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Key Points:

- Enhanced radiation at aviation altitude was observed during the May 2024 geomagnetic storm
- Radiation dose rates experienced by aircraft crews and passengers are compared between two San Francisco-Paris flight paths
- Major geomagnetic storms can significantly elevate radiation levels for flight crews and passengers unless airlines act proactively

Correspondence to:
H. Aryan,
aryan.homayon@gmail.com

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Enhanced Radiation Exposure of Airline Crew and Passengers During the May 2024 Geomagnetic Storm

Homayon Aryan[1], Jacob Bortnik[1], W. Kent Tobiska[2], Piyush Mehta[3], Benjamin Hogan[2], Rashmi Siddalingappa[4], and Harshitha Challa[3]

[1]University of California Los Angeles, Atmospheric and Oceanic Sciences, Los Angeles, CA, USA, [2]Space Weather Division, Space Environment Technologies, Pacific Palisades, CA, USA, [3]West Virginia University, Mechanical and Aerospace Engineering, Morgantown, WV, USA, [4]Department of Computer and Data Science, York St John University, York, UK

Abstract Enhanced radiation at aviation altitudes is a concern for flight crew and passengers. During space weather events, solar flares and coronal mass ejection (CME) driven shocks are sources of energetic particles that can reach Earth's near-space environment and interact with its magnetic field and atmosphere. Although Earth's magnetic field and atmosphere offer some protection, at high aviation altitudes and particularly near the poles, this shielding effect is weaker leading to increasing radiation exposure and related health risks. In this study, we use data from the Automated Radiation Measurements for Aerospace Safety (ARMAS) instrument onboard a commercial United Airlines flight from San Francisco to Paris that deviated its flight path to mitigate the risk of increased radiation doses during the extreme geomagnetic storm in May 2024. This allows investigation of how the crew and passengers may have experienced enhanced radiation onboard the aircraft. For comparison, we estimate radiation exposure for an alternative flight from San Francisco to Paris around the same time that did not deviate from its planned path. The results show that during the 10 May 2024 geomagnetic storm, ARMAS measured sporadic high absorbed dose rates onboard the deviated flight. However, exposure could have been significantly higher (up to three times higher) if the airline had not deviated to lower latitudes, highlighting the need for precautionary measures during space weather events. Additionally, it is shown that precipitating electrons from the Van Allen radiation belts may significantly contribute to radiation levels at flight altitudes during enhanced geomagnetic activity.

Plain Language Summary Flying can expose flight crews and passengers to extra radiation especially during major space weather events such as solar flares and CMEs. These flares and CME-driven shocks result in energetic particles propagating toward Earth if magnetically well-connected. Although our planet's magnetic field and atmosphere usually protects us from them, this shielding is weaker at high altitudes and near the poles where they are able to enter if their energy is sufficient. As a result, higher radiation doses may be received during periods of enhanced space weather activity. In this study, we analyzed the measured radiation dose on a deviated flight route from San Francisco to Paris during the May 2024 geomagnetic storm and estimated the radiation dose in case of no deviation. The results show that during the 10 May 2024 storm, radiation levels were high. However, the radiation would have been significantly higher if the airline had not taken the precautions. This highlights why it's critical for airlines to consider alternative flight routes during strong space weather events to protect everyone on board against high radiation doses.

1. Introduction

Geomagnetic storms are unique global phenomena leading to enhanced deposition of solar wind energy and momentum into the ionosphere-thermosphere system that are usually more intense and occur more often during periods of high solar activity but may also occur during any phase of the solar cycle (Gonzalez et al., 1994). Generally, the most extreme geomagnetic storms occur as a result of CMEs with intense southward oriented interplanetary magnetic field (IMF) (Desai & Giacalone, 2016; Gopalswamy et al., 2000, 2008; Gopalswamy & Thompson, 2000; Reames, 2013; Webb & Howard, 2012). Such geomagnetic storms can cause a global increase in plasmaspheric hiss wave activity within the inner magnetosphere (Aryan et al., 2021; Meredith et al., 2004) and enhanced radiation at aviation altitudes (>9 km) in particular at higher latitudes regions that can pose serious hazards to aircraft crew and passengers (Beck et al., 2005; Friedberg et al., 1992; Scheibler et al., 2022). Atmospheric ionizing radiation is the main source of human radiation exposure at aviation altitudes due to high linear energy transfer radiation (Bagshaw, 2008; Wilson et al., 1995) that can directly damage DNA, a process that may result in adverse health effects, including various forms of cancer. This has been identified as a significant factor in limiting the flight hours of aircrew (Cannon et al., 2013; Jones et al., 2005; Knipp, 2017).

Enhanced radiation at aviation altitudes is largely driven by galactic cosmic rays (GCRs) and solar energetic particles (SEPs) that are known to be the two major radiation sources (Reames, 2013; Vlahos et al., 2019). GCRs are produced in high-energy explosive events outside the solar system (such as high-energy supernova) and their intensity is modulated slowly by the IMF (Blandford & Eichler, 1987), whereas the SEPs originate from solar flaring events and CME driven shock waves (Desai & Giacalone, 2016; Freier & Webber, 1963; Gopalswamy et al., 2004; Reames, 2013). Both GCR and SEP mainly consist of high energy protons and alpha particles that can reach the Earth's atmosphere and enhance the radiation level at aviation altitudes (O'Brien et al., 1996; Velinov, Peter I.Y. et al., 2013).

However, recent studies have shown that there is also a third source of radiation that has a strong correlation with plasmaspheric hiss waves within the inner magnetosphere (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023). Plasmaspheric hiss waves play a crucial role in the removal of energetic electrons from the Earth's radiation belts by precipitating them into the upper atmosphere. Through cyclotron resonant interactions, these waves can scatter electrons over a range of energies from tens of keV up to several MeV (Horne & Thorne, 1998; Li et al., 2007; Ma et al., 2016; Ni et al., 2014; Ripoll et al., 2016, 2019, 2020a). As precipitating high-energy electrons collide with atoms and molecules in the atmosphere, they slow down rapidly and emit electromagnetic radiation through a process known as bremsstrahlung or braking radiation (Marshall & Cully, 2020; Millan & Thorne, 2007). The contribution of GCRs, SEPs, and precipitating electrons from the Van Allen radiation belts to radiation levels at flight altitudes can be observed using the Automated Radiation Measurements for Aerospace Safety (ARMAS) system that continuously measures 10-s absorbed dose and derives effective dose rate (Tobiska et al., 2016, 2018, 2022).

In May 2024, a series of extreme solar flares, CME's and induced geomagnetic storms occurred during solar cycle 25. According to the National Oceanic and Atmospheric Administration (NOAA), the geomagnetic storm on 10 May 2024 was a powerful G5 category storm (Kappenman, 2006) that produced aurora at far more equatorial latitudes than usual in both the Northern and Southern Hemispheres (Grandin et al., 2024) with the disturbance storm time (Dst) index reaching a minimum value of −412 nT. Fortunately, as the geomagnetic storm unfolded on 10 May 2024, the ARMAS instrument was being flown on a commercial United Airlines flight (UAL990) from San Francisco to Paris. United Airlines recognizes the importance of managing radiation exposure for its passengers and crew due to increased risks inherent to high altitude flights (Stills, 2019). Therefore, the flight took a deviated route at lower latitude and altered altitude to mitigate the risks associated with radiation exposure, ensuring the safety and well-being of both passengers and crew. Another reason for deviation from the original route between San Francisco and Paris was United's concern over reported High Frequency (HF) radio communication outages between Newfoundland and Greenland. These issues had been flagged by pilots earlier in the day. To address this dangerous situation, the operations team decided to alter the route, shifting from a high latitude path to one at lower latitudes. This change was made to ensure better HF communication coverage across the continental US, continuing south of Nova Scotia before the route would resume its transatlantic course toward Paris. The ARMAS instrument onboard the deviated United Airlines flight allowed to measure continuously the absorbed radiation dose rates and derived effective dose throughout the entire flight during the extreme geomagnetic storm.

