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Key Points:

- Effects of satellite navigation failure caused by space weather in 2025 on aviation network operation in the Greater Bay Area are simulated
- Air traffic management methods are proposed to address the demand-capacity imbalance problems caused by satellite navigation failure
- Economic costs of flight cancellations and delays are calculated considering aviation network effects

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Forward-Looking Study of Solar Maximum Impact in 2025: Effects of Satellite Navigation Failure on Aviation Network Operation in the Greater Bay Area, China

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Abstract Satellite navigation based on the Global Navigation Satellite System can provide aircraft with more precise guidance and increase flight efficiency. However, severe space weather events can cause satellite navigation failure due to the dramatic increase in total electron content and irregularities in the ionosphere. Consequently, ground navigation has to be used to replace satellite navigation, increasing aircraft separation standards and reducing airspace capacity. As a result, numerous flights may be delayed or even canceled, incurring significant financial losses. The occurrence peak of space weather events generally coincides with the 11-year-cycle solar maximum, and 2025 is expected to be the upcoming solar maximum. The Greater Bay Area (GBA), located in the equatorial ionization anomaly region of China, is particularly vulnerable to space weather impacts. To explore the effects of satellite navigation failure on flight operation, we conduct this looking-forward study and propose solution methods from the standpoint of Air Traffic Management, by simulating satellite navigation failure scenarios. Based on the projected flight volume in 2025 related to the GBA airports, simulation results show that the economic costs can be tens of millions of Euros, which is dependent on the duration of satellite navigation failure and the time interval of ground navigation-based landing. We believe that this study can be a benchmark for evaluating the potential economic effects of forthcoming space weather on flight operations.

Plain Language Summary Space weather events have the potential to disrupt satellite navigation systems due to heightened total electron content and ionospheric irregularities, subsequently decreasing flight efficiency and causing substantial economic loss. Notably, space weather events often align with the solar maximum within the 11-year solar cycle, with the upcoming peak anticipated in 2025. The Greater Bay Area (GBA) is situated in the equatorial ionization anomaly region and is particularly susceptible to space weather effects. With that in mind, we explore the potential effects of satellite navigation failure in 2025 from the perspective of aviation network operation and propose constructive Air Traffic Management solutions. Drawing from a series of essential simulations and underlying assumptions, the potential economic costs related to flight cancellations and flight delays caused by satellite navigation failure within the GBA could amount to tens of millions of Euros. We hope this study can be a foundational benchmark for assessing the potential economic effects of forthcoming space weather events.

1. Introduction

The concept of Communication, Navigation, Surveillance for Air Traffic Management (CNS/ATM) has been proposed to meet the increasing flight demand (Osunwusi, 2020; Vismari & Junior, 2011), taking advantage of the Global Navigation Satellite System (GNSS) and other automation technologies. Satellite navigation system plays an important role in Air Traffic Management (ATM) by providing accurate and reliable positioning, navigation, and timing information (Morton et al., 2021). With satellite navigation, the separation distance standards between aircraft can be reduced, and aircraft can fly closer, enhancing flight efficiency and reducing fuel consumption based on the Area Navigation (RNAV) capability (Enge et al., 2015). RNAV is a method of navigation that permits aircraft operation on any desired flight path instead of the point-to-point paths defined by ground-based navigation aids (López-Lago et al., 2020). Additionally, satellite navigation can also assist aircraft to descend continuously toward landing airports and adjust their speeds to synchronize with other arrival flights (Xue, Hsu, et al., 2021).

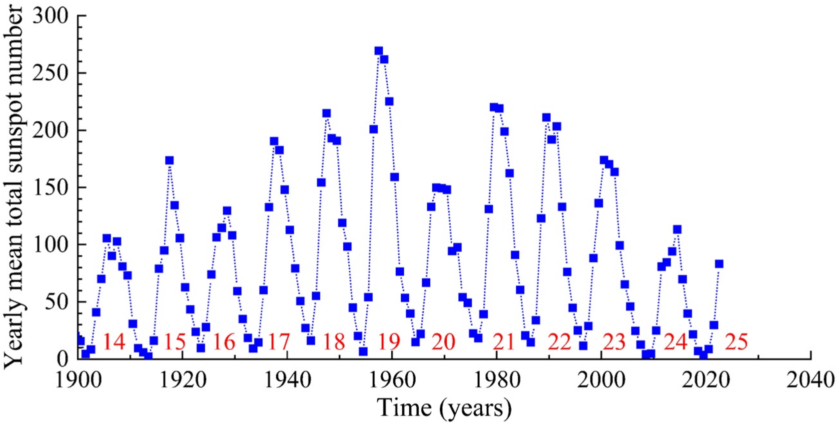

Figure 1. The yearly mean total sunspot number denoted by blue squares and the Solar Cycle numbers indexed from 14 to 25 since 1900. Data source: Sunspot Index and Long-term Solar Observations (SILSO) (https://www.sidc.be/silso/datafiles#total).

However, one of the important factors that greatly affect satellite navigation performance is space weather events, which are generally in the forms of solar flares (Hudson, 2011; Svestka, 2012), Coronal Mass Ejections (CME) (Manchester IV et al., 2004; Webb & Howard, 2012), and Solar Energetic Particles (SEP) (Marqué et al., 2006; Shea & Smart, 2012). Space weather can result in irregularities and an increase in the Total Electron Content (TEC) of the ionosphere (Buzulukova & Tsurutani, 2022), degrading satellite navigation performance significantly or even causing satellite navigation outages (Berdermann et al., 2018; Horne et al., 2013; Kintner et al., 2007). Coster and Yizengaw (2021) have classified the effects as follows: First, the presence of large gradients in ionospheric electron density can lead to significant errors in the range and bending of signals (Hoque & Jakowski, 2011; Sherif et al., 2023). Second, even minor irregularities at a small scale within the ionosphere can cause fluctuations in GNSS signals (also known as scintillation) or even result in the loss of the clock in GNSS signals (David et al., 2023; Liu et al., 2023). Lastly, solar radio bursts can noticeably impact GNSS signals by elevating the level of background noise (Cerruti et al., 2008; Sato et al., 2019).

