Space Weather

RESEARCH ARTICLE

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Key Points:

- Pilots of long-haul flights in high latitude areas may be exposed to cosmic radiation doses higher than the European Union control standard
- Both cosmic radiation and fuel consumption are considered for tactical air traffic management
- A flexible altitude assignment approach can meet radiological protection regulations under accurate cosmic radiation forecasts

Supporting Information:

Supporting Information may be found in the online version of this article.

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An Optimized Solution to Long-Distance Flight Routes Under Extreme Cosmic Radiation

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Abstract During extraordinary space weather, cosmic radiation can be significant enough to pose a threat to aircrew health. Traditional methods of reducing massive cosmic radiation exposure include flight cancellation, lowering flying altitudes, and flight rerouting. However, flight cancellation can result in additional financial expenditures, while lowering flight altitudes and rerouting can consequently cause more fuel consumption or even violation of airspace rights. As a result, we use a multi-objective optimization model to assign optimal flight altitude and speed to reduce the overall weighted sum of cosmic radiation and fuel consumption. The simulation scenario is based on a space weather event with dramatically increased cosmic radiation that occurs during a routine international flight from Tokyo to London. Our results show that the proposed model can reduce fuel consumption while satisfying cosmic radiation limits recommended by the Council of the European Union if the forecasts of cosmic radiation are sufficiently accurate. In addition, a Pareto frontier is provided as a tactical air traffic management guideline. Our study provides insight into future policymaking for air transportation during harsh space weather conditions.

Plain Language Summary Cosmic radiation is made up of high-energy protons and atomic nuclei from the Sun and distant galaxies. The radiation intensity at airplane cruising altitudes and high latitudes is higher, due to reduced protection from Earth's atmosphere and magnetic field, than that at low altitude and low latitude regions. Therefore, aircrews receive more radiation considering their long-term exposure at high altitudes. The radiation level may increase significantly during severe space weather events. Traditionally airlines may cancel flights, reroute flights, or lower flight altitudes to mitigate radiation. However, these traditional methods have drawbacks like greater financial expenditures and fuel consumption and are sometimes even infeasible from air traffic management standpoint. To control the exposure to cosmic radiation and reduce fuel consumption while keeping normal aircraft operation, we propose a multi-objective optimization model to assign flight altitudes and speeds along a multi-segment route. The modeling is applied to an international flight from Tokyo to London assuming a space weather event similar to the one on 20 January 2005 occurs. We demonstrate that the proposed flight routes can successfully minimize fuel consumption while satisfying cosmic radiation limit standards. This can be a valuable example for air traffic management when dealing with space weather effects.

1. Introduction

Humans are exposed to a variety of radiation sources with an estimated annual total effective radiation dose of 2.4 mSv per capita, including inhalation (primarily radon) (1.26 mSv), ingestion of food and water (0.29 mSv), cosmic rays (0.39 mSv), and terrestrial radiation (0.48 mSv) (World Health Organization, 2011). According to the International Commission on Radiological Protection (ICRP), for every 1 Sv increase in effective radiation exposure, the cancer risk increases by 1.65% (Ma et al., 2013). The booming aviation sector in the last decade pays attention to cosmic radiation, which is mainly made up of ionizing particles from Galactic Cosmic Radiation (GCR) and Solar Energetic Particles (SEP) (Sato et al., 2019). It is difficult to quantify exactly how cosmic radiation interacts with tissues and cells, but excessive aviation radiation exposure should be avoided considering the potential long-term consequences in terms of diseases and biological system effects (ICAO, 2012). A previous study has found that aircrew members have approximately twice the rate of melanoma as the general population, which could be attributable to in-flight exposure to UV rays and cosmic radiation (Sanlorenzo et al., 2015).

Table 1
The Total Effective Doses Along Specific Flight Routes Under Different Ground Level Enhancement Events

GLE peak increase rate	Date	Flight route	Total effective dose	Source
29.46%	14 July 2000	London-Los Angeles	24,000 μSv	Clucas et al. (2005)
	14 July 2000	London-New York	10,000 μSv	
57.02%	15 April 2001	London-Los Angeles	51,000 μSv	
	15 April 2001	London-New York	22,000 μSv	
173.80%	29 September 1989	Continuous 10-hr high-latitude flight at 12 km	570 μSv	Copeland et al. (2008)
269.57%	20 January 2005		390 μSv	
269.57%	20 January 2005	Frankfurt-Los Angeles	168 μSv	Matthiä et al. (2009)
		New York-Beijing	189 μSv	
29.46%	14 July 2000	London-New York	633 μSv	Anderson et al. (2014)
		Paris-San Jose	202 μSv	
5,117%	23 February 1956	New York-London	2,670 μSv	Copeland and Atwell (2019)

Note. The GLE peak increase rates are from the neutron monitors of the worldwide network (Firoz et al., 2010).

Limits on radiation dose are subject to regulations. The International Commission on Radiological Protection (ICRP), the Federal Aviation Administration (FAA), and the Council of the European Union (EU) recommend effective cosmic radiation dose limits for aircrew of 20 mSv/yr averaged over 5 years (a total of 100 mSv in 5 years) and 1 mSv/yr for the general public (Bagshaw, 2008). The ICRP recommends a dose limit of 1 mSv for radiation-related pregnant workers throughout their pregnancy (ICRP, 2016). The National Council on Radiation Protection and Measurements also recommends a monthly radiation limit of 0.5 mSv during pregnancy (NCRP, 2013). The cosmic radiation intensity is related to altitude, geomagnetic latitude, and solar activity (Yang & Sheu, 2020). Generally, people on the ground are protected against cosmic radiation because the Earth's atmosphere and magnetic field can shield the Earth's surface from cosmic radiation, with the protective effect being greatest at the equator at lower altitudes and weakest toward the poles at higher altitudes (Tuo et al., 2012).

