Evaluating Impact of Non-nominal Space Mission Event on Conventional Air Traffic

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***Abstract*—The number and diversity of space and higher-airspace missions is rapidly growing worldwide, including Europe. However, the prosperity of these new entrants may become incompatible with that of the conventional aviation, unless their coexistence is regulated. Since "what gets measured gets managed", the impact on the conventional air traffic needs to be evaluated. To that end, we conduct a literature review and propose a methodology to quantify the impact that a real, segregated, special operation within a vertically unlimited volume had on regular air traffic. This methodology is then applied to a recent disruptive event in southern Europe.**

***Keywords*—impact estimation; space; higher airspace; air traffic management**

I. Introduction

Whether for public or commercial interests, space (approximately beyond the altitude of 100 km) and near-space/higher-airspace (approximately from 20 to 100 km) applications are rapidly evolving worldwide. With this prospect, the number of planned missions in the short-to-medium term and the diversity of vehicles are growing. Among the types of vehicles for such missions, there are carrier rockets, space capsules, supersonic/hypersonic aircraft, and high-altitude long-endurance (HALE) vehicles such as balloons, airships and fixed-wing aircraft, each of them with a specific manoeuvrability and flight profile [1].

With the emerging concepts and the volume of upcoming space and higher-airspace operations (SO and HAO, respectively), there is a need for supporting infrastructures, particularly infrastructures on ground. The current shortfall is leading to the construction of new take-off/launch and landing/re-entry sites as well as the conversion of existing airports [2]. For instance, the European Union has recently inaugurated its first orbital launch complex in mainland Europe (Spaceport Esrange, Sweden) [3], which joins the oversea Guiana Space Centre as well as the declared spaceports of Andøya Space Centre in Norway and Cornwall in the UK. Other sites are being built or proposed across Europe [4] as is the case of Italy or Germany.

From the perspective of the airspace (a limited resource), the activity of the new entrants has several consequences. For a start, it brings a higher workload for the space traffic management (responsible for the launch and re-entry of space vehicles, in Europe supported by the Space Surveillance and Tracking service, EU SST [5]). These vehicles also occupy one layer historically exclusive for military operations and the transition of space vehicles – therefore the need for higher-airspace traffic management (devised to be integrated within the traditional air traffic management, ATM, in Europe [6]). Additionally, this new traffic represents a challenge for the ever-growing conventional air traffic. As the demand for the new entrants to transit through the lower layer of the airspace, in less and less remote areas, increases, the degree of disruption to convectional users may jeopardise their coexistence. All these challenges and many others are being addressed in the recently launched ECHO2 project [7].

In order to analyse the progressive integration of SO and HAO, and design a strategy that minimises their impact on the conventional flights, there is a need to develop a performance evaluation framework that this paper seeks to address. Our approach is as follows. In Section II, we review the current and upcoming operations, and the past approaches to estimate the disruption of SO and HAO to commercial aviation. In Section III, we describe the impact metrics chosen for our calculations, along with a methodology to compute them. In Section IV, we define a case study to which the previous methodology is applied. We report the obtained results in Section V. Finally, we provide a summary of the findings and a proposal for future research in Section VI.

II. Background

A. Current and Future Space Operations

Nowadays, when an SO is planned, the vehicle in question (identified as a hazard) is typically segregated from the rest of the airspace users by a temporary airspace closure (notice that if, for example, the affected airspace is located within a military area, the restriction could already exist). Many examples of such restrictions are found in the US where the operations are more frequent; in particular, only SOs authorized by the Federal Aviation Administration (FAA) reached 74 (more than one per week) in 2022 [8]. The dimensions of closed areas (including upper and lower bounds, which are normally unlimited and surface, respectively) respond to the characteristics of the operation, and are designed to confine the unacceptably risky segments of the special activity within them, also accounting for non-nominal events such as malfunction or falling debris, with their associated uncertainties [9]. It is noteworthy that, as experience is gained, risk assessments yield smaller hazard areas than in the past (as is the recent case of Florida [10]).

The notification of space operations to the airspace users occurs via Notice to Airmen (NOTAM), similarly to how military exercises are announced. In addition to the restricted areas, the NOTAM specifies the schedule closures (actual closures could be shorter). According to the FAA [11], since 2018 airspace blockages last something more than two hours on average, an improvement of two hours with respect to what they used to last.

Typically, space-related NOTAMs are issued far enough in advance so that managers and air operators can plan the affected flights accordingly. The primary solution is to re-route the traffic around the restriction, without additional buffer observed in practice [12]. An impact assessment may suggest different strategies such as ground delays. A detailed description of current operations, from pre-operational planning to post-operations can be found in [13].