Generally, satellite navigation performance can be severely degraded in the presence of space weather, jeopardizing the safety of satellite navigation-based flights. When satellite navigation services are unable to meet aircraft operational requirements, ground navigation systems, such as Very High-Frequency Omnidirectional Range (VOR), Distance Measuring Equipment (DME), and Non-Directional Beacon (NDB), would have to be employed (Jakšić & Janić, 2020). This may result in a significant reduction of airspace capacity and cause an imbalance problem between flight demand and airport capacity (Ball & Lulli, 2004; Sandamali et al., 2021). As a result, certain flights will need to be rescheduled or even canceled to address this imbalance. To the best of our knowledge, only a few studies have evaluated the effects of space weather on aviation by systematically considering space weather, satellite navigation, and ATM together. In previous studies, Xue, Yang, and Liu (2022) simulated satellite navigation failure durations and explored the effects on flights on flight cancellations, flight delays (ground delays and airborne delays), and flight diversions. Analyzing the effects of the Halloween storm event in 2003 on the top 50 busiest airports in the Continental United States, Xue et al. (2023) estimated the economic costs caused by failures of Area Navigation and Continuous Descent Approach (CDA).

Solar activity has shown an 11-year cycle (Luhmann et al., 2022; Swiger et al., 2022). The annual mean total sunspot number since 1900 is illustrated in Figure 1. 2025 is expected to be the upcoming solar maximum in Solar Cycle 25 (Hapgood et al., 2022). It is predicted that the maximum sunspot number will be 122.1 (±18.2) in January 2025 (±6 months) (Okoh et al., 2018). The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is located in the Equatorial Ionization Anomaly region (Lin et al., 2007), and five airports with huge flight volumes are located in the GBA region. Hence, it can be expected that flights related to these five airports may be prone to the effects of space weather in 2025. Considering the increasing flight demand and the popularity of satellite-based flight operations in the GBA region, space weather-caused air traffic disruption has become a new challenging problem. Existing forecasts and space weather information provided to the aviation industry are still not sufficient. In addition, it is necessary to combine space weather information with aviation operations and

Figure 2. Case study area and the locations of the five airports in the GBA region, that is, VHHH (22.31°N 113.91°E), VMMC (22.15°N 113.59°E), ZGGG (23.39°N 113.30°E), ZGSD (22.01°N 113.38°E), ZGSZ (22.64°N 113.81°E).

accurately estimate its real impact on the aviation industry in the real world (Saito et al., 2021). To be specific, how the aviation industry should react to different space weather advisories has not been well established. With this in mind, we propose air traffic management methods based on space weather advisory to address the problems caused by satellite navigation failure. Besides, we explore the forward-looking effects of satellite navigation failure on aviation network operation in the GBA region and estimate economic costs caused by flight cancellations and ground delays from the standpoint of airlines and passengers. We believe that this study can be a benchmark for evaluating the potential effects of forthcoming space weather on air traffic management.

2. Data Simulation and ATM Method

Our study aims to investigate the forward-looking effects of satellite navigation failure, caused by space weather in 2025, on the aviation network operations in the GBA region. Thus, the projected flight data in 2025 is simulated according to the flight volume prediction in Section 2.1. In response to the effects of satellite navigation failure on flight operation, the ATM method based on the space weather advisory is proposed in Section 2.2.

2.1. Flight Data Simulation

The GBA region is a city cluster consisting of nine cities and two special administrative regions (Hong Kong and Macao) in South China. With its strategic location, booming industries, and rich cultural heritage, the GBA has become a significant player in global commerce and tourism. The airports are key transportation hubs that connect the GBA with the rest of the world, playing a vital role in economic growth and cultural exchange. Figure 2 shows the five major airports in the GBA: Hong Kong International Airport (VHHH), Macao International Airport (VMMC), Guangzhou International Airport (ZGGG), Shenzhen International Airport (ZGSZ), and Zhuhai Airport (ZGSD).

Though flight volumes are still recovering from the demand drop caused by the COVID-19 pandemic (Sun et al., 2022; Xue, Liu, et al., 2021), it is expected that flight volumes in the Asia Pacific in 2025 will account for 109% of the total in 2019 (IATA, 2023). Therefore, in this study, the historical flight data of 2019 were adopted as a reference to simulate the flight data of 2025. However, it is important to acknowledge that there are seasonal variations in space weather conditions (Chen et al., 2021; Tsiftsi & De la Luz, 2018) and air travel demand (Dobruszkes et al., 2022; Wang et al., 2023). The detailed results are illustrated in Figure 3. Overall, the flight volumes at VHHH, ZGGG, and ZGSZ are higher than those at the other two airports.

The principle of simulating the landing time of each flight is described as follows. The number of hourly arrival flights is N. If $N \leq 30$, the arrival time interval is $\Delta t = \lfloor 60/N \rfloor$ min and the landing time of flight n ($n \in N$) is