Solar activity is a crucial contributor to the transitory elevation of cosmic radiation (Hapgood et al., 2021; Pesnell, 2012). On a calm space weather day (e.g., 15 March 2013), the total effective cosmic radiation doses along a transequatorial flight (Colombo-Jakarta), a transatlantic flight (Paris-New York), and a transpolar flight (Beijing-Chicago) are estimated to be 9.7, 60, and 82 μSv, respectively (Lochard et al., 2016). During extraordinary Solar Particle Events (SPE), SEP-caused cosmic radiation increases dramatically (Meier & Matthiä, 2014). Table 1 lists the total effective doses along specific flight routes on several severe space weather days, some of which exceeded the aforementioned dose limits (0.5 or 1 mSv) (Note that the estimated total effective doses for the same flight during the same SPE can be different, e.g., London-New York on 14 July 2000. This is because different cutoff rigidity thresholds are used in different studies. To be specific, the cosmic radiation dose rates decrease with the increase of the cut-off rigidity threshold.)

Large SPE is recognized as a severe hazard to aircrew and passengers in civil aviation (Kataoka, 2011; Tobiska et al., 2015). Thus the detection and alert of SPE are important. This work can be accomplished in two approaches: high-energy proton detectors on Geostationary Operational Environmental Satellites (GOES) or neutron monitors on the ground (Sato, 2020). Several systems have been developed to issue the SEP exposure alert at flight altitudes, such as Warning System for AVIation Exposure to Solar energetic particle (WASAVIES) (Sato et al., 2014), AVIation DOSimetry (AVIDOS) (Latocha et al., 2009), Nowcast of Aerospace Ionizing Radiation System (NAIRAS) (Mertens et al., 2013), National Tsing Hua University (NTHU) Flight Dose Calculator (Yang et al., 2019), and Civil Aviation Research Institute (CARI)-7A (Copeland, 2021), benefiting the commercial airline industry and other authorities to mitigate the exposure to a high level of cosmic radiation.

In response to SPE-caused high cosmic radiation alerts, airlines may lower flight altitudes or reroute flights to lower latitudes (Matthiä et al., 2015), which can result in increased fuel consumption and aircraft emissions (Fujita et al., 2021; Saito et al., 2021). Particularly, flight rerouting is sometimes constrained by air traffic management regulations. Therefore, airlines may inevitably cancel flights, which can cause additional financial costs (Taylor et al., 2021; Yamashiki et al., 2020) and disrupt passenger itineraries (Hu et al., 2021). To the best of our

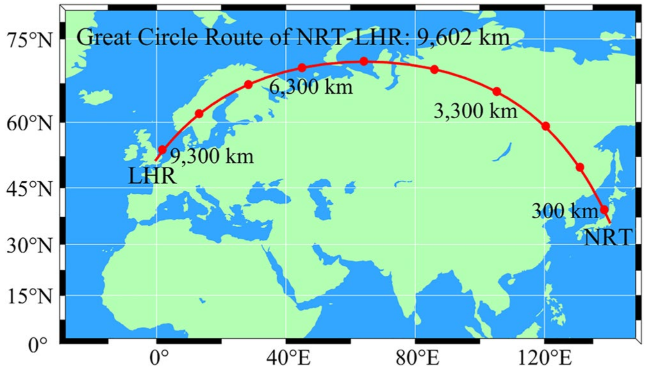

Figure 1. The great circle route from Tokyo Narita Airport (35.765°N, 140.386°E) to London Heathrow Airport (51.477°N, 0.461°W). The cruise phase distance is 9,000 km, and the rest of 600 km is for climbing and descending phases.

knowledge, the cosmic radiation threshold for any given flight trip has not been established. Considering these issues, we first analyze the cosmic radiation of one flight trip of a European airline during a space weather event. We then propose a multi-objective optimization model based on Mixed-Integer Linear Programming (MILP) to assign the optimal flight altitudes and speed with the objective of minimizing fuel consumption and cosmic radiation. In addition, the Pareto frontier is provided as a guideline for tactical Air Traffic Management (ATM) based on various preferences and intentions. Some policy recommendations for European airlines concerning cosmic radiation limits are proposed, which can also serve as an operation reference for other airlines.

2. Cosmic Radiation Levels for European Airlines

Cosmic radiation is more severe in Europe due to weaker shielding of the magnetic field in higher latitude regions than in the lower latitude regions. Considering aircrew health, the EU recommends a cosmic radiation control level C^* of 6 mSv/yr for aircrew (Bagshaw, 2008; Thierfeldt et al., 2009). Aviation radiation exposure is also related to the total flight time, and it is estimated that the average annual flight time $\mathcal{D}$ for airline pilots is ∼700 hr (Flying Staff, 2022). Based on WASAVIES or NAIRAS models, the cosmic radiation rates r in Europe during quiet space weather days can be ∼8 μSv/hr. Therefore, the cosmic radiation dose limit for one flight trip during the elevated cosmic radiation period is estimated to be $C_{\max} = C^* - \mathcal{D}r = 6{,}000\ \mu\text{Sv} - 8\ \mu\text{Sv/hr} \times 700\ \text{hr} = 400\ \mu\text{Sv}$. That is to say if the anticipated cosmic radiation dose of one flight trip exceeds $C_{\max} = 400\ \mu\text{Sv}$, the flight should be canceled. We believe the policy recommendations can serve as a criterion for airline decision-makers to assure financial profit meanwhile without jeopardizing aircrew health by not exceeding the cosmic radiation exposure threshold.

This investigation would greatly benefit the airline industry by protecting airlines from exceeding EU radiation protection standards when extreme space events occur. Aircrew scheduling is a critical and challenging task for airlines (Quesnel et al., 2020), as aircrew cost is the second-largest component of an airline's total operating cost, just after fuel consumption cost (Wen et al., 2022). If the aircrew is expected to experience massive cosmic radiation for a particular flight route, airlines will have to take certain actions to reschedule flight plans, and sometimes it may disrupt the whole aircrew scheduling. This hinders airlines to maintain profitability in the furiously competitive market (Lopes et al., 2016; O'Connell et al., 2020).