To make the growing commercial space activity compatible with aviation, the US [13] and the EU [6] have developed concepts of operations. Although both envisage a transition from disrupting, static airspace closures towards more efficient, dynamic airspace reservations, there are some dissimilarities. From the point of view of the restrictions, the EU concept devises the so-called 4D operating zone, which would account for uncertainties and result from a collaborative process (analogously to the Flexible Use of Airspace concept), whereas the US concept develops three distinct airspace management strategies: the adaptive risk envelope, the space transition corridor and the temporary flight restriction, the first of which is the ideal (least disrupting) solution in the long term, when SOs are reliable enough and the air traffic control system is prepared.

B. *Current and Future Higher-Airspace Operations*

At present, a variety of HAO, such as scientific/weather stratospheric balloons, sounding rockets or military aircraft [14], are occupying the EU airspace. Nonetheless, there are other vehicles starting to be operated, as it happens in the US. Apart from space vehicles transiting through the higher airspace, the majority of these new vehicles are still in an experimental phase. Although some flight demonstrations have already been conducted in open airspace (e.g. [15]), most of the trials occur either within segregated airspace (e.g. [16]) or low-demand areas (e.g. [17]), and therefore their impact on civil aviation is negligible for the time being.

Among HA vehicles, there are notable differences in terms of manoeuvrability and speeds [18]. HALE vehicles such as balloons and airships have either null or limited controllability, and their airspeeds are low, all of which constitutes a hazard when there are high-speed aircraft nearby, implying that the HAO needs to be segregated with some horizontal and vertical margins [19]. Other HALE vehicles such as fixed-wing aircraft may possess more manoeuvrability but their airspeeds are still low. As a peculiarity of the latter, their ascents and descents follow a spiral pattern lasting around one hour (e.g. [20]). Regarding supersonic/hypersonic vehicles (included in the HAO category in the context of the European initiatives [6][14] but still under discussion in the US [21]), their performance capabilities near the aerodrome are rather similar to regular aircraft, which eases their integration, but their reachable speeds climbing/descending through the controlled airspace could be challenging for the air traffic controllers (ATCOs) to manage due to limitations of the current equipment [22].

To protect the mutual development of HAO and commercial aviation, the US [23] and the EU [6] have elaborated concepts of operations that share some aspects and differ in others [24]. In particular, provided that the performance capabilities of the HA vehicles allow it [21], they agree on the gradual transition from dynamic temporary segregation in the short term (while the demand and complexity will remain low), to the dynamic separation kept by active operators in the long term (when the volume and complexity of this special traffic increase).

C. *Evaluation of Impact on Commercial Aviation*

The disruption of SO and high-speed HAO to aviation has been moderately explored. The study cases include vertical launches and re-entries [12][25][26][27][28][29][30][31] as well as horizontal launches/take-offs and landings [27][28][29][30][31][32][33][34]. In particular, the literature covers three re-entry operations in the US: one is a hypothetical re-entry over continental airspace [28], and the others are historical re-entries over the Pacific Ocean (the re-entry of the Dragon capsule in March 2013 [12][27][28], and the re-entry of the Orion capsule in December 2015 [25]). To protect the air traffic in the vicinity, airspace closures are considered in all three cases, with a duration of 30 minutes for the imaginary operation, 27 minutes for the Dragon capsule, and of 3 hours and 9 minutes for the Orion capsule. In the third case, an additional area was restricted to account for the re-entry of the rocket's upper stage (eight times bigger than the area for the capsule). In addition, one hypothetical controlled re-entry in southern England is analysed in [31], using an airspace restriction of 60 minutes.

The impact evaluation is approached from different perspectives, and therefore with different objectives, as part of either a post-operation analysis [12][25][26] or an exercise of strategic planning [27][28][29][30][31][32][33][34][35]. Putting a conceptual study [32] aside, the most distinct papers are [26] where the emphasis is on the statistical significance of given delays, and [35] which describes the construction of a density map with the historical hourly number of flights along each of the route segments connecting the nodes of a certain network, very helpful to carry out fast "what-if" analysis. In the rest of papers, the methods used to quantify the impact are essentially analogous. They consist in: (1) defining a study case; (2) extracting certain performance metrics from the traffic (presumably) affected by the SO or high-speed HAO, formed by either executed flights in the post-operation analysis or simulated flights in the planning exercise; (3) defining a (set of) baseline scenario(s), formed by either forecasted [27][28][29][34] or historical flights [12][25][30][31][33], and calculating the same metrics for the corresponding traffic; (4) comparing the metrics in (2) with those in (3) on a flight-by-flight basis in order to get the individual impacts; and (5) aggregating the impact metrics for all the flights.