The goal of this study is to investigate what the enhanced radiation levels were at this deviated route and compare it with the radiation exposure for Air France flight (AFR83), which flew from San Francisco to Paris around the same time as UAL990 but that did not deviate from its original route. This comparison enables us to estimate the excess radiation that the flight crew and passengers may have been exposed to due to flying at higher latitudes. ARMAS data, wave and electron data collected by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites, as well as geomagnetic indices and solar wind parameters used in this study are described in Section 2. Results of the study are presented and discussed in the following section and Section 4 presents the conclusions.

2. Data and Methodology

In this study, real-time in situ radiation measurements are provided by the ARMAS system with onboard instrument continuously measuring absorbed dose. Effective dose rates are derived after the measurements are transmitted to the ground. The measurement system includes a Teledyne micro dosimeter uDOS001 (uDOS), a GPS chip, a microprocessor, and a Bluetooth transmitter, along with other essential electronics. The uDOS chip is notably sensitive to heavy ions (Fe+), protons, electrons, neutrons, alpha particles, and x-rays, particularly those with energies exceeding 0.5 MeV, as confirmed by extensive ground beam line testing (Tobiska et al., 2016). The ARMAS data are then processed on the ground to calculate tissue-effective dose rates as well as the derived dose in silicon based on specific locations and times (Tobiska et al., 2016, 2018, 2022). The absorbed dose in the environment is quantified using silicon (Si). Background dose rates are estimated using the Nowcast of Atmospheric Ionizing Radiation for Aerospace Safety (NAIRAS) model 3.0 (Mertens et al., 2013), developed by NASA's Langley Research Center, that provides real-time assessments of radiation exposure at aviation altitudes. NAIRAS calculates the absorbed dose rates and effective dose rates for airline passengers and crew due to GCRs and SEPs, thus providing real-time radiation exposure predictions. NAIRAS model results have shown to be in good agreement with ARMAS measurements and calculations (Phoenix et al., 2024).

The wave and electron data utilized in this study were collected by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites. The THEMIS mission consists of five identically equipped satellites (THEMIS-A, THEMIS-B, THEMIS-C, THEMIS-D, and THEMIS-E) that were launched in February 2007 to carry out multipoint investigations of substorm phenomena in the tail of the terrestrial magnetosphere (Sibeck & Angelopoulos, 2008). The THEMIS satellites were positioned close to the magnetic equator with their perigees located below 2 Earth radii (R_E) and apogees exceeding 10 R_E. The THEMIS satellites gradually precess around Earth as they reach apogee with THEMIS-A, THEMIS-D, and THEMIS-E providing the near-Earth magnetospheric data used in this study, whereas THEMIS-B and THEMIS-C were repurposed for the ARTEMIS lunar mission (Angelopoulos, 2008). The search coil magnetometer (SCM) (Roux et al., 2009) and the electricfield instruments (Bonnell et al., 2008) provide wave measurements in a bandwidth from 0.1 to 4 kHz. The fluxgate magnetometers (FGMs) provide spin-averaged background magnetic field measurements with a typical sampling interval of approximately 4 s, corresponding to the spacecraft spin period (Auster et al., 2008) that are used to determine the local electron cyclotron frequency f_{ce} and lower hybrid frequency f_{LH}. The plasmaspheric hiss wave amplitudes are determined using continuous measurements of the magnetic and electric field mean wave power in six logarithmically spaced frequency ranges from 1 Hz to 4 kHz of filter bank (FBK) data. The electron data were measured by the electrostatic analyzer (ESA) in the energy range of 7 eV–26 keV (McFadden et al., 2008).

The Space Environment In Situ Suite (SEISS) onboard NASA's Geostationary Operational Environmental Satellite (GOES) 16 and 18 provides 1-min and 5-min averages Level-2 (L2) NetCDF data of in situ observations of 50 keV–4 MeV electron fluxes and 80 keV–12 MeV proton fluxes from five electron and five proton solid-state silicon detector telescopes.

NASA's GSFC online space physics data facility, OMNIWeb, is used to obtain the geomagnetic indices and solar wind parameters at relatively high resolutions. The OMNIWeb interface provides access to near Earth (1 AU) solar wind magnetic field and plasma parameters data from the Advanced Composition Explorer (ACE) (Stone et al., 1998) and WIND missions (Wilson III et al., 2021).

3. Results and Discussions

The geomagnetic storm on 10 May 2024, also known as the Gannon Storm in recognition and memory of Dr. Jennifer Gannon (Pulkkinen et al., 2024), was a powerful G5 category storm (Kappenman, 2006) and one of the strongest geomagnetic storms during the past 20 years (Grandin et al., 2024). This geomagnetic storm followed a series of CMEs launched on 07 May 2024, which began impacting Earth on 10 May, significantly disturbing the radiation belts and compressing the plasmasphere. In addition, an X5.8 solar flare erupted on 11 May 2024 at 01:00 UT triggering a sudden solar energetic particle (SEP) event with >100 MeV proton flux peaking at 02:45 UT, and a Ground Level Enhancement alert (GLE74) was issued at 02:05 UT. The geomagnetic storm event occurred following a series of coronal mass ejections launched on 7 May 2024, which began impacting Earth on 10 May, significantly disturbing the radiation belts and compressing the plasmasphere. The four upper panels of Figure 1 show the magnetic field and geomagnetic indices recorded from May 10 to 11 May