3. Scenario Background and Models

Our work is to investigate the effect of cosmic radiation under a space weather event on air transport and propose a multi-objective optimization model to minimize both radiation dose exposure to aircrew and fuel consumption. The flight information is introduced in Section 3.1. The cosmic radiation model and the fuel consumption model are described in Sections 3.2 and 3.3, respectively. The multi-objective optimization model is presented in Section 3.4.

3.1. Flight Information

A long-distance international flight from Tokyo Narita Airport (NRT) to London Heathrow Airport (LHR) is selected as the case study subject. The historical flight data (https://opensky-network.org/) indicate that: (a) the aircraft type is B787-900; (b) enroute time is ∼12.5 hr with a cruising speed of 460 kt; (c) the most representative flight altitude is 12,200 m (40,100 ft); and (d) the great circle route is assumed to represent the actual flight route with a distance of about 9,600 km (Figure 1). We assume the climbing and descending segments are each 300 km and thus set the cruising distance to be 9,000 km and divide it into nine flight segments with 1,000 km for each segment. For example, the first flight segment ($i = 1$) is 300–1,300 km from NRT, and the ninth flight segment ($i = 9$) is 8,300–9,300 km from NRT. Most of the flight route is in high latitude regions and therefore is susceptible to high level of cosmic radiation.

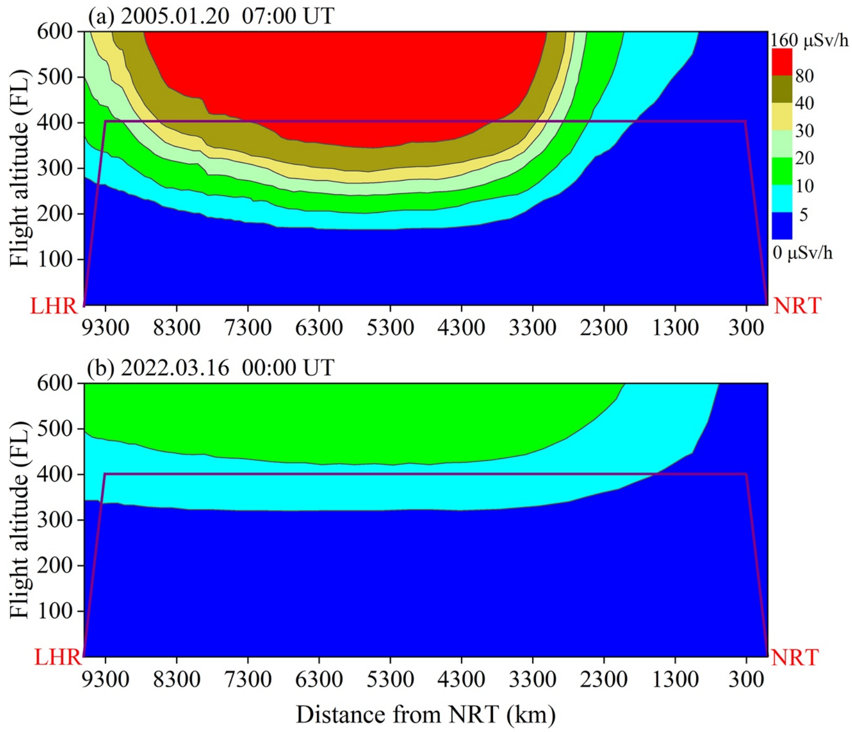

Figure 2. Warning System for AVIation Exposure to Solar energetic particle simulation results of radiation dose rate along the Tokyo Narita Airport-London Heathrow Airport (NRT-LHR) flight route on a severe space weather day like 20 January 2005 and a quiet space weather day (16 March 2022). Purple lines outline the schematic diagram of the flight profile from NRT to LHR with the cruising altitude at 401 FL.

3.2. Cosmic Radiation Model

The SPE on 20 January 2005 was one of the largest GLE events ever recorded in the neutron monitors of the worldwide network since 1956 (Plainaki et al., 2007; Saito et al., 2021). During this event, the effects of the radiation exposure at altitudes of 12 km were estimated to be ~1.8 mSv/hr during 06:50–06:55 UTC in the Antarctic region and about 0.1 mSv/hr at a latitude of 70° in the Northern Hemisphere during 07:10–07:15 UTC (Matthiä et al., 2009; Mishev et al., 2015). WASAVIES is a physics-based forecast model that computes global cosmic radiation dose rates at different altitudes (Kataoka et al., 2014, 2018; Sato et al., 2018). We use their modeling results (https://wasavies.nict.go.jp/about.html) to provide cosmic radiation information along NRT-LHR during this strong space weather event when a remarkable increase in cosmic radiation rate is obtained in the simulation (Figure 2a). For comparison, the radiation is significantly lower during a quiet space weather day on 16 March 2022 (Figure 2b). Constrained by flight altitude regulation (ICAO, 2016), six flight altitudes from 301 to 401 FL (1 FL = 100 ft) with a vertical separation of 20 FL are considered and are indexed by $j = 1, 2, \ldots, 6$. For example, $j = 1$ indicates 301 FL and $j = 6$ indicates 401 FL. Based on WASAVIES simulation results, cosmic radiation rates c_{ij} in flight segment i at flight altitude j are shown in Table 2. If aircraft flies as usual at the altitude of 401 FL without any response to the increased cosmic radiation on 20 January 2005, the total effective cosmic radiation dose would be over 700 μSv assuming that the global effective dose rate distribution in Figure 2a lasted over the entire flight time. Consequently, the radiation dose for this flight journey will exceed the $C_{\max} = 400$ μSv threshold.