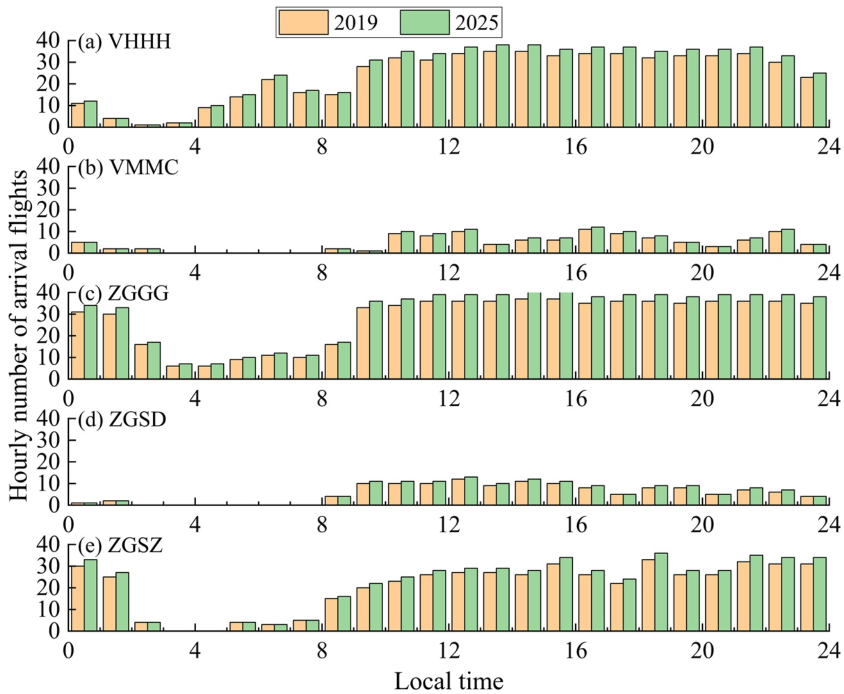

Figure 3. Historical flight data in 2019 and projected flight data in 2025 at the five airports in the GBA region, (a) VHHH, (b) VMMC, (c) ZGGG, (d) ZGSD, and (e) ZGSZ.

$\Delta t(n-1)$ (in the unit of minutes). If $30 < N \leq 40$, the arrival time interval is 1.5 min (ICAO, 2021) and the landing time of flight n is $1.5(n-1)$ (in the unit of minutes).

2.2. ATM Method

To mitigate the effects of space weather on aviation, four Space Weather Centers (SWXCs) have been designated to jointly provide space weather advisories to the aviation industry (Hapgood, 2022). These four SWXCs are (a) the Pan-European Consortium for Aviation Space Weather User Services (PECASUS) including Finland, Belgium, the United Kingdom, Austria, Germany, Italy, Netherlands, Poland, Cyprus, and South Africa; (b) China-Russia Consortium (CRC); (c) NOAA Space Weather Prediction Center (SWPC), and (d) the Consortium of Australia, Canada, France, and Japan (ACFJ). Each SWXC is on duty every 2 weeks, and the other centers serve as backups (Aleshin et al., 2021). The format of the advisory can refer to the ICAO Manual on Space Weather Information in Support of International Air Navigation (ICAO Doc 10100) (ICAO, 2018). Based on the solar dynamics observatory, these SWXCs focus on three significant space weather effect areas, that is, HF Communications (HF COM), GNSS-based navigation and surveillance (GNSS), and radiation effects on avionics and human health (RAD). A fourth effect area (Satellite Communication, SATCOM) has been identified, but advisories for SATCOM will not be published until more work is conducted to create and confirm operationally applicable advisory limits for this impact area. Two intensity criteria, that is, Moderate (MOD) and Severe (SEV), are issued in advisories. As an example, Table 1 shows the space weather advisory for the effect of space weather on GNSS. The forecast indicates that the GNSS-based operations within the high latitudes of the Northern Hemisphere (HNH) from W015° to E015° will not be available for the subsequent 6, 12, 18, and 24 hr.

On the condition that a certain airport $\mathcal{A}$ is forecast to experience satellite navigation failure within a duration of $\mathcal{D}$ from $\mathcal{T}_s$ to $\mathcal{T}_e$, ground navigation will work solely as a backup in $\mathcal{D}$. As flight safety is the priority in civil aviation, the most conservative reaction to satellite navigation failure is to increase the aircraft separation minima (Cai et al., 2023). Consequently, scheduled arrival flight demand may exceed the reduced airspace capacity, causing a demand-capacity imbalance problem. In such a situation, the Ground Delay Program (GDP) is generally adopted to manage the arrival flight flows (Ozgur & Cavcar, 2014), which can transfer the costly and dangerous airborne delays to cheap and safe ground delays. Under the Collaborative Decision Making (CDM) initiative, the

Table 1
An Example of Space Weather Advisory for GNSS

DTG:	20221107/1058Z
SWXC:	PECASUS
ADVISORY NR:	2022/56
SWX EFFECT:	GNSS SEV
OBS SWX:	07/1042Z HNH W015-E015
FCST SWX +6 HR:	07/1700 NOT AVBL
FCST SWX +12 HR:	07/2300 NOT AVBL
FCST SWX +18 HR:	08/0500 NOT AVBL
FCST SWX +24 HR:	08/1100 NOT AVBL
RMK:	Space weather event (ionospheric disturbance) in progress. Impact on GNSS performance possibly leads to loss of GNSS signals and degradation of timing and positioning performance.
NXT ADVISORY	Will be issued by 20221107/1642Z =

Ration-by-Schedule (RBS) method is used to generate available arrival time slots for each GDP flight. From the standpoint of fairness across different airlines, the arrival time for each flight is assigned in the ascending order of their original time of arrival (OTA) (Vossen & Ball, 2006), that is, flights are prioritized according to their scheduled arrival time.

It is easy to understand that the arrival flights, which are scheduled to land before time $\mathcal{T}_s$ at the airport $\mathcal{A}$, can rely on satellite navigation with the arrival time interval of Δt_S. The arrival flights with the OTA after $\mathcal{T}_S$ are denoted as $f_1, \ldots, f_n$. For each flight f_i, let d_i and a_i be the Original Time of Departure (OTD) and the OTA, respectively. According to the ground navigation-based arrival time interval Δt_G, the available landing times in $\mathcal{D}$ can be generated, denoted as: $T_G = \{\mathcal{T}_s, \mathcal{T}_s + \Delta t_G, \ldots, \mathcal{T}_s + m\Delta t_G\}$, where $\mathcal{T}_S + n\Delta t_G \leq \mathcal{T}_e$.