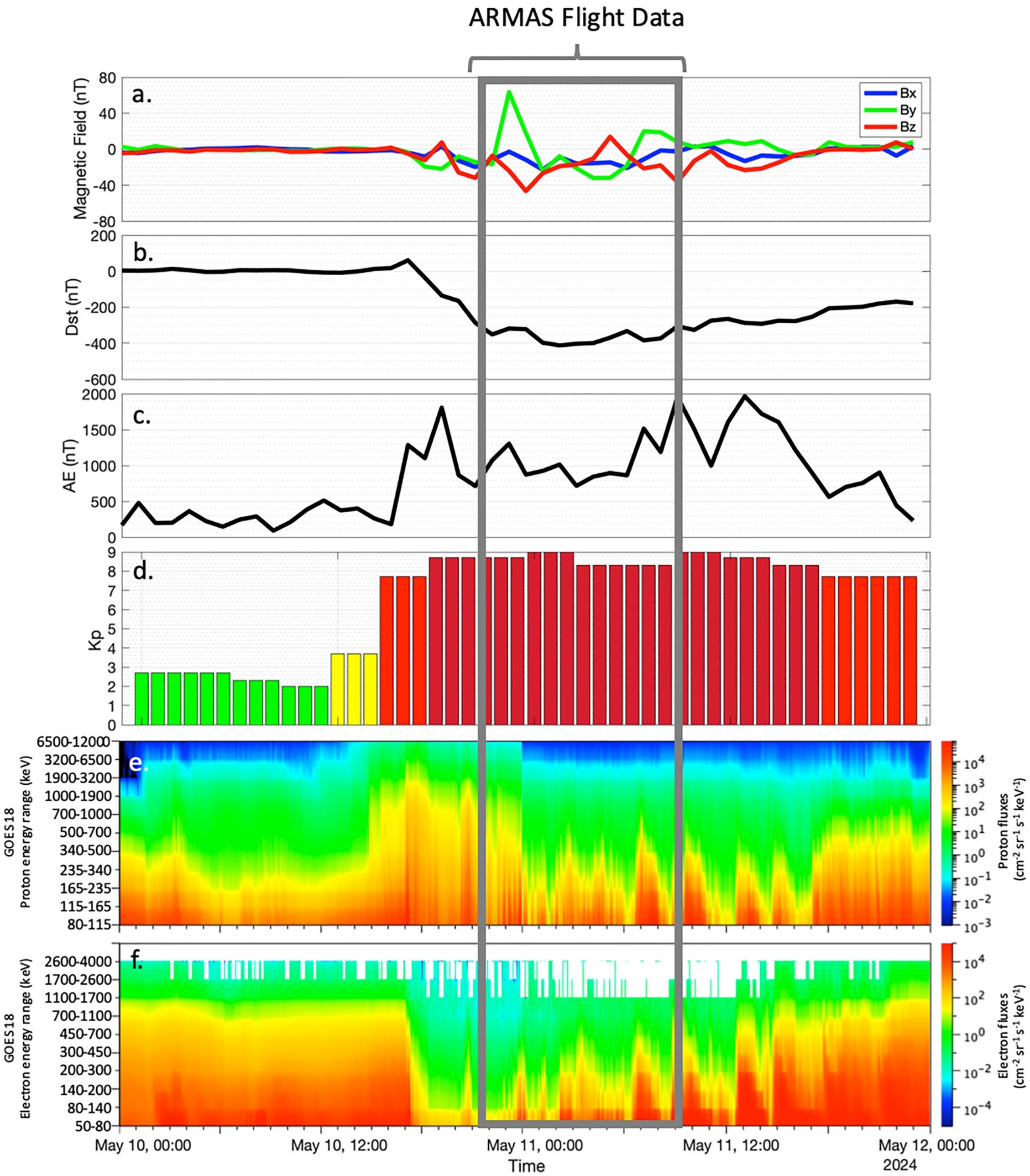

Figure 1. The magnetic field and geomagnetic indices recorded from May 10 to 11 May 2024. (a) Solar wind magnetic field components observed at L1, (b) The Dst index, (c) AE index, and (d) Kp index. Panels (e) and (f) show the time-averaged differential proton and electron fluxes from GOES-18 spacecraft, respectively. Intense geomagnetic activity began in the afternoon on 10 May 2024, indicating a significant disturbance in the Earth's magnetospheric environment. The gray box highlights the flight duration of the deviated commercial United Airlines (UAL990) from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 10 May 2024.

2024. The intense geomagnetic activity began around 12:00 UT on 10 May 2024, indicating a significant disturbance in Earth's magnetospheric environment. The data suggest typical characteristics of a strong CME were observed. Figure 1a shows the solar wind magnetic field with a strong southward component (Bz). The southward orientation of the IMF is crucial because it allows for efficient coupling with Earth's magnetic field. When Bz is negative, it enhances the likelihood of magnetic reconnection leading to increased geomagnetic activity (Gonzalez et al., 1994; Tsurutani et al., 1988). Figure 1b shows a reduction in the Dst index below −400 nT, indicating a significant buildup of the ring current and decrease in the global equatorial magnetic field strength. A Dst value this low suggests that there was substantial ring current build up, which is often associated with enhanced energetic particle injection into the magnetosphere (Gonzalez & Tsurutani, 1987). Figure 1c shows an increase in auroral electrojet (AE) index to approximately 2,000 nT. The AE index is a measure of the strength of the auroral electrojet that reflects substorm activity. Figure 1d shows that the Kp index reached a maximum of 9. This is the highest level of Kp index, signifying an extreme geomagnetic storm. The Kp index is a global midlatitude index that reflects the overall geomagnetic condition and is directly influenced by the solar wind's intensity and structure (Mayaud, 1980; Menvielle & Berthelier, 1991; Rostoker, 1972). Figures 1e and 1f show the time-averaged differential proton and electron fluxes from GOES-18 spacecraft, respectively. Figures 1e and 1f show significant radiation belt disturbances occurring on the afternoon of May 10 that are consistent with storm-related acceleration processes within the magnetosphere. The space environment and geomagnetic conditions shown in Figure 1 strongly indicate an intense geomagnetic storm with enhanced auroral activity with the potential for enhanced radiation level at aviation altitudes.

As the geomagnetic storm unfolded on 10 May 2024, the ARMAS instrument was being flown on a commercial United Airlines flight (UAL990) from San Francisco Airport (SFO) to Paris Charles de Gaulle Airport (CDG). United Airlines work closely with NOAA's Space Weather Prediction Center (SWPC) to monitor space weather and adjust flight paths when necessary, such as deviating flight paths to lower latitudes and altitudes to increase atmosphere shielding and hence mitigate radiation exposure risks ensuring safety during flights (Stills, 2019). In this case, the United Airlines flight departed from San Francisco around 3p.m. local time and in anticipation of possibly enhanced radiation at high latitudes, the flight took a deviated route with a much lower latitude and altered altitude. The ARMAS instrument onboard the deviated United Airlines flight allowed to measure continuously the absorbed radiation dose rates throughout the entire flight.

Figure 2a shows the absorbed radiation dose rate measurements (circular symbols) recorded by the ARMAS instrument onboard the United Airlines flight. The data projected on a geographic map provide a detailed profile of the absorbed dose rates experienced by the aircraft crew and passengers. Figure 2b shows the altitude profile of the deviated flight projected on a polar azimuthal map. Figure 2c shows the time profile of the absorbed dose rates during the flight where the absorbed dose rates measured by ARMAS instrument during the flight are generally larger than the background absorbed dose rates estimated by NAIRAS.

At the beginning, United Airlines flight ascended to cruise altitudes while flying in a north-easterly direction over the United States. This phase of the journey occurs at lower latitudes where ARMAS (onboard the United Airlines flight) records relatively low absorbed dose rates ($\sim 1\ \mu$Sv/h), indicating that the flight is within relatively safe radiation environments at lower altitudes and latitudes. As the United Airlines flight approached the USA-Canada border, it deviated from its initial course and turned eastwards flying over the United States at lower latitudes. This adjustment is part of the airline's strategy to minimize exposure to high radiation levels typically encountered at higher latitudes during significant space weather events. Despite the extreme geomagnetic activity, the ARMAS instrument largely recorded moderate absorbed dose rates ($\sim 1\ \mu$Sv/h), along this deviated route, with occasional spikes where the absorbed dose rate reached higher levels with bursts nearing $\sim 3\ \mu$Sv/h.

To assess what radiation levels might have occurred on the original flight path without such a deviation, we analyzed a comparable Air France flight (AFR83), which departed San Francisco just over an hour after the United Airlines flight on the same day. Like United Airlines, Air France implements space weather mitigation strategies to protect crew health. However, their policy framework is structured around cumulative exposure thresholds aiming to keep crew members below a reference level of 6 mSv over any rolling 12-month period. If a crew member approaches a threshold of 4 mSv, operational measures, such as flight schedule adjustments, may be enacted to prevent further exposure (Desmaris, 2016). Based on this approach, the Air France flight followed a more direct, high-latitude route to Paris, as shown in Figure 3a (indicated by diamond symbols), with the altitude profile presented in Figure 3b.