Differences between the methodologies proposed in the aforementioned papers appear when defining the conditions to incorporate a flight into the analysis (e.g. having actually flown within 50 NM of the restricted area [12], with an actual flown distance 10 NM longer than the average of the most recent baseline scenarios considered [25], planned to fly within an affected area [27], planned to intersect the restricted area [30][31], or planned to fly over the area control centre of interest [28][29][34]), the baseline scenarios (e.g. set of 5 days with similar weather and similar actual flights [12], same day of week for 30 weeks prior to the day of the operation, the D-day, [25], or the same reference traffic used as input for the simulation [27][28][29][30][31][33][34]), and the disruption metrics (see Table I). Another important difference is that while the majority of papers consider temporary flight restrictions, there are a few devising innovative, and less disrupting, airspace management strategies [27][28].

TABLE I. IMPACT METRICS.

Metric	Ref.
# of affected flights	[12][25][27][28][29][30][31][34][35]
Extra distance	[12][25][27][28][31][34]
Extra duration	[12][25][27][28][30][31][34]
Extra fuel burned	[12][27][28][31][34]
Cost index	[25]
Arrival delay	[26]
Planned time inside hazard areas	[29][30]
Planned distance inside hazard areas	[29]
Sector occupancy	[28]
Extra fuel burned cost	[30]
Operating cost	[34]
# of re-routings	[31]

One limitation specific to those studies covering a real special operation is the assumption that the impact on conventional air traffic is linked to such operation. In practice, there are almost always other events that may have contributed to the impact on the air traffic such as adverse weather, different pattern of winds, air traffic flow and capacity management regulations, strikes, radar malfunction, etc. Authors try to minimise these circumstantial effects by choosing baseline scenarios with similar weather [12], same day of week [25], or even by considering a collection of cases that account for the impact fluctuations [12][25][26]. However, there is room to further isolate the effect due to the SO or high-speed HAO; in particular, because a similar weather may still be different from the actual weather, and because the hypothesis that traffic on the same day of week behaves in a similar way may be wrong [29].

Another limitation of the cited works is that they are mainly focused on operations in the US. To the best of our knowledge, only [29][31][33] present hypothetical cases over Europe. Thus, it would be interesting to further analyse the disruption that these types of operations (will) have on the European air traffic network, which is different from the US network in terms of demand, capacity, structure, fragmentation, staff training, etc. as well as, of course, experience in managing these operations.

III. METHODOLOGY

The current section details a methodology to quantify the impact that a real, segregated, special operation within a vertically unlimited volume had on regular air traffic.

A. *Performance Evaluation Metrics*

Before proceeding, it should be emphasised that the number of metrics computed in this work is limited by the available data. Had we had flight plans and airspace information such as scheduled/actual sectorisation, sector geometries, and maximum en-route capacity values, we could have definitely enriched this study. That said, the performance metrics are:

1) Ground track distance: it is the sum of the lengths of all the loxodromic segments considered for each flight (more details about this in Section III-E).

2) Flight duration: it is the time needed to fly along the aforementioned trajectory segments of each flight. For the affected flights, it is calculated based on the timestamps of their 4D trajectories, whereas for the baseline flights, it is calculated based on the timestamps returned by the methodology explained in Section III-D.

3) Fuel consumption: the Total Energy Model, provided in the manual of *Base of Aircraft Data (BADA) version 4.2* [36], is used to find the engine thrust along the trajectories. From the thrust force, the corresponding thrust coefficient can be derived, which is used to obtain the fuel coefficient. The fuel flow is then calculated according to:

$$F = \delta\theta^{1/2} W_{mref} a_0 L_{HV}^{-1} C_F, \tag{1}$$

where δ is the pressure ratio, θ is the temperature ratio, W_{mref} is the weight force of the aircraft, a_0 is the speed of sound at mean sea level, L_{HV} is the fuel lower heating value and C_F is the fuel coefficient. In the iterative process of determining the engine thrust and calculating the fuel flow at each point of the trajectory, the aircraft mass is constantly being reduced by the amount of fuel burned. The initial mass of the aircraft is set to the value of the nominal mass, provided in the BADA performance file for each aircraft type.