3.3. Fuel Consumption Model

According to the Base of Aircraft Data (BADA) (EUROCONTROL, 2022), the nominal fuel flow f_{ij} (kg/min) in flight segment i at flight altitude j is related to true airspeed (TAS) $\boldsymbol{v}_{ij}$ and the standard air density ρ_{ij}. For detailed information, please see Appendix A. The results of f_{ij} in different altitudes are shown in Figure S1 in Supporting Information S1. The wind speed $\boldsymbol{w}_{ij}$ in flight segment i at flight altitude j (Figure S2 in Supporting Information S1) also plays an important role in flight time and consequently affects fuel consumption. The ground

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Table 2
Warning System for AVIation Exposure to Solar Energetic Particle Simulation Results of Average Effective Radiation Dose Rate (μSv/hr) Along the Tokyo Narita Airport-London Heathrow Airport Flight Route at Different Flight Levels

		Flight segment								
Flight level		$i = 9$	$i = 8$	$i = 7$	$i = 6$	$i = 5$	$i = 4$	$i = 3$	$i = 2$	$i = 1$
401	$j = 6$	33.8	60	118	120	120	84	22.1	4.5	2.5
381	$j = 5$	25	60	96	120	120	72	20.3	4	2.5
361	$j = 4$	21.7	52	78	120	108	56	15	3.5	2.5
341	$j = 3$	19	39	60	60	60	49	13.3	3	2.5
321	$j = 2$	14.8	28	50	60	60	40	10.4	2.5	2.5
301	$j = 1$	12	21	32	52	35	27	9.5	2.5	2.5

speed $\boldsymbol{g}_{ij}$ vector can be expressed as $\boldsymbol{g}_{ij} = \boldsymbol{w}_{ij} + \boldsymbol{v}_{ij}$. Therefore, the ground speed (km/hr) can be expressed by $g_{ij} = |\boldsymbol{w}_{ij} + \boldsymbol{v}_{ij}|$. For a given flight route of distance L (km), the fuel consumption F_{ij} (kg) in flight segment i at flight altitude j can be expressed as:

$$F_{ij} = 60 \cdot f_{ij} \cdot \frac{L}{g_{ij}} \tag{1}$$

3.4. Multi-Objective Optimization Model

We use a multi-objective optimization model based on Mixed-Integer Linear Programming (MILP) to quantify the optimal values for both flight altitude j and true airspeed v_{ij}. This optimization is performed based on the following assumptions. First, we use the WASAVIES simulation results to specify the distribution of the global effective dose rates. Then we assume that distribution does not change during the whole flight time, which is similar to the study in (Saito et al., 2021). Second, we ignore the impact of altitude-changing phases between 301 and 401 FL on final results since these two phases (i.e., climbing from 300 to 400 FL and descending from 400 to 300 FL) contribute less than 1% to the total effective radiation doses and fuel consumption. Our modeling is to minimize the objective function (2) of the total weighted radiation dose and fuel consumption.

$$z = \sum_{i\in I}\sum_{j\in J}\sum_{v\in V_j} x_{ijv}\left(\alpha\frac{\delta C_{ijv}}{C_r} + \beta\frac{F_{ijv}}{F_r}\right) \tag{2}$$

where $I = 9$ is the total number of flight segments indexed by i; $J = 6$ is the total number of feasible flight altitudes indexed by j; V_j is the feasible TAS at flight altitude j constrained by the flight envelope; x_{ijv} is a binary decision variable; α and β are the weights of radiation dose and fuel consumption, respectively; δ represents the error in the global cosmic radiation calculation, defined as the ratio of the True cosmic radiation to the Forecast cosmic radiation (RTF); C_{ijv} is the WASAVIES simulated cosmic radiation dose in flight segment i at flight altitude j with TAS v_{ij}; F_{ijv} is the corresponding fuel consumption; $C_r = 100$ μSv is the referential cosmic radiation dose from NRT to LHR; $F_r = 60$ tons is the referential fuel consumption from NRT to LHR. The detailed flowchart of the proposed model is illustrated in Figure 3.

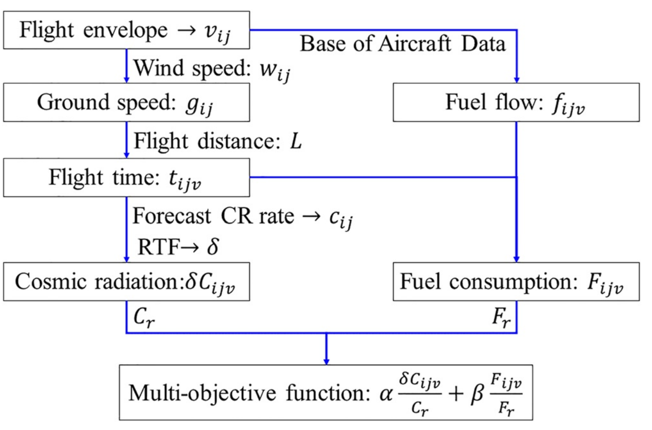

Figure 3. Multi-objective optimization model flowchart. Considering the specific true airspeed v_{ij}, and wind speed w_{ij}, and flight distance L, we can obtain flight time $t_{ijv} = L/g_{ij}$. Then the cosmic radiation dose C_{ijv} in flight section i at flight altitude j can be calculated by $C_{ijv} = \delta c_{ij} t_{ijv}$ based on the Warning System for AVIation Exposure to Solar energetic particle simulated cosmic radiation rate c_{ij} and Forecast cosmic radiation δ. The fuel consumption F_{ijv} in flight segment i at flight altitude j can be calculated by $F_{ijv} = f_{ijv} t_{ijv}$, where the fuel flow f_{ijv} is based on Base of Aircraft Data.