After $\mathcal{T}_e$, the arrival time intervals recover to Δt_S, and the available landing times are denoted as $T_s = \{\mathcal{T}_e, \mathcal{T}_e + \Delta t_S, \ldots, \mathcal{T}_e + n\Delta t_S\}$. When the GDP is implemented, the Controlled Time of Departure (CTD) and Controlled Time of Arrival (CTA), denoted as d_i' and a_i' ($a_i' \in \{T_G \cup T_S\}, a_i' \geq a_i$), respectively, are assigned to f_i. Assuming that the enroute flight time L_i is deterministic and known, the CTD can be calculated by $d_i' = a_i' - L_i$, and thus the assigned ground delay time is $g_i = d_i' - d_i$. If the ground delay g_i for the flight f_i is less than a specific delay threshold (e.g., 100 minutes), this flight may accept the ground delay time, labeled by $x_i = 1$, otherwise, this flight will be canceled, labeled by $x_i = 0$, and the associated arrival time slot can then be used by other flights based on the compression algorithm (Manley & Sherry, 2010). Therefore, the number of canceled flights is calculated as $N_c = \sum(1 - x_i)$, and the total ground delay time $D_t = \sum x_i g_i$. The schematic diagram of the GDP method is shown in Figure 4. The GDP begins at $\mathcal{T}_s$, and the first four flights have ground delays of 0, Δt_G–Δt_S, 2(Δt_G–Δt_S), and 3(Δt_G–Δt_S), with a total delay of 6(Δt_G–Δt_S), where Δt_S is set to be 1.5 min based on (ICAO, 2021).

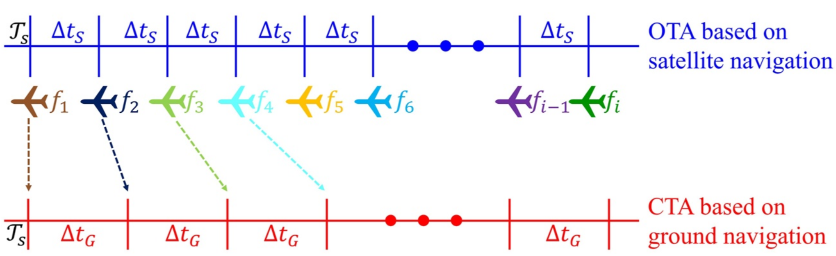

Figure 4. Schematic diagram of the switch from satellite navigation to ground navigation. The minimum arrival time interval based on satellite navigation is Δt_S, and the minimum arrival time interval based on ground navigation is Δt_G.

Table 2
Description of Simulated Scenarios

Scenario	Satellite navigation failure time	Ground navigation-based arrival time interval
S1	12–16 LT	3 min
S2	12–16 LT	5 min
S3	10–18 LT	3 min
S4	10–18 LT	5 min
S5	08–20 LT	3 min
S6	08–20 LT	5 min

3. Result Analysis

This section aims to explore the effects of satellite navigation failure on aviation network operation and also estimates the corresponding economic costs. As the severity levels of the forthcoming weather events in 2025 are unknown, three severity levels with different durations of satellite navigation failure, that is, 12–16 LT, 10–18 LT, and 08–20 LT, are simulated. It should be noted that the arrival time interval based on ground navigation, that is, Δt_G, is determined by various factors, including ground navigation procedures, air traffic control considerations, and other operational factors. Thus, to carry out a comprehensive study, Δt_G is set to a value of 3 min or 5 min based on the Air Traffic Control (ATC) experience. The simulated scenarios are listed in Table 2.

3.1. Flight Plan Adjustment

In the event of satellite navigation failure, pilots have to rely on ground-based aids such as VOR, NDB, and DME for navigation. However, these aids have limitations in terms of coverage, accuracy, and availability, resulting in longer approach procedures and more fuel consumption. Besides, pilots need to communicate more frequently with air traffic control to obtain navigation assistance, and updates on navigation aids, or to coordinate alternative procedures. This increased communication can also add workload for pilots and ATC personnel. In this study, we only focus on the effects of satellite navigation failure on flight plan adjustment, that is, flight rescheduling and flight cancellations. According to Figure 3, the number of hourly arrival flights at VMMC and ZGSD will not exceed 12 in 2025, so it can be expected that these two airports may not experience severe flight disruptions due to satellite navigation failure.

In contrast, the effects of satellite navigation failure on the other three larger and busier airports are more pronounced compared to those on VMMC and ZGSD. Figure 5 shows the results of the CTA of each flight based on the proposed ATM method at different airports in various scenarios. It is obvious that the lengths of recovery time of these three airports are different despite the same simulated scenarios. This is because of the difference in flight volumes and the distribution of planned arrival times at the three airports. Specifically, the recovery time of ZGGG is the longest, and the recovery time of ZGSZ is the shortest. For a certain airport, the length of recovery time increases with the duration of satellite navigation failure. Moreover, when considering a specific airport like VHHH, the original arrival times are represented by black circles marked with “O.” The deviation in arrival times at VHHH between various scenarios and the baseline “O” on the *y*-axis indicates the delay time for each flight. Therefore, the total flight delays for all flights landing at VHHH in S1 can be calculated based on the difference values between the red circles and the black circles.

Additionally, Figure 6 shows the number of canceled flights at different airports in various scenarios. Overall, VHHH is expected to have the most flight cancellations, followed by ZGGG and ZGSZ. In the case of the same airport and the same duration of satellite navigation failure, a longer arrival time interval (5 min) can cause more flight cancellations than shorter arrival time interval (3 min). This implies that advanced facilities in communications, navigation, and surveillance for ATM systems are critically important. Furthermore, the specific effects on flight scheduling will depend on the duration of the satellite navigation failure and the availability of alternative navigation methods and solutions.