4) Airport throughput: in number of total operations per time period, it is computed based on the whole traffic data and their corresponding actual take-off times; therefore, this metric is a bit independent of the main discussion. Further decisions about the airports of interest, the duration of the time periods and the total number of periods are to be made on a case-by-case basis, depending on the location and dimensions of the restricted airspace as well as its time window.

B. Identification of Impacted Traffic

Because the airspace restriction is active during a specific time interval $[t_{ri}, t_{rf})$, and flights, to a greater or lesser extent, are generally subject to 4D deviations, we identify the affected traffic by using executed flight trajectories rather than planned flight trajectories (even though this decision complicates the identification of affected flights). Additionally, to delimit the search, three assumptions are made. First, the traffic inside the restricted area starts being cleared off some time Δt_1 in advance of t_{ri}. Secondly, the traffic resumes its operation inside the restricted area as soon as the restriction is lifted (t_{rf}). Thirdly, the air traffic system is resilient enough to recover from the disruption after some time Δt_2.

With the previous information in mind, one flight is incorporated into the analysis if:

- it crossed an enlarged area formed by the restricted area plus some spatial buffer Δs during $[t_{ri} - \Delta t_1, t_{rf})$; and/or
- it flew over the restricted area during $[t_{rf}, t_{rf} + \Delta t_2)$.

The targeted flights of the former condition are those that circumnavigated the restriction, plus flights following other possible strategies: flights delayed airborne within the buffer, flights allowed to penetrate the restriction through a corridor, flights deviated to an alternate airport, etc. In contrast, the latter condition accounts for flights that were strategically re-routed, delayed on ground, delayed airborne beyond the buffer, etc. The buffers Δt_1, Δt_2 and Δs should be adjusted on a case-by-case basis by means of a preliminary post-operation analysis (e.g. a visual inspection of the trajectories).

Even though the two conditions above are intended to minimise the inclusion of unaffected flights, some may still be wrongly identified. For this reason, a visual inspection of the resulting flights is recommended. In addition, note that both conditions are compatible with whichever metrics are chosen; for instance, the second condition would be helpful to calculate the departure/arrival delays of the flights that took off/landed inside the restriction.

C. Baseline Scenarios

To calculate the impact on individual flights, it is necessary to have a reference for each of them. One option for such a reference is the corresponding flight plan. However, for the same reason why the executed trajectories were chosen for the identification of affected flights, historical actual flights with identical callsigns (typically defining flights operated under similar conditions) are preferred for the baseline (even though the flight plan would be indispensable for other metrics such as departure delays).

With the awareness that there is some variability among the actual flights with the same callsign, a set of n baseline flights for each affected flight is chosen. The general criteria to form the baseline set for each affected flight is defined by the following conditions: (a) same callsign; (b) same origin and destination; (c) no apparent disruption resulting from the comparison between its duration and a threshold (e.g. 15% over the 90th percentile of those of the rest of n baseline flights); (d) closest to the D-day up to six months before and after; (e) similar schedule; and (f) same aircraft model. Since for some affected flights these conditions may not yield a requested number n of baseline flights, conditions (e) and (f) could be relaxed. If there are still affected flights without the required minimum n, before discarding them from the analysis, they should be visually inspected to detect possible deviations to an alternate airport, in violation of condition (b). Also, if there are flights using the same callsign for subsequent connections (legs), the connections that do not overlap spatiotemporally with the restriction should be excluded, with the exception of the connections of the affected flights that result from a deviation to an alternate airport.

The number of baseline flights (n) for each affected flight could be decided on a case-by-case basis. For this work, n=30 is used as trade-off between representativeness and time consumption. Note that, as explained in the previous paragraph, the baseline flights may have been executed up to six months before and after the D-day.

Lastly, it is also necessary to define a baseline scenario for the airport throughput metric. Since it is highly dependent on such factors as seasonality, day of week, or closeness to public holidays, a preliminary review of historical data should be conducted to identify dates with similar total throughput. Thus, the throughput of the selected airports during a time window on the D-day will be compared with that of the same airport during the same time window on the dates found.