Although in situ radiation measurements are not available for the Air France flight on 10 May 2024, we can infer likely radiation exposure levels using a two-step approach to estimate the radiation dose rates that may have been experienced along its flight path. First, we identify a comparable flight operating along a similar high-latitude route during a period with low geomagnetic activity for which onboard radiation measurements are available. This provides a baseline observational data set. Second, we use prior work establishing correlations between radiation dose rates at aviation altitudes and plasmaspheric hiss wave power (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023) and multiparameter plasmaspheric hiss wave models (Aryan et al., 2021). By combining these relationships, we can

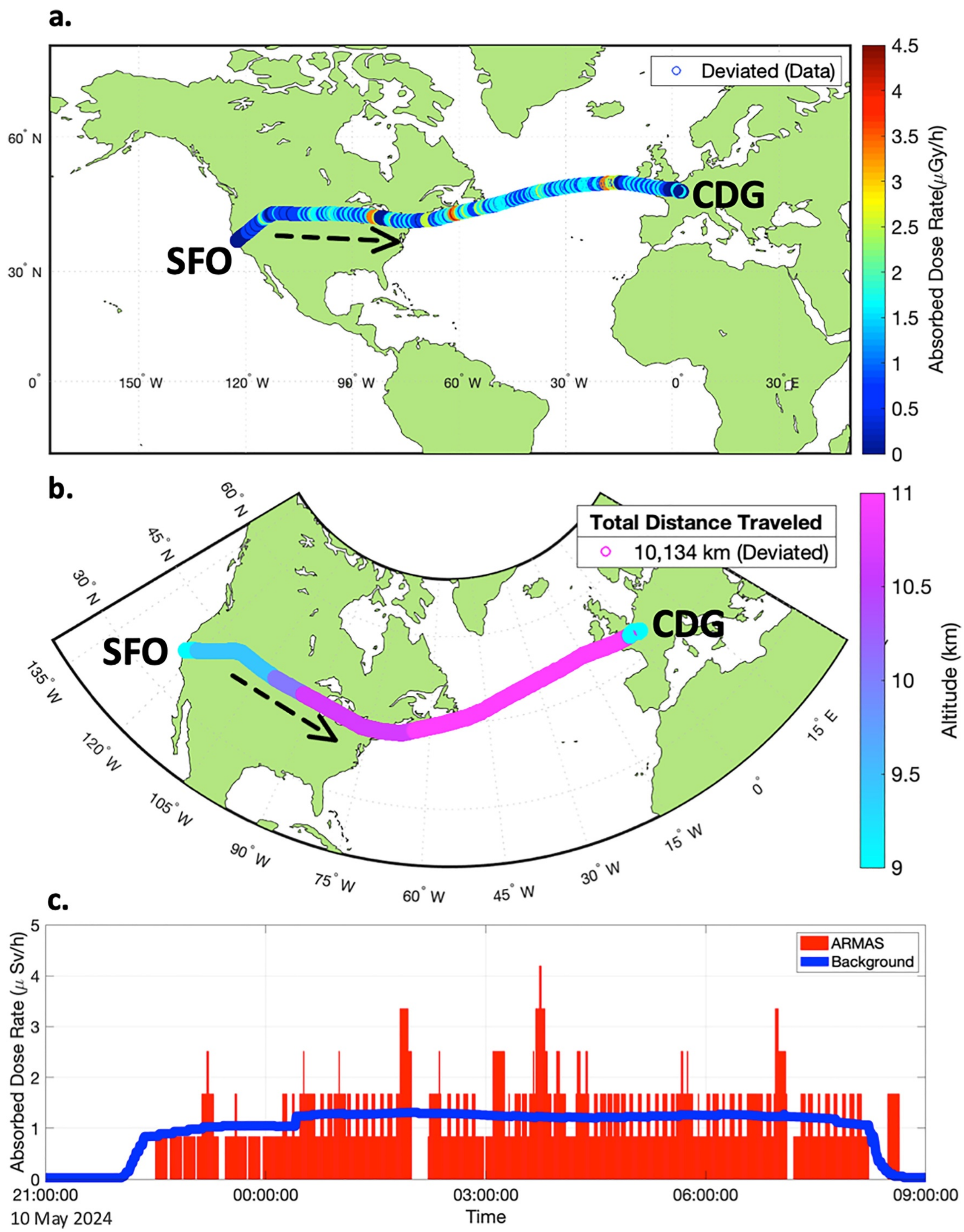

Figure 2. The ARMAS measurements recorded onboard a deviated commercial United Airlines flight (UAL990) from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 10 May 2024, during the extreme May 2024 geomagnetic storm. Panel (a) shows the absorbed radiation dose rate measurements (circular symbols) recorded by the ARMAS instrument onboard the United Airlines flight. Panel (b) shows the altitude profile of the deviated United Airlines flight and Air France flight from SFO to CDG, projected on a polar azimuthal. Panel (c) shows the time profile of the absorbed dose rates during the flight.

map the radiation exposure estimates for the undeviated Air France flight during quiet conditions to the extreme geomagnetic conditions of the May 2024 storm. This approach provides a physics-informed, data-constrained method for reconstructing the radiation exposure level in the absence of direct flight measurements. Figure 4

