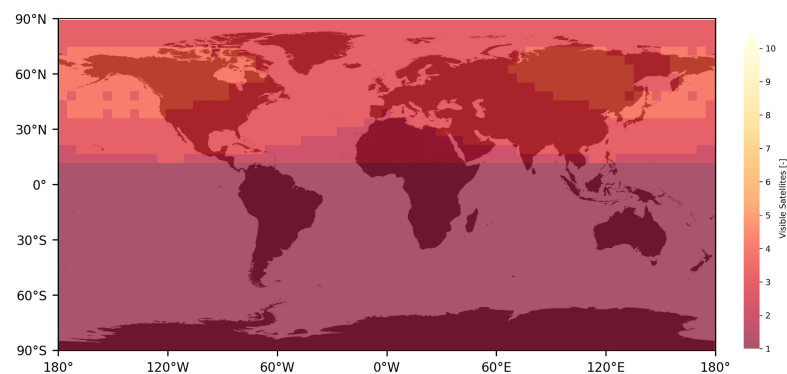


Figure 7. Global coverage of 3×3 satellite constellation system over the northern hemisphere indicating at least 3 visible satellites over the region.

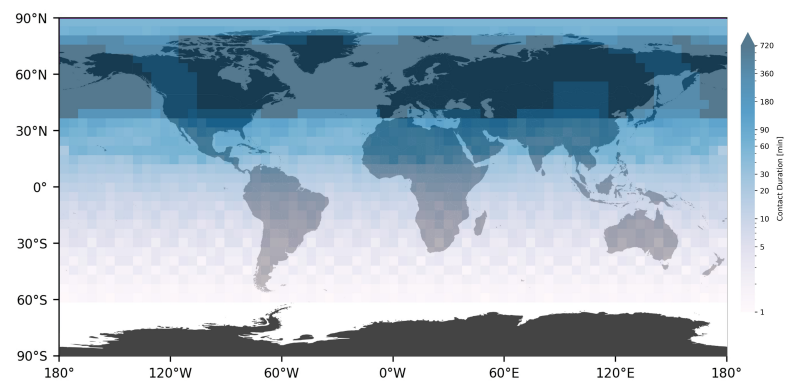


Figure 8. Average contact duration of the satellites in constellation over the northern hemisphere.

4.4. Alternative Approaches

While CubeSats offer a powerful tool for contrail monitoring, they are most effective when integrated into a broader, multi-layered monitoring network that includes other types of satellites, ground-based sensors, and airborne platforms. Such a network would leverage the strengths of each system, providing a comprehensive picture of atmospheric conditions and enabling more accurate and reliable contrail predictions.

Ground-based sensors, such as lidar and radar systems, could provide additional data on atmospheric conditions, particularly in regions where satellite coverage is limited or where real-time data are critical. These sensors could be used to validate the data collected by the CubeSats, ensuring their accuracy and reliability.

Airborne platforms, such as high-altitude drones or research aircraft, could also play a role in this integrated monitoring network. These platforms could be deployed in

specific regions where contrail formation is expected, collecting in situ data on atmospheric conditions and providing real-time feedback to the CubeSat system. This approach would allow for more targeted monitoring, ensuring that the CubeSats are focused on the areas where they are needed most.

Integrating these various systems would require the development of sophisticated data fusion algorithms, capable of combining data from multiple sources to produce a unified, accurate picture of atmospheric conditions. This could involve the use of machine learning techniques to identify patterns and correlations between the different datasets, improving the accuracy of contrail predictions and enabling more effective mitigation measures.

5. Future Roadmap and Implementation

5.1. Phased Implementation Strategy

The successful deployment of a CubeSat-based contrail monitoring system will require a carefully planned, phased approach that addresses the technical, logistical, and regulatory challenges involved. The implementation strategy could be divided into several key phases, each building on the progress of the previous phase and gradually expanding the system's capabilities and coverage.