D. Normalisation of Weather Conditions

Thus far, nothing has been said about the weather conditions of the baseline flights. Flight timestamps (and consequently durations and fuel burned) are strongly correlated with the corresponding weather conditions, especially with the winds. Since each baseline flight occurred under a unique meteorology, and each baseline flight represents a possible realisation of the corresponding affected flight without the restriction, we decided that their timestamps should be re-evaluated for the same weather conditions experienced by the corresponding affected flight. To do that, two steps are taken. First, the actual take-off time of the baseline flights are all set equal to the actual take-off time of their corresponding affected flights. Secondly, the subsequent timestamps t are calculated as in [37], that is, by numerically solving the following differential equation along a discretised segment, segment after segment:

$$\frac{dt}{dr} = \frac{1}{V_g(r, H)}, \tag{2}$$

where r is the distance along the discretised segment, (r, H) represent the 3D coordinates of each waypoint along the discretised segment, and the ground speed V_g is given by

$$V_g(r, H) = \sqrt{(V_{TAS} \cos \gamma)^2 - w_{XT}^2} + w_{AT}. \tag{3}$$

Here, V_{TAS} is the true airspeed, γ is the flight path angle, w_{XT} is the crosswind, and w_{AT} is the along-track wind. To be compatible with the original flight profile, the real winds are calculated at each waypoint by interpolating from the gridded weather data (at the correct time instant), the value of the true airspeed is the one given by BADA at each altitude, and the flight path angle is calculated for each segment as $\arctan(\Delta H/\Delta r)$.

E. Impact Evaluation

In order to minimise unrelated effects in the metrics, we trim the trajectories, that is, only the segments inside a selected region are considered in the computations. Including the restricted area, this region should be as small as possible to exclude unrelated effects, but, at the same time, large enough so as not to introduce bias due to its geometry and so as to account for strategic deviations (visual inspection is needed).

For each of the resulting trimmed trajectories, the performance metrics described in Section III-A are calculated. Then, the extra distance, the extra duration and the extra fuel burned are evaluated for each affected flight and baseline flight. If there are m affected flights, there will be n impact metrics of each performance indicator for each affected flight, and mn impact metrics of such performance indicator in total.

To aggregate the results for all the affected flights, the first step is the computation of the mean value of each impact metric for each affected flight. After that, the total mean of each impact metric is approximated as the sum of the individual means (normality assumption).

IV. Case Study

The selected case study corresponds to the disruption experienced in the Spanish airspace on November 4th, 2022. This disruption was caused by the uncontrolled re-entry into the atmosphere of the 20-tonne, 30-metre long core stage of the Chinese Long March 5B rocket. Although the remains eventually fell in the South Pacific Ocean, the EU SST detected that its trajectory threatened several European countries, and therefore raised the alarm. Under the risk of debris hitting an aircraft, the authorities in some of the impacted countries closed large portions of their airspaces. This work focuses on the restriction in the Spanish airspace, where the closure took place over a 200-km wide strip centred on the debris track and extended from northern Portugal to Catalonia (see Figure 1). The restriction was active from 08:37 to 09:17 UTC and, according to authorities, this measure affected around 300 of the flights that were planned to operate in Spanish airports, causing an average delay of 30 minutes [38][39].

This case study brings to the fore the importance of international collaboration to effectively limit the impact that future SO/HAO may have on conventional aviation. Furthermore, it shows the effect of an operation that, unlike most of the published cases, was known only 4–5 hours in advance [38].

A. Historical Traffic Data

In this work, we use the Automatic Dependent Surveillance - Broadcast (ADS-B) flight trajectories from the historical dataset of the OpenSky Network [40], with a better resolution than trajectories provided by Eurocontrol. To download them, we have used the open-source Python package *traffic* [41].

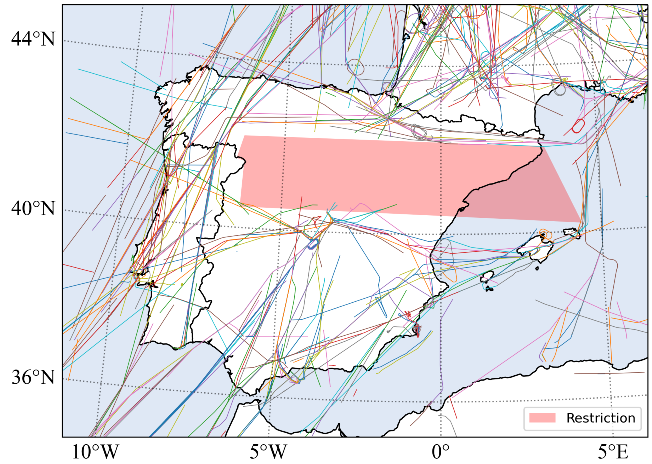


Figure 1. Traffic around the part of the Spanish airspace closed on 04 Nov 2022 8:3709:17 UTC because of the uncontrolled re-entry of the Chinese Long March 5B rocket.

Note that the search of the desired trajectories in the Opensky database can be done by indicating both the callsign and the departure/arrival airport. According to our experience, the process of searching and filtering is less time-consuming when entering at least the callsign.