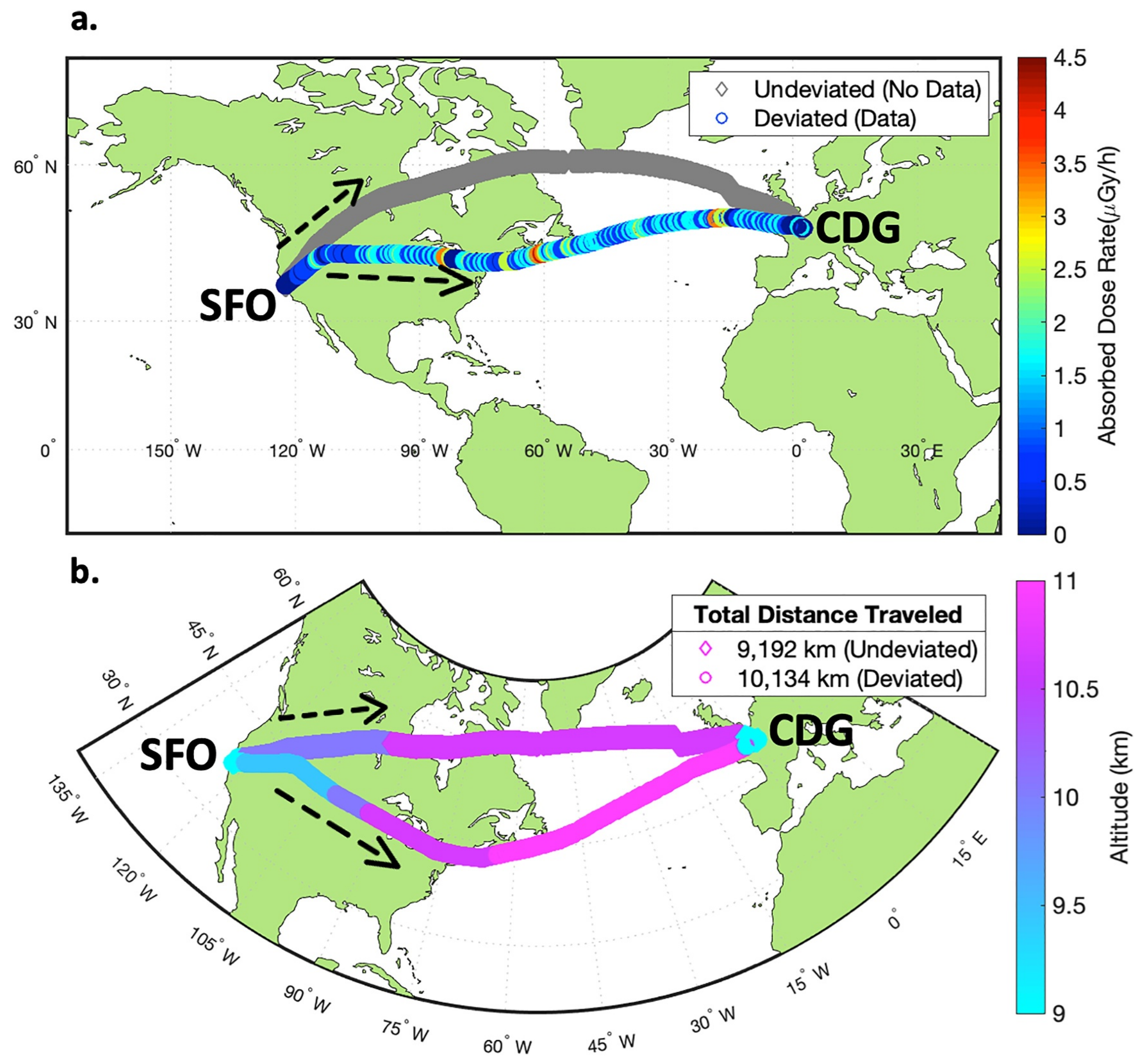

Figure 3. The ARMAS measurements recorded onboard a deviated commercial United Airlines flight (UAL990) from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 10 May 2024, during the extreme May 2024 geomagnetic storm. Panel (a) shows the absorbed radiation dose rate measurements (circular symbols) recorded by the ARMAS instrument onboard the United Airlines flight and the flight path of the undeviated Air France flight (square symbols) from San Francisco to Paris on 10 May 2024. Panel (b) shows the altitude profiles of both flights from SFO to CDG.

shows the absorbed dose rate measurements recorded by the ARMAS instrument onboard a commercial United Airlines flight from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 7 June 2019. These measurements provide a continuous, high-resolution profile of the radiation exposure experienced by the flight crew and passengers along an undeviated, high-latitude transatlantic flight path.

This reference flight took place during a period of quiet geomagnetic conditions, in sharp contrast to the significantly disturbed geomagnetic conditions observed during the 10 May 2024 geomagnetic storm. Figure 5 shows the magnetic field and geomagnetic indices recorded on June 7 and 8 June 2019 where panels a–d show the magnetic field strength, Dst index, AE index, and Kp index, respectively. Panels e and f show the time-averaged differential proton and electron fluxes from GOES-16 spacecraft, respectively. Unlike Figures 1e, 1f, and 5e, 5f do not show any significant radiation belt disturbances occurring especially during the ARMAS data period marked by the gray box. The results strongly indicate quiet geomagnetic conditions and potentially low radiation levels at aviation altitudes.

To estimate the radiation exposure likely experienced by the undeviated Air France flight on 10 May 2024—when no direct radiation measurements were available—we use the 7 June 2019 ARMAS data as a baseline reference. These baseline measurements are then scaled using the established correlation between dose rates and

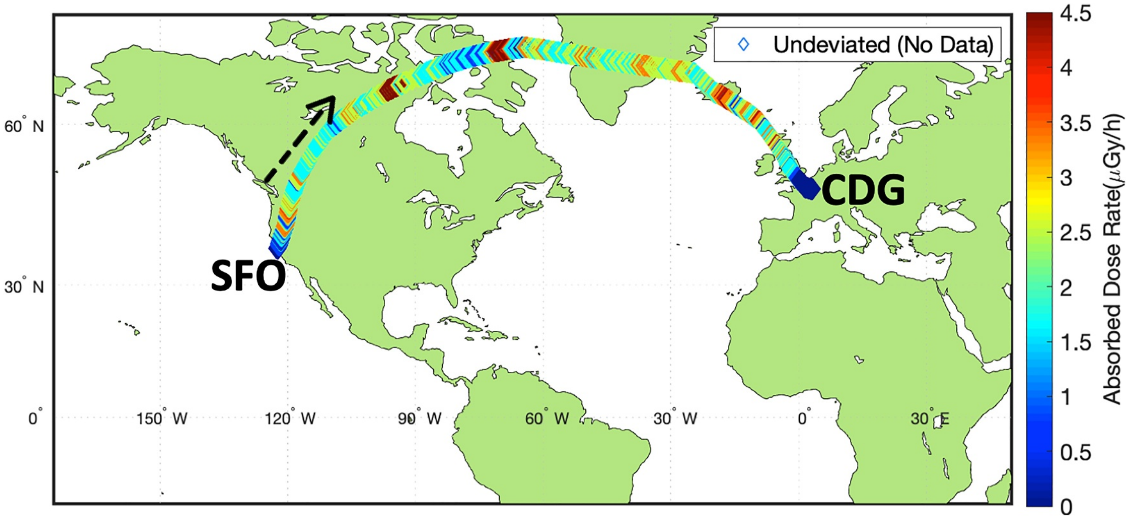

Figure 4. The ARMAS measurements recorded onboard an undeviated commercial United Airlines flight from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 7 June 2019 during relatively quiet geomagnetic conditions.

plasmaspheric hiss wave power (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023). Multiparameter plasmaspheric hiss wave power models (Aryan et al., 2021) are then applied to scale the hiss wave power from the quiet conditions of 7 June 2019 to the extreme conditions of 10 May 2024. Through this method, we estimated the radiation exposure profile along the undeviated Air France flight path under the heightened space weather conditions of the 10 May 2024 geomagnetic storm.

Figure 6a shows the absorbed radiation dose rate measurements (circular symbols) recorded by the ARMAS instrument onboard the United Airlines flight and the estimated absorbed radiation dose rates (diamond symbols) for the undeviated Air France flight from San Francisco to Paris on 10 May 2024. Figure 6b shows the altitude profile of the deviated United Airlines flight and Air France flight from SFO to CDG projected on a polar azimuthal map to highlight the altered flight path. The results show that the crew and passengers onboard the undeviated Air France route would have experienced more than three times the absorbed dose rate throughout most of the flight. This suggests that flights operating at higher latitudes, such as the Air France route, can be subject to significantly higher radiation levels. As a result, there is an increased risk of radiation exposure for flight crew and passengers especially during periods of heightened space weather activity, reinforcing the need for careful route planning to mitigate these risks.

However, adjusting flight routes can lead to significant additional costs for airlines. Figure 6b shows the total distances traveled by the deviated United Airlines flight (circular symbols) compared to the undeviated Air France flight (diamond symbols) on 10 May 2024. The United Airlines flight took a longer route of 10,134 km, almost 1,000 km more than the Air France flight path, which covered 9,192 km. The extra distance traveled by the United Airlines is approximately equivalent to flying from Denver to Chicago or flying from London to Munich, thus incurring significant additional fuel and operational expenses.