The constraints are listed as follows:

$$\alpha + \beta = 1 \text{ with } 0 \le \alpha \le 1 \text{ and } 0 \le \beta \le 1 \tag{3}$$

$$\sum_{j\in J}\sum_{v\in V_j} x_{ijv} = 1, \forall i \in I \tag{4}$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{v\in V_j} \delta x_{ijv} C_{ijv} \le C_{\max} \tag{5}$$

Table 3
Results of Fuel Consumption and Cosmic Radiation Dose in Two Traditional Solutions: Lowering Flight Altitudes Versus Rerouting

			Cosmic radiation dose (μSv)				
Methods	Flight level	Fuel consumption (ton)	$\delta = 0.8$	$\delta = 0.9$	$\delta = 1.0$	$\delta = 1.1$	$\delta = 1.2$
Lowering flight altitudes	401	61	579	652	724	796	869
	381	62	531	598	664	730	797
	361	64	469	527	586	645	703
	341	66	319	359	399	439	479
	321	68	278	312	347	382	416
	301	70	199	224	249	274	299
Rerouting	401	89	47	53	59	65	71

$$\sum_{i \in I} \sum_{j \in J} \sum_{v \in V_j} x_{ijv} F_{ijv} \leq F_{\max} \tag{6}$$

$$x_{ijv} \in \{0, 1\} \tag{7}$$

Constraint (3) defines the cosmic radiation weight α and fuel consumption weight β. Constraint (4) states that each flight segment i should be assigned only one flight altitude j with only one TAS (v_{ij}). Constraint (5) indicates that the total cosmic radiation dose cannot exceed $C_{\max} = 400$ μSv according to Section 2. Constraint (6) indicates that the total fuel consumption cannot exceed $F_{\max} = 90$ tons based on aircraft fuel tank capacity. Constraint (7) indicates that if a TAS v_{ij} is set for flight segment i and flight altitude j, $x_{ijv} = 1$, otherwise, $x_{ijv} = 0$.

4. Results

4.1. Traditional Solutions

The following two solutions are intuitive, which are also discussed in Saito et al. (2021).

1. Lower flight altitude while maintaining the same flight route and speed as the original flight plan. The new flight altitudes for the test are 301, 321, 341, 361, and 381 FL. Considering different δ, the final results of cosmic radiation dose and fuel consumption are summarized in Table 3. The calculated cosmic radiation dose with $\delta = 1.0$ is less than $C_{\max}$ only when the flight altitude decreases to 341 FL or below. However, fuel consumption is 66 tons at 341 FL or more at lower altitudes.
2. Reroute while maintaining the same flight altitude and speed as the original flight plan. Referring to the rerouting method proposed for theoretical analysis in (Saito et al., 2021), Figure 4 outlines the new flight route: first from NRT (35.765°N, 140.386°E) to T (35.765°N, 0.461°W) along the same latitude, and then from T (35.765°N, 0.461°W) to LHR (51.477°N, 0.461°W) along the same longitude. The cosmic radiation rates can be estimated using Figure 4 and RTF δ. In the first segment, the distance from NRT to T is $2\pi r \times \cos(35.765°) \times (0.461° + 140.386°)/360° = 12{,}708$ km, where r is the mean radius of the Earth, equal to 6,371 km. Accordingly, the flight time from NRT to T is 12,708 km/(460 × 1.852 km/hr) = 14.91 hr. The cosmic radiation is 3δ μSv/hr × 14.91 hr = 44.76δ μSv. In the second segment, the distance from T to LHR is $2\pi r \times (51.477° - 35.765°)/360° = 1{,}747$ km. The flight time from T to LHR is 1,747 km/(460 × 1.852 km/hr) = 2.05 hr. The cosmic radiation is about 3δ μSv/hr × 2.05 hr × 2/3 + 15δ μSv/hr × 2.05 hr × 1/3 = 14.35δ μSv. Thus, the total cosmic radiation is 59δ μSv, and the total fuel consumption is (14.91 + 2.05 hr) × 60 min/hr × f = 89 tons, where $f = 87.66$ kg/min is the nominal fuel flow at 401 FL at a cruising speed of 460 kt. Therefore, it can be concluded that rerouting can reduce the cosmic radiation dose to 59δ μSv, unlikely to exceed $C_{\max} = 400$ μSv; but it will increase fuel consumption by about 50%, nearly approaching the maximum fuel tank capacity (90 tons), and also produce more aircraft emissions. In practice, Air Navigation Service Providers (ANSPs) can assist with flight rerouting in reaction to such space weather events. However, airlines may also decide not to accept the re-designed flight route based on considerations such as flight duration, aircraft and crew allocation, and additional crew expenses (Britto et al., 2012).

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Table 4
Results of Cosmic Radiation and Fuel Consumption Under Various Weighting Values α in the Case of Different Forecast Cosmic Radiation δ

	$\delta = 0.8$		$\delta = 0.9$		$\delta = 1.0$		$\delta = 1.1$		$\delta = 1.2$	
α	CR	FC	CR	FC	CR	FC	CR	FC	CR	FC
0	399.9	60.3	399.9	61.1	399.9	62.0	399.9	62.9	399.8	63.6
0.01	399.9	60.3	399.9	61.1	399.9	62.0	399.8	62.9	399.8	63.6
0.02	399.9	60.3	399.5	61.1	399.9	62.0	397.9	62.9	398.8	63.6
0.03	393.6	60.4	398.3	61.1	399.9	62.0	391.3	63.0	393.2	63.7
0.04	332.2	61.6	373.7	61.6	323.7	63.8	355.6	63.8	365.9	64.3
0.05	259.0	63.8	289.5	63.8	303.5	64.4	331.5	64.4	321.0	65.7
0.06	244.0	64.3	271.2	64.4	266.9	65.7	292.1	65.8	315.6	65.9
0.07	240.2	64.5	239.0	65.8	264.1	65.8	286.9	66.0	310.8	66.1
0.08	212.5	65.8	234.7	66.0	260.8	66.0	281.8	66.3	302.3	66.5
0.09	208.6	66.0	233.6	66.1	254.0	66.4	276.4	66.5	298.9	66.7
0.1	207.6	66.1	228.5	66.4	251.2	66.5	272.5	66.8	295.0	66.9
0.2	176.2	69.5	196.5	69.8	216.2	70.1	235.4	70.4	255.4	70.7
0.3	168.6	71.1	189.4	71.1	210.1	71.2	230.1	71.4	250.4	71.6
0.4	166.9	71.6	187.3	71.8	207.5	72.0	228.2	72.0	248.7	72.1
0.5	165.8	72.1	184.9	73.0	205.3	73.1	225.6	73.2	245.6	73.6
0.6	163.9	73.3	184.4	73.4	204.8	73.4	225.2	73.5	245.4	73.8
0.7	163.7	73.6	184.1	73.7	204.5	73.7	225.0	73.7	245.2	74.0
0.8	163.5	74.0	183.9	74.0	204.4	74.0	224.8	74.0	245.2	74.0
0.9	163.5	74.0	183.9	74.0	204.4	74.0	224.8	74.0	245.2	74.0
1	163.5	74.0	183.9	74.0	204.4	74.0	224.8	74.0	245.2	74.0