Because the flight trajectories are sometimes affected by noise and errors, it is mandatory to pre-process them to avoid undesired input data. In this work, several cleaning, filling and smoothing techniques are applied, and unacceptably faulty trajectories are withdrawn.

B. Historical Weather Data

The temperatures and winds used in this work are calculated by interpolating the hourly 3D weather information available at the ECMWF Reanalysis v5 [42].

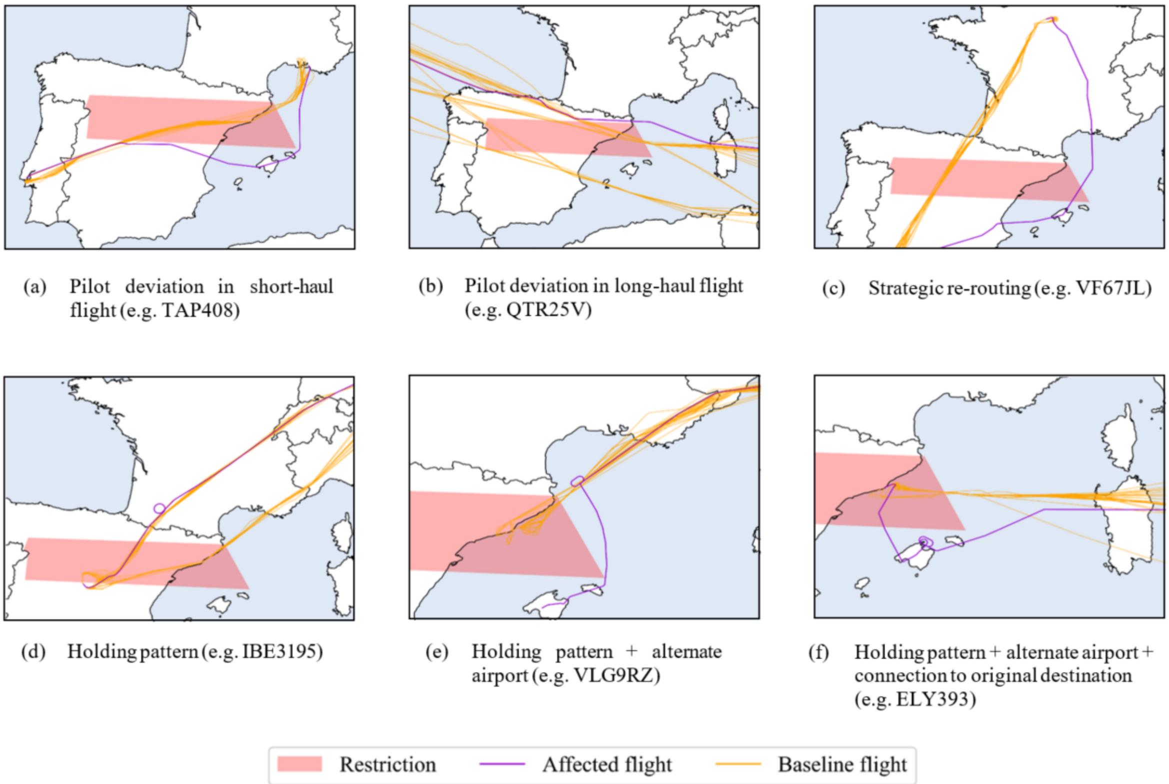
V. Results

The results of the case study are presented and discussed in the following three subsections.

A. Preliminary Analysis

The filter criteria specified in Section III-B (with Δt_1 = 10 min, Δt_2 = 60 min, and Δs = 100 NM resulting from visual inspection) and Section III-C, plus the pre-processing techniques mentioned in Section IV-A, yield 233 presumably affected flights, which corresponds to a total of 7223 flight trajectories.

The inspection of the 233 affected flights indicates that there were 12 (5.2%) very short-haul flights (less than 500 km), 89 (38.2%) short-haul flights, 103 (44.2%) medium-haul flights (between 1500 and 4000 km), and 29 (12.4%) long-haul flights. Furthermore, there were 53 (22.7%) flights that took-off from an airport inside the restriction, and, based on the comparison with their baseline flights, there were 72 (30.9%) flights expected to land at an airport inside the restriction, and 108 (46.4%) flights expected to either cross the restriction or pass nearby.