Furthermore, recent research has demonstrated a significant correlation between plasmaspheric hiss waves in the inner magnetosphere and increased radiation levels at aviation altitudes (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023). These studies suggest that plasmaspheric hiss waves play a critical role in the enhancement of radiation that affects aircraft crews and passengers. Therefore, we searched for possible conjunctions between the ARMAS instrument onboard the United Airlines flight and satellites within the inner magnetosphere with plasmaspheric hiss wave measurement capabilities. We found that there was a close conjunction between THEMIS-A and the ARMAS instrument onboard the United Airlines flight. During this period, both THEMIS-A and the ARMAS instrument were positioned on the dayside of the Earth and located within 1L (L-Shell) of each other providing a good opportunity for coordinated observations.

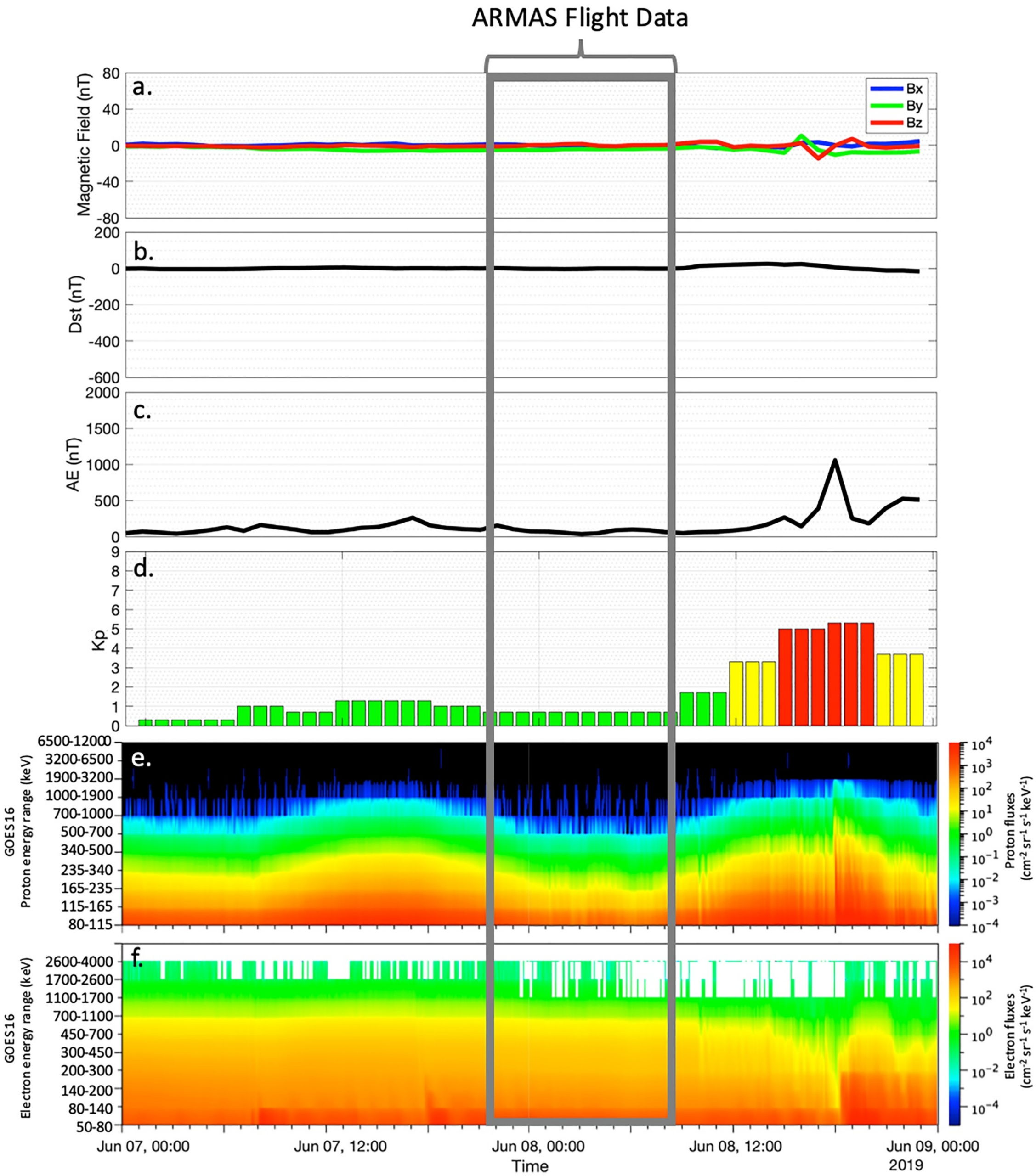

Figure 5. The magnetic field and geomagnetic indices recorded from June 7 to 8 June 2019. (a) Solar wind magnetic field components, (b) The Dst index, (c) AE index, and (d) Kp index. Panels (e) and (f) show the time-averaged differential proton and electron fluxes from GOES-16 spacecraft respectively. The gray box highlights the flight duration of the undeviated commercial United Airlines from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 7 June 2019.

Figure 7 presents the in situ measurements from the THEMIS-A satellite recorded between 18:00 and 00:00 UT on 10 May 2024 during the main phase of the geomagnetic storm, including (Figure 7a), the magnetic field (Figure 7b), the filter bank (FBK) spectrogram (Figure 7c), the electron spectrometer analyzer (ESA), and (Figure 7d) the Solid State Telescope (SST) measurements. The magnetic field measurements indicate that the THEMIS-A satellite is passing through its perigee as shown in Figure 7a. During this outbound trajectory, THEMIS-A experiences a close conjunction with the ARMAS instrument onboard the United Airlines flight between 22:10 and 22:30 UT (highlighted with black box). During this time, THEMIS-A detects the presence of plasmaspheric hiss waves that are of significantly higher intensity compared to the previous orbit, as shown in