3.2. Aviation Network Effect

Flight cancellations and delays can disrupt the connectivity of the aviation network (Lykou et al., 2020). Passengers who are scheduled to connect to other flights may be stranded, leading to a ripple effect of delays and cancellations throughout the network as subsequent flights are also affected. In addition, airport congestion is not uncommon, especially during peak travel periods. Passengers from those affected flights may rebook alternative flights, leading to increased passenger traffic and a potential pressure on the airport capacity. This congestion can further delay other flights and the overall schedule of airlines can be disrupted due to a cascading effect. Consequently, the operation of the entire aviation network is affected (Bubalo & Gaggero, 2021).

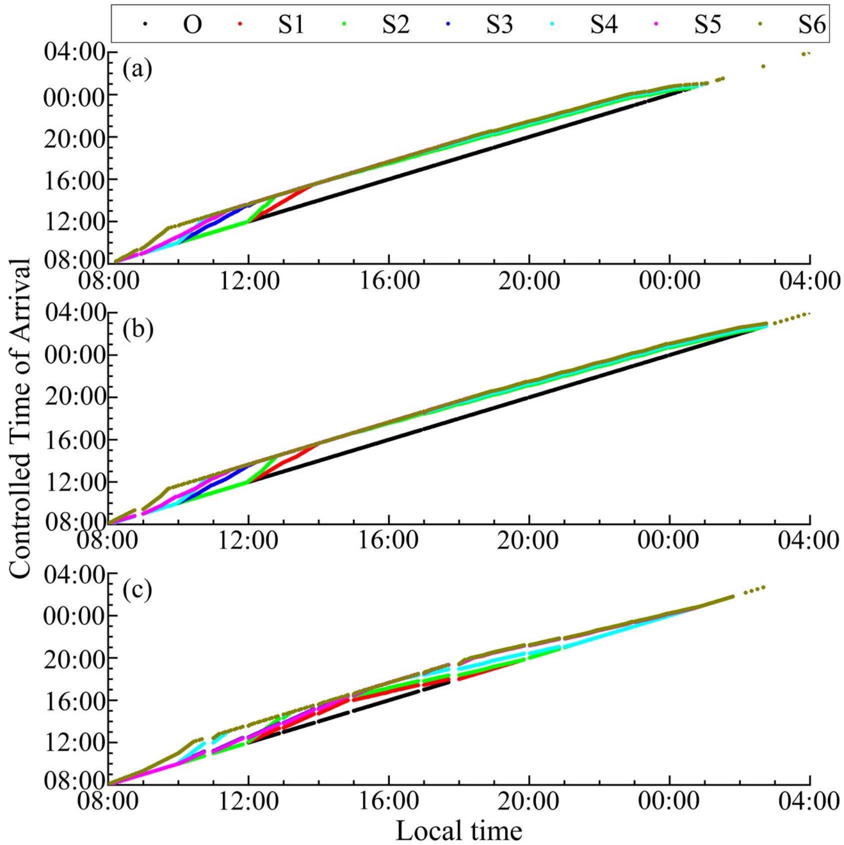

Figure 5. The CTA of each flight at airports (a) VHHH, (b) ZGGG, and (c) ZGSZ in different scenarios denoted by S1–S6. As a reference, "O" is the original time of arrival (OTA).

Considering this domino effect, the operation schedule for a certain aircraft is simulated in Figure 7 based on several assumptions and regulations. The service time is from 06 LT to 01 LT on the next day. An aircraft can finish five flight plans, and the total time of each flight plan is 4 hours, including 3 hours for airborne time and 1 hour for ground time. Due to the propagation of flight delays and flight cancellations throughout the aviation system (Sun et al., 2021), if the first flight plan (06–09 LT) is canceled, the subsequent four flight plans are also canceled. If the third flight plan is delayed by 50 min, the fourth and fifth flight plans are also delayed by 50 min. Cancellations or delays of previous flights can have a domino effect on subsequent flights due to various operational and logistical factors. Therefore, we introduce the notation C to quantify the chain reaction effect of the cancellation and delay of previous flights on subsequent flights. To be specific, C is equal to 5 for the flights with an initially planned landing time within 06:00–10:00, and similarly, C is equal to 2 for the flights with an initially planned landing time within 18:00–22:00.

The aviation network effects of satellite navigation failure in the GBA region are calculated under different scenarios. For example, in the scenario of S5, the number of canceled flights related to VHHH is $5 \times 0 + 4 \times 42 + 3 \times 68 + 2 \times 6 + 1 \times 0 = 384$; the flight delays related to VHHH is $5 \times 561.5 + 4 \times 8{,}497.5 + 3 \times 7{,}952 + 2 \times 12{,}095.5 + 1 \times 4115.5 = 88{,}960$ min Table 3 lists the results of flight cancellations and flight delays in different scenarios in detail. Generally, the number of flight cancellations and flight delays increases with the duration of satellite navigation failure and ground navigation-based arrival time intervals. Compared to the effects related to VHHH and ZGGG, the flight cancellations and flight delays related to ZGSZ are less due to lower projected flight volume in 2025 in ZGSZ. Moreover, the flight cancellations under 5-min arrival time interval are more than those under 3-min arrival time interval. For example, in the scenario of satellite navigation duration failure from 12 to 16 LT, the maximum number of allowable aircraft to be landed is 120 if 3-min arrival time interval is adopted, while the maximum number of allowable aircraft to be landed is only 48 if 5-min arrival time interval is used. This means that more flights have to be canceled in the 5-min arrival time interval case. As more flights