(a) Pilot deviation in short-haul flight (e.g. TAP408)

(b) Pilot deviation in long-haul flight (e.g. QTR25V)

(c) Strategic re-routing (e.g. VF67JL)

(d) Holding pattern (e.g. IBE3195)

(e) Holding pattern + alternate airport (e.g. VLG9RZ)

(f) Holding pattern + alternate airport + connection to original destination (e.g. ELY393)

Figure 2. Examples of strategies performed by pilots to avoid the part of the Spanish airspace closed on 04 Nov 2022 8:3709:17 UTC because of the uncontrolled re-entry of the Chinese Long March 5B rocket.

As shown in Figure 2, pilots and ATCOs followed multiple strategies to avoid the closed airspace, namely: pilot deviations/tactical re-routing, strategic re-routing, holding patterns, or deviations to alternate airports. Ground delays are not considered in this work.

B. Analysis of the Impact Metrics

After the identification of the flights, the pre-processing step and the re-evaluation of the timestamps for the baseline flights, the trajectories are trimmed to exclude the segments beyond the region from 20ºW to 25ºE, and 30ºN to 60ºN. Subsequently, the impact is obtained in terms of extra distance, extra duration and extra fuel burned for each affected flight. We present the results in Table II.

Additionally, the impact is evaluated per each length category (i.e. very short-haul, short-haul, medium-haul and long-haul). The results are also gathered in Table II and, for example, can be analysed according to the average total divided by the corresponding number of flights. In terms of the extra distance, the most disrupted flights are the medium-haul flights, followed by the long-haul flights, then by the short haul flights, and finally by the very short-haul flights. In terms of the extra duration, the most disrupted flights are the medium-haul flights, followed by the short-haul flights, then by the very short haul flights, and finally by the long-haul flights. In terms of the extra fuel burned, the most disrupted flights are the medium-haul flights, followed by the short-haul flights, then by the very short haul flights, and finally by the long-haul flights. Notice the high impact on short- and medium-haul flights (the largest groups), and that the impact on the long-haul flights is negative for some metrics. Apparently, long-haul flights were less affected by the airspace closure. Figure 2.b shows two reasons: first, a long-haul aircraft can adapt more easily to obstacles; and secondly, long-haul routes present more variability. However, it should be noted that 11 out of 29 long-haul flights either took off or landed at Madrid–Barajas Airport, which continued operating despite being over the edge of the restriction (more details in Section V-C).

C. Analysis of the Airport Throughput

In this case study, the impact on the Spanish airports is examined, with the exception of the ones in the Canary Islands, Ceuta and Melilla, considered to be sufficiently far from the impacted area. In particular, the analysis comprises the visual comparison between the airport throughput on the D-day and some baseline scenarios over a time interval that includes the restriction time window. These baseline scenarios are the operations in the same airports over the same time interval, on the same day of week, during the next five weeks, in 2022 and 2019 (similar number of operations [43]).

The visual inspection indicates that the airports can be classified into three categories: (a) inside the restriction with all the routes to/from the airport blocked; (b) approximately over the edge of the restriction; and (c) completely outside the restriction. In the first category, there were six airports (by their ICAO codes, LEBL, LEGE, LERS, LESA, LEVD and LEZG),

TABLE II. IMPACT METRICS.