4.2. Optimized Solutions

In the objective function, α and β are the weights of cosmic radiation and fuel consumption, respectively. As airlines may have different preferences about cosmic radiation and fuel consumption, dispatchers will assign various weights to these two parameters. Sensitivity analysis is conducted to provide dispatchers with sensible decisions about flight planning. Taking the cosmic radiation forecast error into consideration, Table 4 lists the detailed results of cosmic radiation and fuel consumption under various weighting values α. For a given α, the fuel consumption increases with the increased δ, because aircraft have to fly at lower altitudes to satisfy the constraint of total cosmic radiation dose. As the accuracy of forecast models will be determined more precisely, airlines may set a more sensible value of δ.

Taking $\delta = 1.0$ (accurate forecast) as an example, Figure 5 illustrates the assigned optimal flight altitudes in the case of $C_{\max} = 400$ μSv and $F_{\max} = 90$ tons. An obvious trend is that the optimal flight altitudes decrease with the increased α, especially for flight segments $i = 5, 6, 7$ due to these segments in high latitude with considerable cosmic radiation rates (Figure 2a). According to the B789 flight envelope, the feasible TAS at various flight altitudes j may range from $400 + (j - 1) \times 10$ kt to $550 + (j - 1) \times 10$ kt. The speeds are assigned in discrete increment of 10 kt to reduce the calculation time of the proposed model, which is reasonable and practical in air traffic management. Thus, the number of available TAS at each flight level is 16. Figure 6 shows the optimal assigned TAS v_{ij} in each flight segment under various α. When α is in a lower range, that is, when the target function emphasizes more on fuel savings, the aircraft will fly at higher altitudes (Figure 5) at fuel-saving speeds (Figure S1 in Supporting Information S1). Consequently, the assigned speeds vary greatly when $\alpha = 0$–0.03. When α is more than 0.2, the priority is to minimize cosmic radiation. Thus, aircraft would fly at greater speeds at lower altitudes. Specifically, the assigned speed at 301 FL is 550 kt.

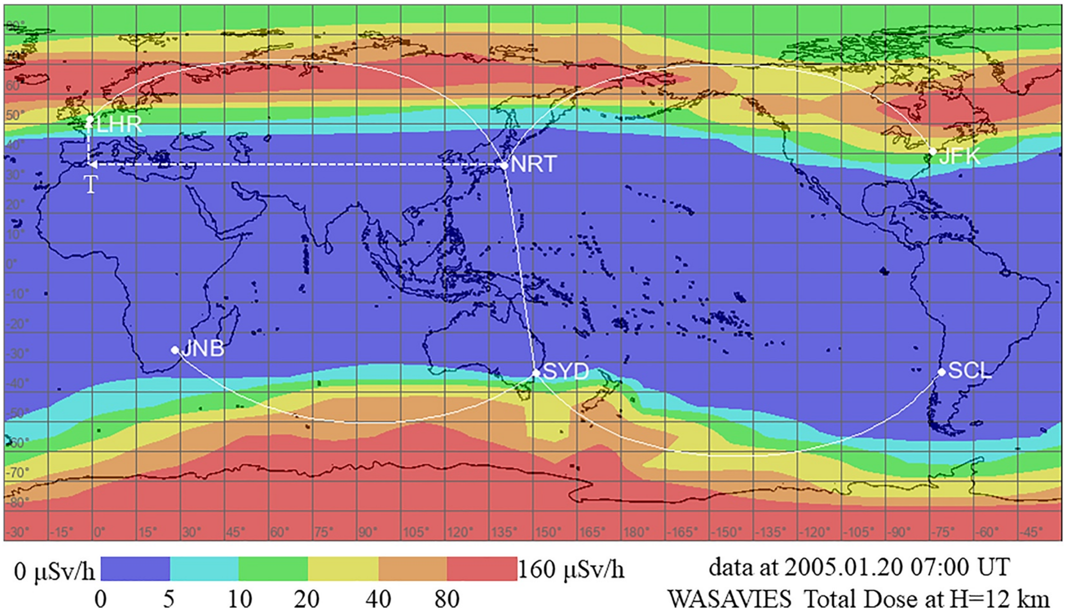

Figure 4. Worldwide map of calculated dose rate during GLE69 (07:00 UT, 20 January 2005) drawn using Warning System for AVIation Exposure to Solar energetic particle (https://wasavies.nict.go.jp/about_e.html).

The Pareto frontier for the cosmic radiation dose versus fuel consumption is presented in Figure 7. In multi-objective optimization, the Pareto frontier is the set of all Pareto efficient solutions. Therefore, the selection of the optimal solution is dependent on the criteria of the decision-makers. Rather than evaluate the whole range of every parameter, decision-makers just need to make tradeoffs within this set. To the best of our knowledge, airlines have not yet implemented multi-objective optimization that considers both fuel consumption and cosmic radiation. Specifically, dispatchers do not make tactical flight plans for fuel consumption and cosmic