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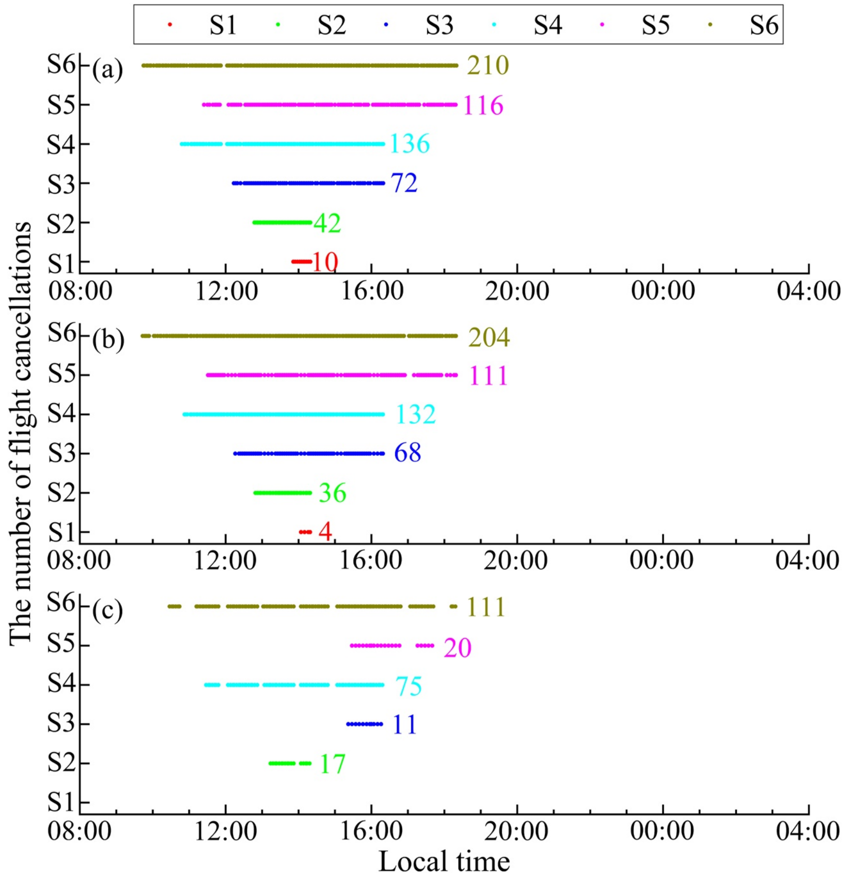

Figure 6. The number of canceled flights at airports (a) VHHH, (b) ZGGG, and (c) ZGSZ in different scenarios as denoted by S1–S6.

have been canceled in the 5-min interval case, flight delays of the remaining uncanceled flights in the 5-min arrival time interval case are consequently lower than those in the 3-min arrival time interval.

3.3. Economic Cost

Flight cancellations and delays can result in economic costs to both airlines and passengers. The costs associated with flight cancellations include service recovery costs (costs associated with passenger care and compensation), loss of revenue, interlining costs, loss of future value, crew and catering costs, passenger compensation for denied boarding and missed connections, luggage delivery costs, operational savings (fuel, airport, and navigation fees, maintenance, handling outstations, lounge outstations, etc.), and operational savings (fuel, airport, and navigation

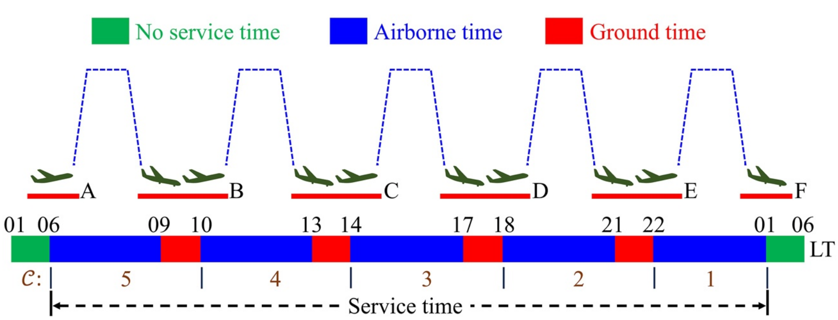

Figure 7. Schematic of flight operation schedule for a specific aircraft. Airports are denoted as A to F.

Table 3
Flight Cancellations and Delayed Time Related to Different Airports in Various Scenarios Considering Aviation Network Effects

Airports	Scenario	Number of canceled flights	Flight delay (min)
Related to VHHH	S1	33	75,186
	S2	158	70,808
	S3	248	87,098
	S4	485	72,532
	S5	384	88,960
	S6	728	71,365
Related to ZGGG	S1	12	77,676
	S2	137	74,101
	S3	234	88,908
	S4	471	74,794
	S5	371	94,132
	S6	711	76,713
Related to ZGSZ	S1	0	19,928
	S2	63	32,847
	S3	33	46,926
	S4	262	44,198
	S5	60	55,760
	S6	379	57,038

fees). Passengers may face financial losses due to missed connections, additional expenses, or impacts on their business or travel plans.

This section aims to estimate the economic cost of flight cancellations and delays to airlines and passengers caused by satellite navigation failure in 2025. Table 4 lists the flight cancellation costs considering aviation network effects (EUROCONTROL, 2020). Space weather events are uncontrollable events, and airlines are not responsible for compensating passengers (U.S. Department of Transportation, 2022). Thus, the total flight cancellation costs are the sum of the cancellation costs of the particular flight and its subsequent flights which will also be canceled (Fujita et al., 2021). Figure 8 displays the types of the top five most used aircraft at each airport based on the 2019 flight data. Particularly, the cancellation costs for the typical aircraft types A333 (at VHHH) and B738 (at ZGGG and ZGSZ) are €39,990 and €11,810, respectively. In addition, the average cost of flight delay per minute to commercial passenger airlines is €174, considering the network effect (EUROCONTROL, 2020). Therefore, based on the results in Table 3, the economic cost of flight cancellations and delays for airlines related to VHHH is €14.4 million (33 flights × €39,990 per flight +75,186 min × €174 per min) at the background of S1.