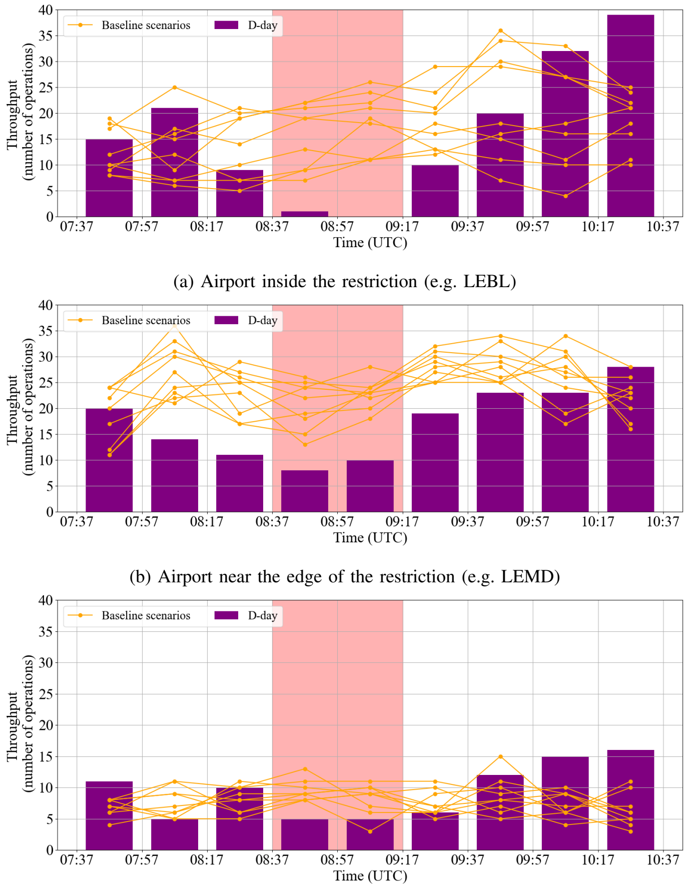
Impact metric	Category	Average total	Standard dev. of the total	Average total per flight
Extra distance	Whole set	5324 NM	417.6 NM	22.8 NM
	Very short-haul	14.7 NM	47.3 NM	1.2 NM
	Short-haul	1639 NM	162.3 NM	18.4 NM
	Medium-haul	3024 NM	242.2 NM	29.4 NM
	Long-haul	646.1 NM	295.3 NM	22.3 NM
Extra duration	Whole set	32.3 h	2.2 h	8.3 min
	Very short-haul	0.77 h	0.17 h	3.8 min
	Short-haul	14.2 h	0.49 h	9.6 min
	Medium-haul	17.8 h	2.0 h	10.4 min
	Long-haul	−0.46 h	0.66 h	−0.9 min
Extra fuel burned	Whole set	15374 kg	4731 kg	66 kg
	Very short-haul	736.6 kg	310.1 kg	61.4 kg
	Short-haul	7816 kg	1602 kg	87.8 kg
	Medium-haul	10357 kg	3788 kg	100.6 kg
	Long-haul	−3535 kg	2317 kg	−121.9 kg

all of which were severely disrupted, with their operations plummeting to zero (see Figure 3.a). In the second category, there are two airports (by their ICAO codes, LEHC and LEMD), but only Madrid–Barajas Airport has enough traffic to show the effect of the airspace closure. As illustrated in Figure 3.b, the volume of operations in Madrid dropped by half, which was anticipated because the southern routes to/from the airport remained open. Finally, the third category has twenty-six airports impacted to different extent. Perhaps, the most interesting finding is that medium-to-large size airports such as the ones in Palma de Mallorca, Alicante-Elche, Malaga, and Seville were moderately disrupted (see Figure 3.c), possibly due to connections to/from severely affected airports. Only Pamplona Airport and Vigo Airport increased their operations during the restriction.

VI. CONCLUSIONS AND FUTURE WORK

In this work, we present the methodology to quantify the impact on regular air traffic due to a real, segregated, special operation (either SO or HAO). Built on the relevant literature, this methodology introduces some filter criteria to identify the presumably affected flights and their probabilistic baselines as well as a method to normalise their weather conditions. Once developed, it has been applied to a recent historical case over Europe, an unplanned large-scale event. The impact has been calculated in terms of the extra distance, the extra duration, the extra fuel burned and the airport throughput.

Classifying by distance, short- and medium-haul flights seem to be the most affected ones. Furthermore, the flights expected to land inside the restriction while this was active were clearly penalised, especially in terms of extra duration resulting from holding patterns and deviations to alternate airports. From the perspective of airports, those inside the restriction were clearly penalised. Had we had the flight plans, we could have calculated the arrival and departure delays. Notice that although an extra duration does not necessarily mean an arrival delay, it is highly likely that most of the flights



(a) Airport inside the restriction (e.g. LEBL)

(b) Airport near the edge of the restriction (e.g. LEMD)

(c) Airport outside the restriction (e.g. LEPA)

Figure 3. Airport throughput at several example airports affected by the closure of a part of the Spanish airspace on 04 Nov 2022 8:3709:17 UTC because of the uncontrolled re-entry of the Chinese Long March 5B rocket.

with an extra duration reached their destinations later than planned. These arrival delays must have caused reactionary delays in subsequent journeys. The negative consequences of these delays for passengers, as well as those caused by late departures inside the restriction, are often significant. Avoiding this situation in future operations would make a difference.

Next steps towards the development of an impact assessment framework should include gaining a better knowledge about the future operations over Europe, estimating the impact due to the most imminent operations (considering additional metrics such as departure/arrival delays, evolution of the reactionary delays during the rest of the day, evolution of the delays at the airports inside the restriction, number of cancellations, sector occupancies, sector congestion, complexity metrics, unused airspace capacity, passenger-oriented enhanced metrics [44], etc.), detecting likely hotspots that may jeopardise their integration, defining a unified criterion to recommend that an operation should not be conducted, and the identification of alternative solutions. These steps are left for future works.

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