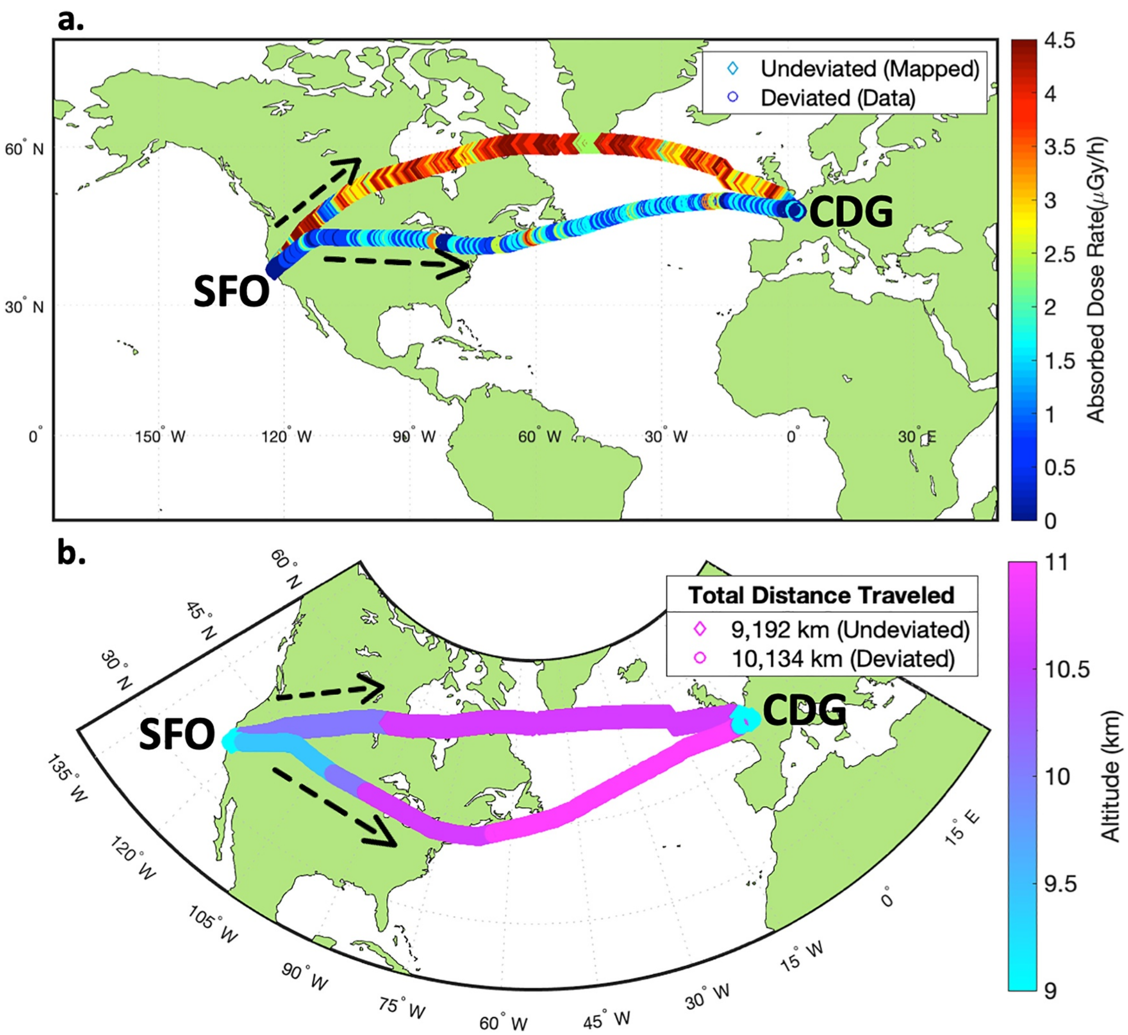

Figure 6. The ARMAS measurements recorded onboard a deviated commercial United Airlines flight (UAL990) from San Francisco (SFO) to Paris Charles de Gaulle (CDG) on 10 May 2024 during the extreme May 2024 geomagnetic storm. Panel (a) shows the absorbed radiation dose rate measurements (circular symbols) recorded by the ARMAS instrument onboard the United Airlines flight and the estimated absorbed radiation dose rate for the undeviated Air France flight (square symbols) from San Francisco to Paris on 10 May 2024 for comparison. Panel (b) shows the altitude profiles of both flights from SFO to CDG.

Figure 7b, consistent with previous results (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023).

The data collected from the electron spectrometer analyzer (ESA) reveal an intensification of the energetic particle fluxes shown in Figure 7c. This broad energy range indicates that THEMIS-A encountered a significant population of energetic electrons during its transit. Conversely, the data from the Solid State Telescope (SST) suggest that there are elevated fluxes of low-energy electrons whereas the detection of high-energy electrons remains relatively low consistent with a plasma-sheet injection. This contrasting distribution underscores the dynamic interactions within the magnetosphere during this geomagnetic event and highlights the varying energy profiles of the electron populations observed by THEMIS-A.

During this close conjunction, the ARMAS instrument was still at a low altitude and latitude onboard the deviated United Airlines flight, which was ascending to its cruise altitude. As a result, ARMAS did not initially record any enhanced radiation. However, once the flight reached its cruising altitude and entered the conjunction region, ARMAS measured radiation levels approximately 2.5 times higher than the background radiation levels as estimated by the NAIRAS model as shown in Figure 8b.

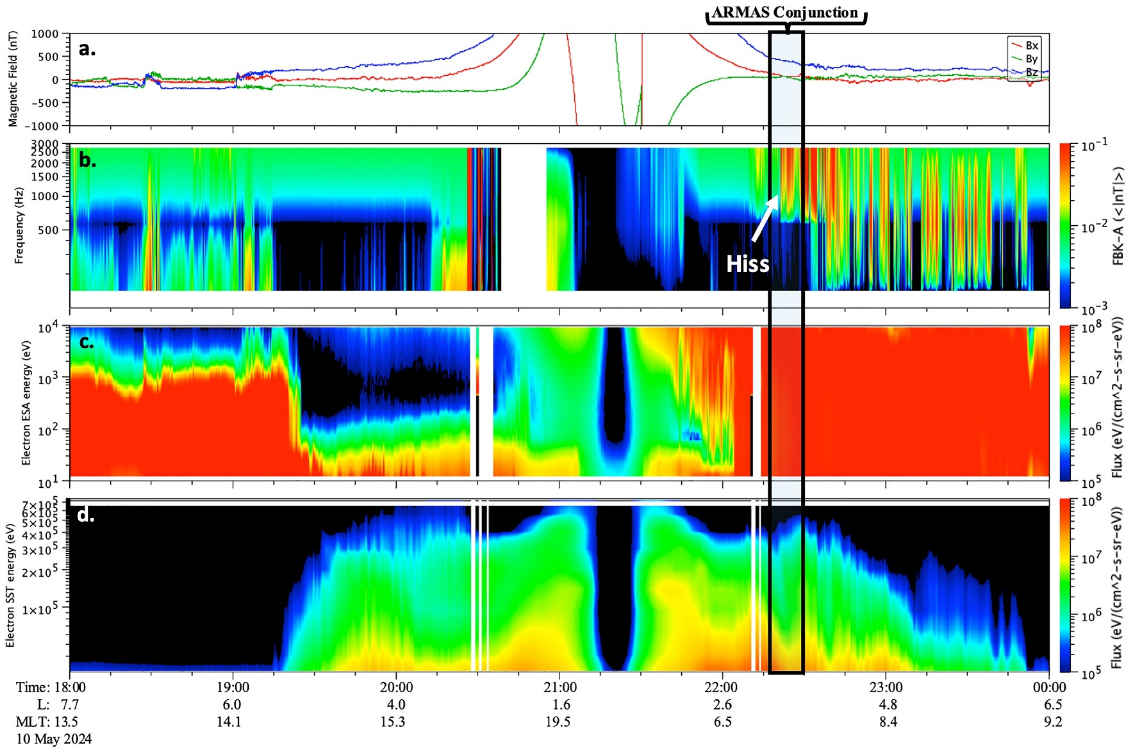

Figure 7. The in situ measurements from the THEMIS-A satellite recorded between 18:00 and 00:00 UT on 10 May 2024 during the main phase of the geomagnetic storm. (a) The magnetic field, (b) the filter bank (FBK) spectrogram, (c) the electron spectrometer analyzer (ESA), and (d) the Solid State Telescope (SST) measurements, respectively. The ARMAS-THEMIS conjunction period is highlighted in the black box, showing an enhancement of hiss wave power during the close conjunction window.