According to Landau et al. (2015), for each passenger, the flight delay cost is €41.34 per hr. As an example, at the background of S1, the estimated flight delay cost for passengers at VHHH amounts to €10.4 million (250 × 80% × 75,186×€41.34/60) based on the assumption of an 80% occupancy rate for A333. Figure 9 shows the economic costs caused by satellite navigation failure. The primary aircraft type frequently utilized at VHHH is the A333, accommodating up to 250 passengers. The cancellation expenses for each A333, exclusive of passenger welfare and compensation, amount to €39,900. Conversely, at ZGGG and ZGSZ, the predominant aircraft type is the B738, which accommodates 180 passengers. The cancellation cost for each B738, exclusive of passenger welfare and compensation, is €11,810. Additionally, the expected number of canceled flights at VHHH is higher than those at ZGGG and ZGSZ. Therefore, the cancellation cost at VHHH is the highest. Overall, the total economic costs, regardless of the simulated scenarios, exceed 10 million Euros. To reduce the network effects of flight plan disruptions, airlines and stakeholders within the aviation industry should take action, such as proactive scheduling, efficient communication, and contingency planning.

4. Discussions and Conclusions

Space weather events can cause sudden increases in total electron content and irregularities in the ionosphere. In severe cases, this might result in satellite navigation failure, consequently jeopardizing flight safety. As a result, the navigation mode will be switched from satellite navigation to ground navigation. However, this switch will decrease the airspace capacity and subsequently cause the imbalance problem of flight demand exceeding airspace capacity. With the 11-year solar activity cycle, 2025 is expected to see the upcoming solar maximum. To explore the potential 2025 solar maximum space weather effects on satellite navigation failure, and subsequent

Table 4
EUROCONTROL Recommended Flight Cancellation Costs (EUROCONTROL, 2020)

Cancellation cost (€)	Narrow-body aircraft			Wide-body aircraft	
Number of Seats	50	120	180	250	400
Cancellation costs (€)	6,540	16,040	24,900	82,730	120,830
Passenger care and compensation (€)	3,280	8,020	13,090	42,740	68,390
Cancellation costs excluding passenger care and compensation (€)	3,260	8,020	11,810	39,990	52,440

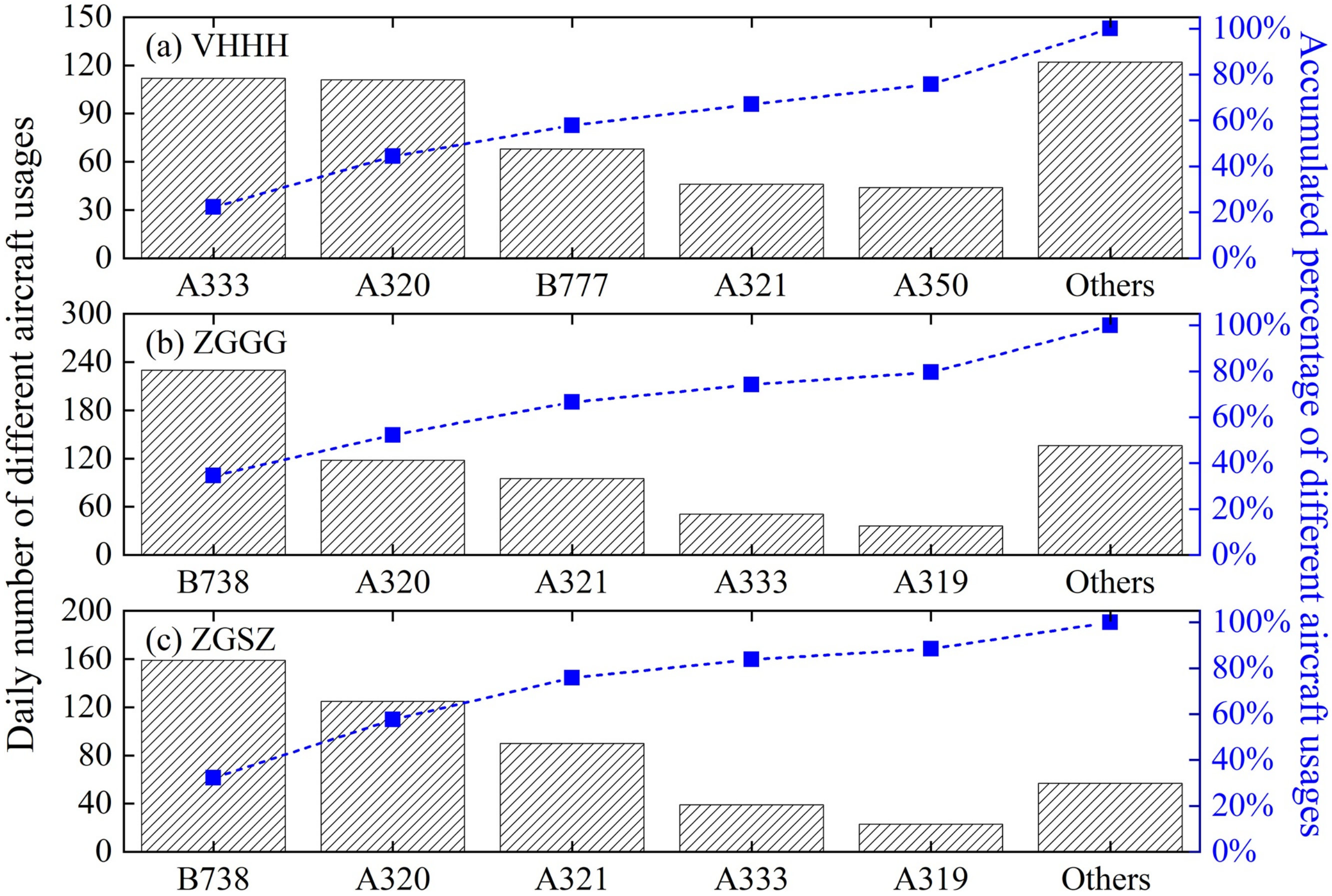

Figure 8. Aircraft usages in 2019, ranked in frequency, related to three airports (a) VHHH, (b) ZGGG, and (c) ZGSZ. The seating capacity of each type of aircraft is as follows: 128 (A319), 150 (A320), 230 (A321), 250 (A333), 280 (A350), 180 (B738), and 340 (B777).