The implementation of the CubeSat-based contrail monitoring system is structured into a phased strategy, as illustrated in Figure 9. This approach begins with a pilot deployment to validate technology, followed by expanded regional integration, a global rollout, and a final phase focused on sustaining and upgrading the system while fostering international collaboration. This phased strategy ensures scalability and adaptability to changing environmental and technological requirements.

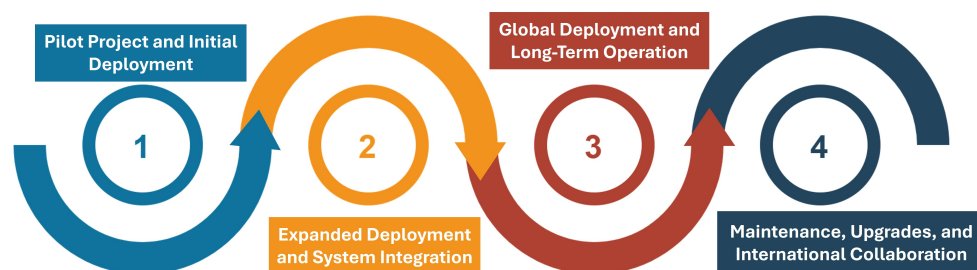


Figure 9. Phased implementation strategy for the CubeSat-based contrail monitoring system.

Phase 1: Pilot project and initial deployment

The first phase of the implementation strategy would involve a small-scale pilot project focused on a high-priority region, such as the North Atlantic Corridor. This pilot project would involve the deployment of 9 CubeSats equipped with the necessary sensors and communication systems to monitor contrail formation in real time. The primary objectives of this phase would be to validate the technology, identify any technical challenges, and refine the system design before scaling up.

During this phase, the CubeSats would collect data on atmospheric conditions, which would be processed and analyzed using machine learning algorithms to predict contrail formation. The data would also be used to validate and refine the predictive models, ensuring their accuracy and reliability. The results of the pilot project would be used to inform the design of the full-scale deployment, identifying areas where improvements can be made. More specifically, the proposed system integrates KalmanNet [58], a hybrid model-based (MB) and data-driven (DD) framework, to process and combine multi-source data for contrail prediction and mitigation. KalmanNet is particularly suited for handling partially known or non-linear dynamics, making it ideal for atmospheric state estimation from noisy, diverse data sources, such as CubeSats, airborne sensors, and ground-based observations.

The proposed contrail mitigation system, illustrated in Figure 10, leverages KalmanNet, to enhance atmospheric state estimation by learning the Kalman gain (KG) directly from data. As shown in Figure 10, the system integrates data from three primary sources: space-

based atmospheric variables (e.g., temperature and humidity) derived from CubeSats, real-time flight data (e.g., aircraft emissions, speed, aerosol, ice particles, and pressure), and ground-based meteorological observations and climate models. These inputs feed into the Kalman Filter Module, which performs two critical steps: a prediction step to estimate a priori state variables (e.g., supersaturation levels) using partially known system dynamics, and an update step to refine these estimates by incorporating real-time observational data through the neural network-aided Kalman gain. The refined estimates are then passed to the Neural Network Module, which is responsible for predicting contrail formation probability and generating actionable strategies for flight path adjustments, such as altitude or route changes.

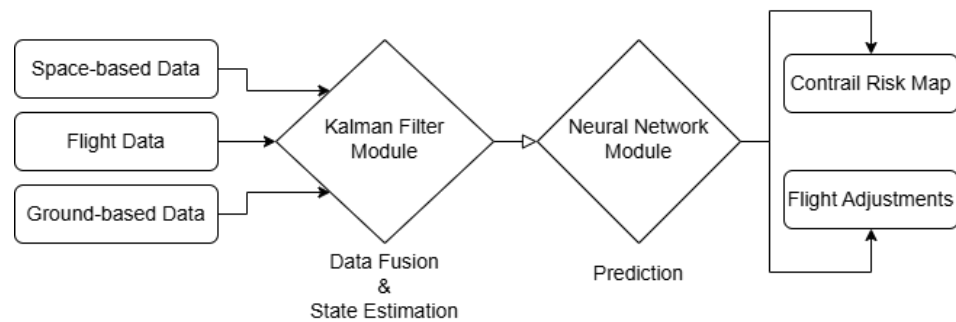


Figure 10. Schematic representation of the KalmanNet-based contrail mitigation system.