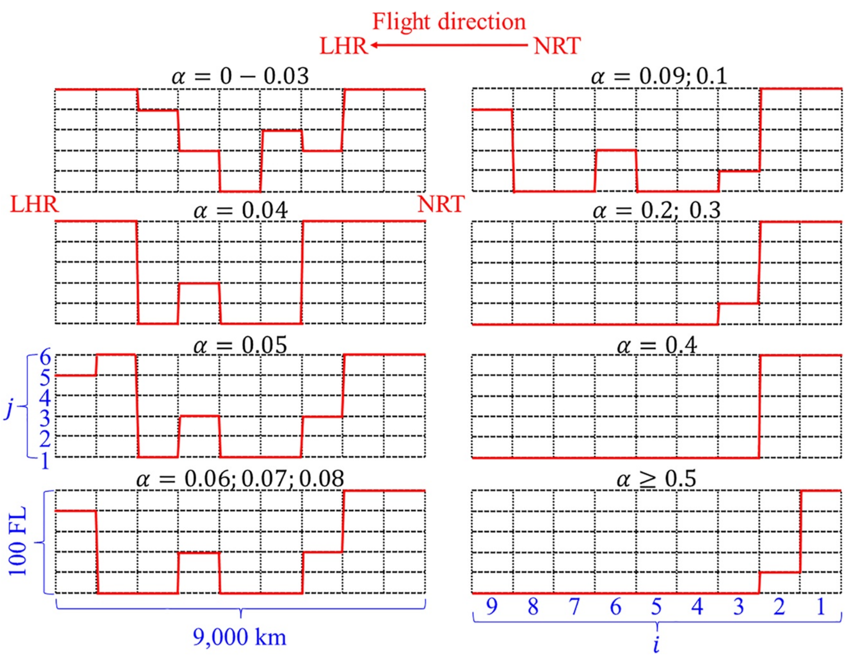

Figure 5. The optimal flight altitude assignment in each flight segment under different weights assigned to radiation dose. The flight direction is from Tokyo Narita Airport to London Heathrow Airport with a cruising distance of 9,000 km, labeled by i. The range of the change of flight altitudes is 100 FL, labeled by j.

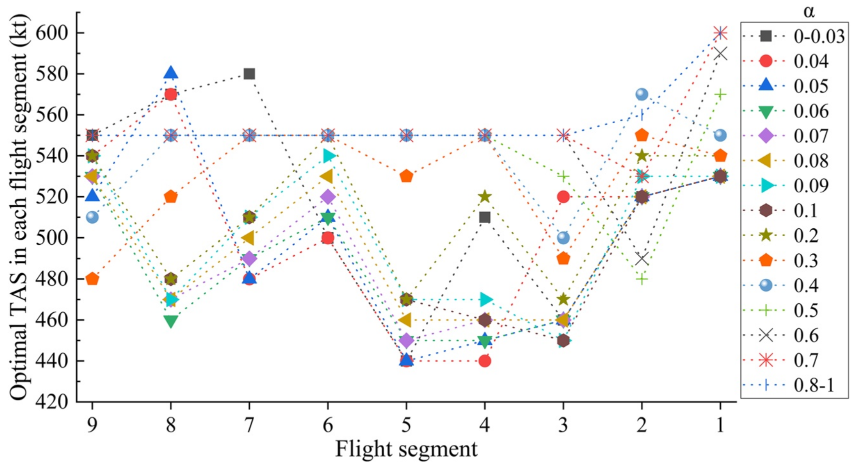

Figure 6. The optimal true airspeed v_{ij} in each flight segment under various weighting values α assigned to cosmic radiation.

radiation from quantitative perspectives. There may be various preferences among airlines regarding fuel usage and aviation radiation exposure. Consequently, we believe that the Pareto frontier may help airlines make timely and efficient decisions based on their unique operational conditions.

The extreme points at $\alpha = 0$ and $\alpha = 1$ correspond to only considering fuel consumption and only considering cosmic radiation dose, respectively. The cosmic radiation dose decreases from 399.96 to 204.37 μSv with α increasing from 0 to 1. In contrast, fuel consumption shows an opposite trend, increasing from 67.78 to 74.01 tons, which indicates that $F_{\max}$ ranging from 75 to 90 tons does not affect the final optimal solutions. We divide the weights of cosmic radiation dose into three classes, that is, lower α (0–0.05), medium α (0.06–0.1), and higher α (0.2–1). Compared to the results at $\alpha = 0$, the cosmic radiation dose at $\alpha = 0.05$ decreases by 24.1%, and fuel consumption increases only by 3.8%. When α increases from 0.2 to 1, fuel consumption increases from 70.1 to 74.0 tons, while cosmic radiation doses only decrease from 216.2 to 204.4 μSv.

Supposing that the aircraft just lowers flight altitude to 341 FL in response to high cosmic radiation, fuel consumption is 66 tons and cosmic radiation dose is 399 μSv. Obviously, the optimized results under $\alpha = 0$–0.08 in Figure 7 can reduce both cosmic radiation and fuel consumption. Specifically, the fuel consumption under $\alpha = 0$–0.03 is only 62 tons, reducing fuel by 4 tons. The cosmic radiation under $\alpha = 0.08$ is 261 μSv, which is only 65.4% of 399 μSv. If the aircraft lower flight altitude to 321 FL, fuel consumption is 68 tons and cosmic radiation dose is 347 μSv, which is inferior to the optimized results under $\alpha = 0.04$–0.1. Similarly, if aircraft lower flight altitude to 301 FL, fuel consumption is 70 tons and cosmic radiation dose is 249 μSv, while the optimized result under $\alpha = 0.15$ is 68 tons and 233 μSv. These positive outcomes validate the value of our work.

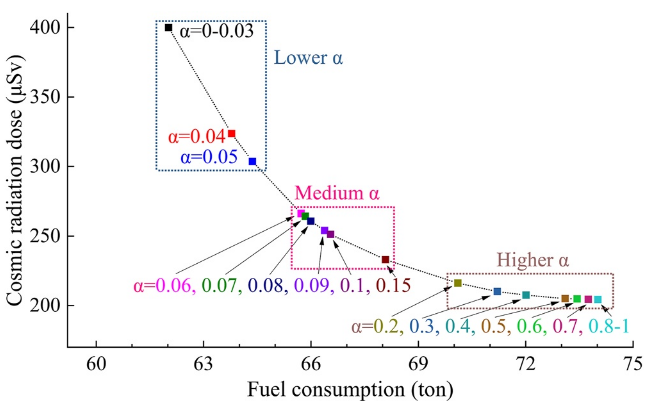

Figure 7. Pareto frontier for the cosmic radiation dose versus fuel consumption. The optimized solutions are mainly classified into three classes, that is, lower α, medium α, and higher α.