effects on flight operation from the perspective of aviation networks, we have conducted a simulated study for the airports in the GBA (a low latitude region) with several assumptions. We also propose air traffic management methods based on the space weather advisories. Our results show that the potential satellite navigation failure will have minimal effects on Macao Airport and Zhuhai Airport. This is primarily due to the relatively low number of flights anticipated for the year 2025 at these two airports. However, considerable flight delays and flight cancellations are expected to occur at the Hong Kong International Airport, Guangzhou International Airport,

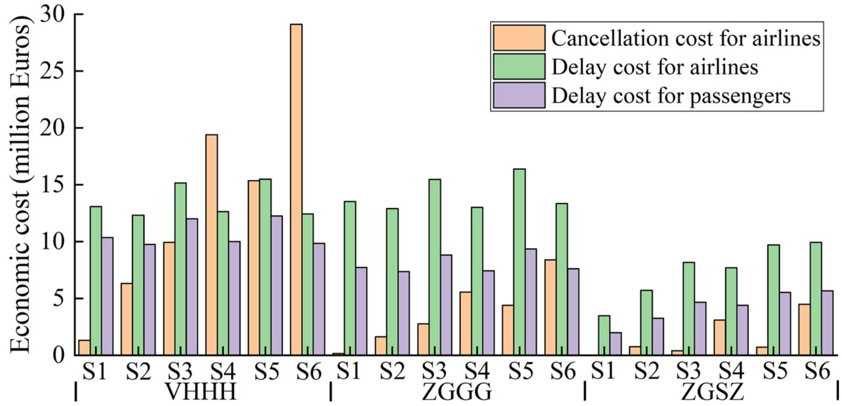

Figure 9. Results of flight cancellation costs and flight delay costs for airlines, and flight delay costs for passengers in different scenarios.

and Shenzhen International Airport, leading to economic costs of tens of million Euros. The results are derived based on the assumptions used, especially the estimated number of flights in 2025 and the minimum arrival time interval based on ground navigation. However, they clearly indicate that the demand-capacity imbalance problem caused by satellite navigation failure can be substantial and tremendous.

However, in a practical situation, the effects of space weather on GNSS may be different from the forecast information in the advisory, likely causing unnecessary flight delays and flight cancellations, and additional economic costs. This highlights the importance of aviation GNSS monitoring procedures, including Receiver Autonomous Integrity Monitoring (RAIM) and the Wide Area Augmentation System (WAAS), in ensuring the accuracy and reliability of satellite navigation systems. RAIM allows a GNSS receiver to check the integrity of the satellite signals (Jerez et al., 2023; Sun, 2020). If any signal anomalies or inconsistencies are detected, the receiver can provide an alert or exclude unreliable satellite signals from navigation calculations. WAAS is another integrity monitoring system used in the United States and other regions (Demyanov et al., 2019; SenthamilSelvan et al., 2022). It provides corrections and integrity monitoring over a wide area, improving the accuracy and reliability of GNSS for aviation. During space weather events, these two aviation GNSS monitoring procedures can play crucial roles in improving the safety and reliability of satellite navigation in aviation, helping pilots ensure the reliability of flight navigation, especially during critical phases of flight such as landing and approach.

Apart from satellite navigation failure, space weather can also affect flight operations in other ways. For instance, solar flares and geomagnetic storms can cause radio blackouts and disruptions in high-frequency (HF) radio communications (Ledvina et al., 2022; Reddybattula et al., 2020). This can impact the normal communication between pilots, air traffic controllers, and ground stations, leading to difficulties in coordinating flight operations. Space weather events, particularly solar particle events (SPEs) and geomagnetic storms can enhance radiation levels in the upper atmosphere and at high altitudes (Bain et al., 2023; Shea & Smart, 2012). Pilots and crew members flying at high altitudes, such as those on long-haul flights or polar routes, may experience increased radiation exposure (Tezari et al., 2022; Xue, Yang, Liu, & Wang, 2022). Airlines need to monitor these events to ensure the safety of crew and passengers, taking necessary precautions and potentially rerouting flights if required. As an advanced surveillance technology, GNSS-based Automatic Dependent Surveillance-Broadcast (ADS-B) is extensively used in modern aviation. This means that under space weather events, deteriorated GNSS accuracy can impair surveillance accuracy, which may result in potential aircraft conflicts and collisions due to the loss of separation. Although these effects are not the focus of this study, it shows that space weather can have significant impacts on the aviation industry (Kauristie et al., 2021).

By understanding the implications and developing strategies to prepare for space weather impacts, the aviation industry can enhance the resilience of air traffic management systems, ensuring the safe and efficient operation of aircraft even in the face of severe space weather events. Continued research and collaboration among stakeholders are crucial to address emerging challenges and maintain the integrity of navigation services in the future. The future research work includes continuing to improve the accuracy of space weather forecasts, the modeling of flight delays and flight cancellations, and the estimation of total costs resulting from one space weather event.

Conflict of Interest

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

Data Availability Statement

The authors thank the VariFlight Company for providing the flight data, which can be accessed via the following link: https://flightadsb.variflight.com/. To access flight data, readers are required to create an account and subsequently enter either the airport's ICAO code or the flight callsign. The yearly mean total sunspot number was obtained from Sunspot Index and Long-term Solar Observations (SILSO), available at: https://www.sidc.be/silso/datafiles#total.

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