The outputs of this system, as depicted in Figure 10, include a contrail risk map and flight adjustment recommendations, providing airlines with real-time information to minimize contrail formation. KalmanNet’s hybrid design ensures data efficiency by combining domain knowledge with labeled datasets, while its robustness allows it to handle uncertainties in system dynamics and sensor noise. Furthermore, its low computational complexity makes it feasible for real-time operation, enabling continuous dynamic adaptation [58,59]. While this paper outlines the conceptual framework and application of the system, further algorithm development, including training and validation methodologies, will be detailed in a dedicated future publication.

Phase 2: Expanded deployment and system integration

The second phase would involve the expansion of the CubeSat constellation to cover additional high-priority regions, such as the North Pacific Corridor and key flight routes in Europe and Asia. This phase would also involve the integration of the CubeSat system with existing monitoring networks, including larger satellites, ground-based sensors, and airborne platforms. The goal would be to create a comprehensive, multi-layered monitoring network capable of providing real-time data on atmospheric conditions across the globe.

During this phase, the system would be integrated with flight management systems (FMSs) and other aviation infrastructure, allowing airlines and air traffic controllers to make real-time adjustments to flight paths based on the latest data. This integration would require close collaboration with industry stakeholders, including airlines, aviation regulators, and technology providers, to ensure that the system meets operational standards and receives the necessary certifications.

Phase 3: Global deployment and long-term operation

In this phase, the CubeSat network would be fully operational, offering real-time monitoring and prediction of contrail formation across the globe. The system would continuously gather data on atmospheric conditions, which would be processed by advanced machine learning algorithms to provide accurate, up-to-the-minute forecasts of contrail-prone areas. Airlines would be able to integrate these data directly into their flight management systems, allowing for dynamic route adjustments that minimize the environmental impact of contrails.

Maintenance and upgrades of the CubeSat constellation would be ongoing tasks in this phase. Given the relatively short lifespan of CubeSats, typically ranging from one to five years, regular launches would be necessary to replace aging satellites and ensure

the continuity of the monitoring network. Advances in CubeSat technology could also be incorporated into new satellites, such as improved sensors, enhanced communication systems, and more efficient power management, further increasing the accuracy and reliability of the system over time.

This phase would also involve scaling the data processing infrastructure to handle the large volumes of data generated by the global CubeSat network. This could include expanding ground station networks, improving data storage solutions, and enhancing the algorithms used for data analysis. Collaboration with cloud service providers could offer scalable and flexible data management solutions that support the real-time needs of the system.

Furthermore, the global deployment phase would require the establishment of international agreements and collaborations to ensure the system's sustainability. As the CubeSat constellation would be monitoring airspace over multiple countries and regions, it would be essential to secure cooperation from international aviation organizations, such as the International Civil Aviation Organization (ICAO) [60], and national regulatory bodies. These agreements would govern data sharing, operational protocols, and regulatory compliance, ensuring that the system operates smoothly and effectively on a global scale.

In regions with high air traffic density, such as the North Atlantic Corridor, ensuring the safety of multiple aircraft implementing contrail avoidance strategies is a critical consideration. While the CubeSat system provides real-time atmospheric data to predict contrail formation, the operational responsibility for managing aircraft separation remains with air navigation service providers (ANSPs) [61]. Existing air traffic management practices, such as vertical and horizontal stacking and coordinated cruise Mach numbers, could be adapted for contrail mitigation scenarios [62]. These strategies have been successfully employed in constrained airspaces lacking traditional navigation aids and are well suited for managing re-routed traffic. Further collaboration with ANSPs will be essential to integrate contrail avoidance into existing airspace management systems without compromising safety.