However, this event did not feature a perfect conjunction between ARMAS and THEMIS-A, as there was no exact overlap in L-shell and MLT at the same time. THEMIS-A passed through the region about 1 hour before ARMAS. During that earlier time, the ARMAS instrument was still at low altitude and latitude on the ascending United Airlines flight and did not detect enhanced radiation. About an hour later, once the flight reached cruising altitude and entered the conjunction region, ARMAS recorded radiation levels approximately 2.5 times higher than the background levels estimated by the NAIRAS model as shown in Figure 8b (This assumes that the plasmaspheric hiss observed by THEMIS-A persisted with a short time delay, as supported by Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, and Hogan. (2025), Aryan, Bortnik, Tobiska, Mehta, Hogan, et al. (2025). Figure 8a shows a close up of the THEMIS FBK spectrogram observed during the ARMAS conjunction, highlighting the measured wave activity. The observations indicate a correlation between plasmaspheric hiss wave in the inner magnetosphere and enhanced radiation at aviation altitudes supporting recent studies that have shown a strong correlation between plasmaspheric hiss waves within the inner magnetosphere and enhanced radiation at aviation altitudes (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023) but not linked to any other wave mode. This suggests that not only GCRs and SEPs contribute to radiation levels at flight altitudes but also precipitating electrons from the Van Allen radiation belts.

4. Conclusions

The powerful geomagnetic storm of May 2024, triggered significant space weather disturbances, affecting various sectors including aviation. It demonstrated the severe impact space weather can have on aviation safety with substantial geomagnetic activity causing heightened radiation exposure at high latitudes and altitudes. We used the ARMAS measurements onboard a deviated commercial United Airlines flight traveling from San Francisco to Paris during the extreme geomagnetic storm to investigate how the crew and passengers could have experienced enhanced radiation and also estimated the radiation exposure for an alternative flight from San Francisco to Paris at around the same time that did not deviate for comparison.

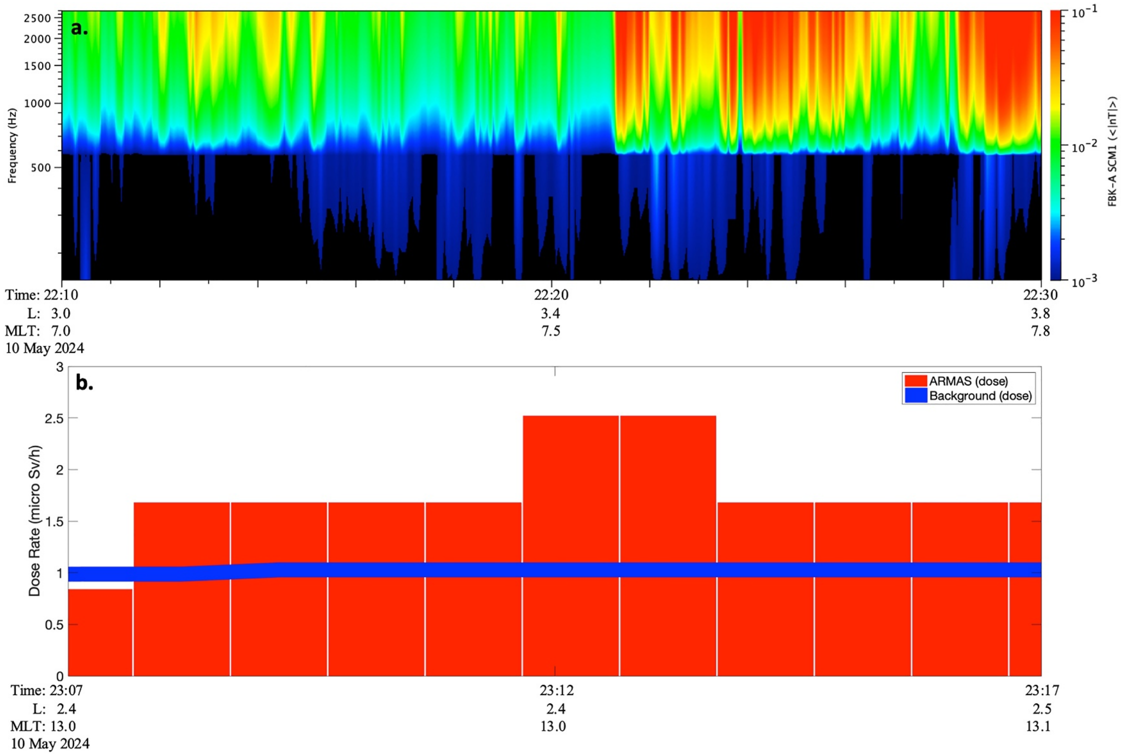

Figure 8. A close conjunction event between ARMAS and THEMIS-A satellite on 10 May 2024. (a) Plasmaspheric hiss waves observed by THEMIS-A in the inner equatorial magnetosphere. (b) The background absorbed dose rate (blue line) and the measured absorbed dose rate (red bars) by ARMAS onboard the deviated United Airlines flight from San Francisco to Paris.

United Airlines and Air France are known to have different mitigation strategies. The Air France approach aims to optimize protection by establishing a reference level of 6 mSv cumulative absorbed over a 12-month rolling period with a trigger threshold set at 4 mSv, after which adjustments to their duty roster may be made to limit further exposure, ensuring radiation doses remain within safe limits (Desmaris, 2016). On the other hand, during this event, United Airlines implemented a proactive strategy, choosing to deviate its flight to lower latitudes to reduce radiation exposure during individual periods of heightened space weather activity. Results show that the deviated United Airlines flight experienced significantly reduced radiation exposure by deviating to lower latitudes.

We also identified a close conjunction between THEMIS-A and ARMAS instrument onboard the United Airlines flight on 10 May 2024. The conjunction between the ARMAS instrument and NASA's THEMIS-A satellite provided further insights into the storm's impact. THEMIS-A detected plasmaspheric hiss waves in the inner magnetosphere during its pass. This supports a strong connection between these waves and increased radiation at aviation altitudes. The link is especially clear after the aircraft reached cruising altitude. These observations align with recent studies showing a strong correlation between hiss waves and radiation enhancements at flight altitudes (Aryan, Bortnik, Tobiska, Mehta, Hogan, et al., 2025; Aryan, Bortnik, Tobiska, Mehta, Siddalingappa, et al., 2025; Aryan et al., 2023). They also infer that current and future dosimetry tools should in addition to GCRs and SEPs also consider precipitating electrons in their dose rate calculations.

These observations highlight the critical role of monitoring space weather events to ensure the safety of airline passengers and crew especially during periods of increased geomagnetic activity. Flights operating at higher latitudes can be subject to significantly higher radiation levels. As a result, there is an increased risk of radiation exposure that may impact the health of flight crew and passengers especially during periods of heightened space weather activity. Airlines, such as United Airlines, respond to such events by adjusting flight paths and altitudes reducing radiation exposure risks for high-latitude flights during extreme solar storms. These adjustments follow from NOAA SWPC advisories that are mainly based on the proton fluxes measured by the GOES satellite. However, rerouting flights to avoid radiation hazards can result in substantial additional costs for airlines. These costs arise from increased fuel consumption, extended flight times, and potential disruptions to schedules, all of which can affect operational efficiency and profitability. The risk to airline crew and passengers must be carefully balanced against the additional costs and potential losses incurred by flight operators.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The geomagnetic index (AE) is freely available from NASA's GSFC online space physics data facility, OMNIWeb (https://omniweb.gsfc.nasa.gov/form/omni_min.html). NASAs GOES data are free available at https://www.ncei.noaa.gov/products/goes-r-space-environment-in-situ (https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes18/l2/data/mpsh-l2-avg1m_science/ and https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes16/l2/data/mpsh-l2-avg1m/). The airline flight data is available online at https://www.flightaware.com/. The ARMAS data is freely available from Space Environment Technologies ARMAS website at https://sol.spacenvironment.net/ARMAS_Archive/. THEMIS data is freely available online at https://themis-data.igpp.ucla.edu/.

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