4.3. Economic Benefits

Assuming a 250-seat B789 aircraft with an occupancy of 80%, there will be 200 passengers. According to www.google.com/travel/flights, the airfare for a one-way direct flight from Tokyo to London in August 2022 is about $2,000 for economy class, which means the total ticket price is $400,000. The B789 flight cancellation cost is $82,730, of which $42,740 is allocated to passenger care and compensation (EUROCONTROL, 2020). As space weather is classified as an exceptional occurrence, airlines are not compelled to compensate passengers (U.S. Department of Transportation, 2022). Therefore, the cancellation cost is about $0.44 million (400,000 + 82,730 − 42,740). If the flight plan is executed, the fuel cost is about $85,425 ($1,139/ton × 75 tons) (IATA, 2022). Accordingly, the economic benefit for airlines might be up to $0.44 million − $85,425 = $0.35 million compared to flight cancellations. In addition, flight cancellations can change passenger itineraries and the incurred costs are considerable. Compared to lowering flight altitudes to

341 FL, the optimized solutions can save fuel at least 4 tons, resulting in a saving of \$4,556. Compared to rerouting, the economic benefit (\$1,139/ton × (89–62) tons = \$30,753, where 89 tons is from Table 3 and 62 tons is from Table 4) is more substantial.

5. Discussion and Conclusions

According to average pilot working hours, background cosmic radiation, and regulations of the European Union, we set $C_{\max} = 400\,\mu$Sv as the upper threshold of cosmic radiation dose per flight in our case study. Under this threshold, the optimal flight profiles and true airspeed can be obtained by using the proposed multi-objective optimization approach. The basis of scenario generation is mainly based on cosmic radiation forecast models such as WASAVIES and NAIRAS. As a result, the final objective function relies heavily on forecast accuracy. In tactical air traffic management, the forecast lead time is equally crucial. Furthermore, air-ground communications can also be problematic in high-latitude regions during strong space weather events (Kubo et al., 2015), which is especially prevalent for polar flights (Shea & Smart, 2012). Although the issue of communication failure is not considered in this study, it is still important when choosing an alternative flight route.

The assigned flight profiles show that aircraft need to change flight altitude several times during long-distance travel, which may cause passenger discomfort (Bagshaw & Illig, 2019; Muhm et al., 2007), increase the workload of pilots and air traffic controllers ATC, and affect flight safety (Bongo & Seva, 2022). However, please note that the distance of each flight segment is 1,000 km, which is equivalent to the distance of typical flight routes such as Beijing-Shanghai, London-Madrid, or Atlanta-Houston. That is to say, the discomfort is not significant.

During space weather, cosmic radiation rises dramatically and poses a threat to aircrew health. To reduce the massive aviation radiation exposure, traditionally airlines may cancel flights, lower flight altitudes, or reroute flights, which can cause increased fuel consumption and financial costs. After investigating a long-distance flight during an extreme cosmic radiation event using the multi-objective optimization approach, our study suggests that: (a) traditional solutions may either violate the radiological protection recommendations or be uneconomical; (b) a multi-segment flying profile with varying flight altitudes and speed can protect the aircrew and passengers from radiation at a safe radiation dose level and simultaneously have an economically acceptable fuel consumption; (c) the economic benefits of the proposed method may range from \$4,556 to \$0.35 million; (d) the economic benefits will increase with improved accuracy of cosmic radiation forecasts.

Appendix A

The nominal fuel flow f_{ij} (kg/min) for B787-900 in flight segment i at flight altitude j is defined as a function of thrust specific fuel consumption η_{ij} (kg/(min·kN)) and engine thrust T_{ij} (N).

$$f_{ij} = \frac{\eta_{ij} \cdot T_{ij}}{1000} \tag{A1}$$

where η_{ij} is related to the thrust-specific fuel consumption coefficients $C_{f_1} = 0.5466$, $C_{f_2} = 1198.1$, and the true airspeed (TAS) v_{ij} (km/h).

$$\eta_{ij} = C_{f_1}\left(1 + \frac{v_{ij}}{1.852 \cdot C_{f_2}}\right) \tag{A2}$$

During the cruise phase, the thrust is assumed to be equal to the drag force D_{ij} (N) in A3, and the drag force can be calculated using formulas A4–A6.

$$T_{ij} = D_{ij} \tag{A3}$$

$$D_{ij} = \frac{1}{2} C_{D.ij} \cdot \rho_{ij} \cdot \left(\frac{v_{ij}}{3.6}\right)^2 \cdot S \tag{A4}$$

$$C_{D.ij} = C_{D_0.CR} + C_{D_2.CR} \cdot (C_{L.ij})^2 \tag{A5}$$

$$C_{L.ij} = \frac{2 \cdot m \cdot g_0}{\rho_{ij} \cdot v_{ij}^2 \cdot S \cdot \cos\theta} \tag{A6}$$

where $C_{D.ij}$ is the standard drag coefficient; ρ_{ij} is the standard air density (kg/m^3); $S = 360.5$ m^2 is the wing reference area (m^2); $C_{D_0.CR} = 0.021871$ and $C_{D_2.CR} = 0.034141$ are drag coefficients; $C_{L.ij}$ is the lift coefficient, which is related to the aircraft mass ($m = 213{,}220$ kg) and bank angle $\theta = 0°$.

Data Availability Statement

The authors thank GLE database for neutron monitor count rates during GLE caused by solar energetic particles https://gle.oulu.fi/#/; B787-900 flight data from Tokyo to London https://zenodo.org/record/7309430#.Y2yOonZBxdg; National Centers for Environmental Prediction (NCEP) for wind data https://rda.ucar.edu/datasets/ds083.2/index.html#sfol-fw?g=22022; Base of Aircraft Data from EUROCONTROL https://www.eurocontrol.int/model/bada; and WASAVIES for cosmic radiation rate data https://wasavies.nict.go.jp/about.html.

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