5.2. Integration with Flight Management Systems (FMSs)

The integration of CubeSat data into flight management systems (FMSs) [63] is a critical component of the overall strategy for mitigating the environmental impact of contrails. FMSs are sophisticated onboard systems that assist pilots in planning and executing flight paths, optimizing fuel efficiency, and ensuring safety. By integrating real-time atmospheric data from CubeSats, FMSs can be enhanced to include environmental considerations, such as the avoidance of contrail-prone areas.

The process of integrating CubeSat data into FMSs would involve several steps:

1. **Data processing and interpretation:** The raw data collected by CubeSats would need to be processed and interpreted in real time to generate actionable insights. This would involve the use of machine learning algorithms that can predict contrail formation based on current atmospheric conditions, such as temperature, humidity, and the presence of ice-nucleating particles.
2. **Real-time data transmission:** The processed data would then be transmitted to aircraft in real time, allowing pilots and FMSs to make informed decisions during flight. This would require the development of secure and reliable communication channels between the CubeSat network and aircraft systems, potentially leveraging existing aviation communication networks, such as ACARS (Aircraft Communications Addressing and Reporting System) [64] and satellite-based datalinks.
3. **FMS interface and decision making:** The final step would involve integrating these data into the FMS interface, where it could be presented to pilots as part of their flight management tools. This could include visual overlays on navigation displays indicating contrail-prone areas, as well as automated suggestions for altitude changes or route adjustments that would minimize the likelihood of contrail formation. Pilots would retain ultimate control over these decisions, but the enhanced FMS would pro-

vide valuable guidance to help reduce environmental impact without compromising safety or efficiency.

4. Pilot training and system validation: Successful integration would also require training pilots to use the enhanced FMS effectively. This would involve familiarizing them with the new environmental data inputs and how to interpret and act on them. Additionally, rigorous validation processes would be needed to ensure that the integration does not inadvertently introduce any safety risks or operational inefficiencies.

Figure 11 illustrates the integration of CubeSat data into the flight management system (FMS) architecture to enable contrail-aware flight planning. Real-time atmospheric data from CubeSats, including humidity, temperature, and contrail prediction information, is fed into the flight planning and navigation modules. These data allow for dynamic adjustments to flight paths, helping to mitigate contrail formation. By incorporating CubeSat inputs, the system optimizes flight routes to reduce environmental impact while maintaining operational efficiency.

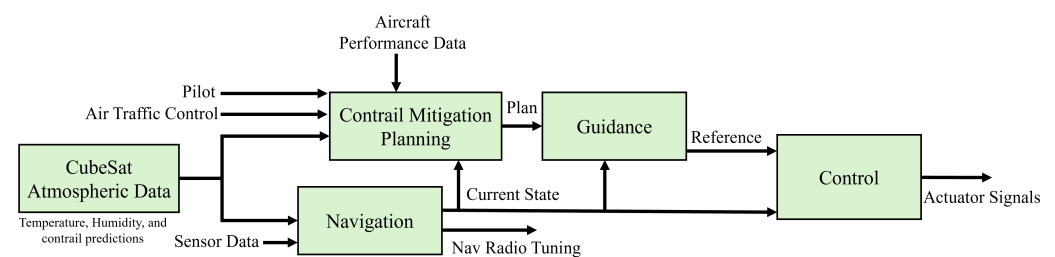


Figure 11. Integration of CubeSat data into flight management system (FMS) for contrail-aware flight planning.

Figure 12 illustrates the end-to-end data processing workflow for contrail detection in the CubeSat-based monitoring system. Data collected from CubeSats are transmitted to a central processing unit, where they undergo machine learning analysis and contrail detection algorithms. This process enables real-time monitoring and mitigation of contrail formation in aviation.

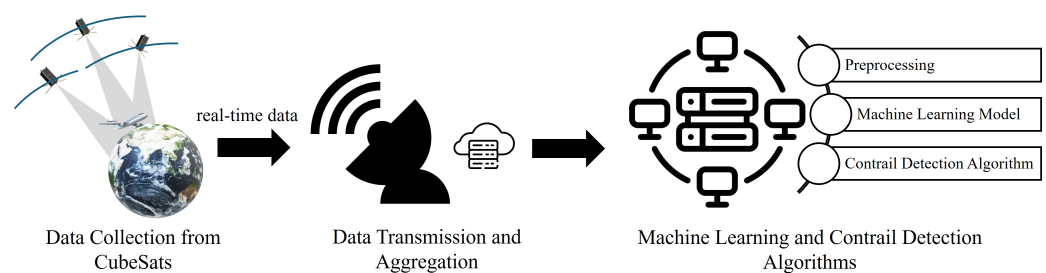


Figure 12. Workflow of data processing and contrail detection in the CubeSat-based monitoring system.

One practical application of the CubeSat-based contrail monitoring system is its integration into flight management systems to dynamically adjust flight paths. The system identifies contrail-prone regions using real-time atmospheric data and suggests alternate routes that avoid supersaturated areas or minimize their impact. To ensure feasibility, this approach evaluates environmental benefits against operational costs, akin to the aviation cost index methodology. With advancements in airspace management, such as reduced navigation performance (RNP) and unified airspace systems, flight paths are no longer constrained to fixed navigational beacons, enabling smoother and more flexible routing. This flexibility supports the practical implementation of contrail mitigation strategies while maintaining economic viability.

5.3. Regulatory and Policy Considerations

The deployment and operation of a CubeSat-based contrail monitoring system, along with its integration into aviation practices, would require careful navigation of regulatory and policy frameworks. Several key areas would need to be addressed:

1. **Regulatory approval for CubeSat launch and operation:** The deployment of a large CubeSat constellation involves securing approval from various national and international space agencies. These approvals would cover the launch, orbital deployment, and frequency use for communication with the satellites. Given the growing number of objects in low Earth orbit, regulatory bodies such as the Federal Communications Commission (FCC) [65] in the United States, Ofcom in the United Kingdom [66], and the International Telecommunication Union (ITU) [67] would play critical roles in managing spectrum allocation and preventing interference with other satellite operations.
2. **Data privacy and security:** The system would collect and process vast amounts of atmospheric data, some of which may be considered sensitive, particularly if they include information related to flight operations. Ensuring that these data are securely stored, transmitted, and used is essential to maintaining trust among stakeholders. Compliance with international data protection regulations, such as the European Union's General Data Protection Regulation (GDPR), would be necessary to protect the privacy of individuals and organizations.
3. **Standardization and certification:** To ensure widespread adoption of the CubeSat monitoring system, standardization of the data formats, communication protocols, and integration methods with FMSs would be essential. International aviation organizations, including ICAO and regional authorities like the European Aviation Safety Agency (EASA) [68], Civil Aviation Authority (CAA) [69], and the Federal Aviation Administration (FAA) [70] would need to collaborate on developing these standards. Additionally, the certification of the enhanced FMS and CubeSat system would be necessary to ensure it meets safety and operational standards.
4. **Environmental regulations and incentives:** Governments and regulatory bodies could play a crucial role in encouraging the adoption of contrail mitigation technologies by introducing policies that incentivize their use. This might include tax breaks or subsidies for airlines that adopt CubeSat-enhanced FMSs or the introduction of environmental regulations that require airlines to report and reduce their contrail-related emissions. Such policies would help accelerate the deployment of these technologies and ensure they contribute effectively to global climate goals.
5. **International collaboration and agreements:** The global nature of aviation means that any significant change in flight management practices, such as the widespread adoption of contrail mitigation strategies, would require international cooperation. This could involve the development of global agreements on contrail monitoring and mitigation, supported by organizations such as the ICAO. These agreements would set out common goals, standards, and practices for contrail management, ensuring that efforts in different regions are aligned and mutually supportive.

5.4. Long-Term Vision and Impact on Global Aviation

By integrating real-time atmospheric data into flight operations, airlines could minimize their contribution to global warming by reducing contrail-induced radiative forcing. This would represent a significant step in the broader effort to decarbonize the aviation industry and mitigate its environmental impact. The successful implementation of this system could have several profound implications for global aviation.

1. **Redefining environmental standards in aviation:** The introduction of contrail mitigation technologies could lead to a re-evaluation of environmental standards within the aviation industry [71]. As airlines adopt CubeSat-enhanced FMSs, the reduction in contrail formation could become a key performance indicator for environmental sustainability, alongside traditional metrics such as fuel efficiency and CO₂ emissions.

2. Influencing airline business models: The ability to minimize contrail formation and its associated environmental impact could become a competitive differentiator for airlines. Passengers, increasingly aware of the environmental impact of air travel, may favor airlines that demonstrate a commitment to sustainability through the adoption of advanced technologies. This could drive airlines to integrate contrail mitigation into their business models, offering “green flights” that prioritize environmental responsibility [72,73].
3. Shaping future aircraft design and operations: The availability of real-time contrail data could influence the design of future aircraft, leading to innovations that further reduce the likelihood of contrail formation. This might include new engine designs that produce fewer particulates or the development of flight paths and altitudes optimized for minimizing environmental impact. Additionally, the operational practices of airlines could evolve to incorporate contrail avoidance as a standard procedure, much like the current practices for avoiding turbulence or severe weather [74,75].
4. Contributing to global climate goals: The widespread adoption of CubeSat-based contrail monitoring and mitigation technologies could play a significant role in helping the aviation industry meet its climate commitments. By reducing the non-CO₂ effects of aviation, such as contrail-induced warming, airlines could make a meaningful contribution to global efforts to limit temperature increases in line with the Paris Agreement [29].
5. Encouraging innovation in environmental monitoring: The success of CubeSat technology in contrail monitoring could inspire further innovation in environmental monitoring, both within aviation and across other industries. The concept of using small, modular satellites to provide real-time data on environmental conditions could be applied to other areas, such as monitoring air quality, tracking deforestation, or assessing the health of marine ecosystems. This could lead to the development of new tools and technologies that support global sustainability efforts across multiple sectors.

6. Conclusions

In conclusion, the study demonstrates that a 3×3 satellite constellation system in highly eccentric orbits is an effective and practical solution for continuous contrail monitoring over the North Atlantic Corridor. Through simulation analysis, it was shown that increasing the number of planes and satellites per plane reduces blackout durations, maximizes the number of visible satellites, and extends contact periods, optimizing coverage for contrail monitoring. The configuration proposed in Section 4.3 provides uninterrupted signal availability across the target region of interest—a notable improvement compared to the 20% availability a single satellite can provide. This constellation design ensures that the northern hemisphere, particularly high-traffic regions like the North Atlantic, benefits from almost constant satellite availability. However, further research and refinements are recommended, particularly in optimizing handover timing and improving communication systems, to address the inherent challenges of signal transmission in eccentric orbits. This approach paves the way for improved atmospheric data collection and contributes to more sustainable aviation practices.

Author Contributions: Conceptualization, N.P., C.C. and V.P.; methodology, N.P. and L.C.; software, N.P. and L.C.; validation, N.P., L.C., C.C. and V.P.; writing—original draft preparation, N.P.; writing—review and editing, N.P., L.C., C.C. and V.P.; visualization, N.P. and L.C.; project administration, N.P., C.C. and V.P. All authors have read and agreed to the published version of the manuscript.

Funding: Luis Cormier is funded by the EPSRC Centre for Doctoral Training (CDT) in Geospatial Systems (ref EP/S023577/1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RFI	Radiative Forcing Index
GOES	Geostationary Operational Environmental Satellite
LEO	Low Earth orbit
FMS	Flight management system
MB	Model based
DD	Data driven
KG	Kalman gain
ANSP	Air Navigation Service Providers
ACARS	Aircraft Communications Addressing and Reporting System
RNP	Reduced navigation performance
FCC	Federal Communications Commission
ITU	International Telecommunication Union
GDPR	General Data Protection Regulation
ICAO	International Civil Aviation Organization
EASA	European Aviation Safety Agency
CAA	Civil Aviation Authority
FAA	Federal Aviation Administration

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