Influence of a volcanic eruption on a flight route: The case of the 2020 Taal eruption in the Philippines

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Abstract

This study uses the case study of the 2020 Taal volcano eruption in the Philippines to analyze the influence of a large volcanic eruption on flight routing, by applying trajectory clustering technology and proposing ways to avoid accidents and system malfunctioning risks caused by the volcanic ash. We adopt the hierarchical density-based spatial clustering of applications with noise (HDBSCAN) algorithm to classify the trajectories. Additionally, we use the Fréchet distance to measure the distance among trajectories of the same flight. We downloaded the observation data, recorded from January 1, 2020 to January 31, 2020, from Flightradar24 as well as the information of the diffusion of the volcanic ash from Tokyo Volcanic Ash Advisory Center (VAAC). Through the case study, we found that (i) the airlines either cancel or reroute flights that fly through or near a heavily ash-contaminated area within 24 h; (ii) after 24 h, airlines have two options for flights that depart within a couple of hours: “keeping the special operation” or “getting back to the regular” in the case of the 2020 Taal volcano.

1. Introduction

Volcanic disasters have caused serious problems in the aviation industry. The stalling of an aircraft’s engine due to volcanic ash has caused some serious accidents in the past. For example, the cases of Mt. Galunggung, Java in 1982[1] and Mt. Redoubt, Alaska in 1989[2] are representative of engine stall. The 2010 case of Eyjafjallajökull of Iceland is one of the most serious cases.

On April 14, 2010, a large eruption of the Eyjafjallajökull occurred and interfered with heavily used intercontinental airways, which led to major airspace closure in Europe. The International Air Transport Association (IATA) reported that the airspace in Europe had to be completely closed from April 15 to 20, and this airspace closure resulted in the disruption of over 100,000 flights and ten million passengers’ journeys (IATA 2010). Such a big disruption led to the biggest air traffic disruption in modern civil aviation history. The global economic damage that resulted was estimated to be five billion USD. Because the negative impact of Eyjafjallajökull was so huge, stakeholders in the aviation sector thought that a long-term total airspace shutdown was not desirable, to reduce the damage owing to the enormous eruption; therefore, policies and guidelines were reviewed and improved in many ways. The main change was made in the area of decision-making on the airspace status in Europe. Prior to the 2010 event, European states completely closed airspace contaminated with ash. Under the new guideline, the airspace mainly remains open, and the decision on whether to fly should be made by aircraft operators. The same approach was adopted in the Asia/Pacific region (ICAO 2017). To conduct a flight in an airspace that is ash-contaminated or forecasted to be ash-contaminated, operators are required to implement appropriate mitigation measures in accordance with their safety risk assessment (SRA). Safety oversight procedures are used for the evaluation of operators’ capabilities to conduct flight operations safely into the airspace forecasted or known to be contaminated with volcanic ash. This is completed and evaluated according to the State Civil Aviation Authority. Unfortunately, although the guidelines have been set up, details on how to avoid the challenges and accidents resulting from volcanic ash are decided by local authorities so far. To improve this situation, the nature of issues caused by volcanic ash should be discussed. The issues can be classified as ground-side or airside issues.

For the ground-side issues, some studies highlighted the seriousness of airport closure and acceptance of evacuation flights due to the massive ash fall. Arreeras and Arimura (2021) discussed the way of choosing a shelter airport for evacuating flights in the case of a huge eruption of Mt. Hakone-yama, which is close to the Tokyo metropolitan area. Takebayashi et al. (2021) discussed capacity shortage for accepting evacuation flights when Mt. Sakura-jima, located in the southwestern part of Japan, had an enormous eruption. Both studies argued that an enormous eruption will harm wider areas than expected and lead to a bigger impact on the aviation sector. These studies obtained meaningful
outputs for reducing the damage caused by the volcanic ash, but they considered the airport-side (ground-side) problem; they did not deal with the airside problem, that is route-setting.

Regarding the airside issue, performing route-setting or route analysis for improving air traffic efficiency can lead to a solution. Historically, there are many studies about this topic. Most of the studies focused on the classification of trajectories (Yuan et al., 2016; Bosson and Nikoleris 2018; Olive and Basora 2019; Corrado et al., 2020; Olive et al., 2020; Olive and Basora 2020). These studies proposed some useful methodologies, such as the trajectory clustering technology. The outcomes of these studies are highly beneficial for discussing better route design for usual flights; furthermore, this methodology can provide useful information for avoiding risks during emergencies. As mentioned previously, air transport is sometimes impacted by a major disaster affecting a wide area, as in the case of the 2010 eruptions of Eyjafjallajökull. To reduce the risk posed to air transport by volcanic ash, categorizing the methods to avoid risk and finding the characteristics (or features) of such methods would be beneficial; the trajectory classification technology mentioned above can be used for this.

Our research motivation is to apply the trajectory clustering technology to the case of the volcanic ash disaster in the aviation market and find ways to prevent risks caused by the volcanic-ash-contaminated air. This outcome will benefit the aviation industry as it will improve their decision-making process when a large eruption occurs.

This paper has four Sections. Following the introduction, we briefly explain the case we are dealing with and the proposed methodology in Section 2. In Section 3, we discuss the application of the method to the case and discuss how flight route-setting helps to prevent risks caused by volcanic-ash contaminated air. In Section 4, we present the conclusions of the study by summarizing our findings and discussing recommendations for future research.

[1] The British Airways Flight 009, which was a four-engine aircraft Boeing 747, flew into the ash cloud rising from Mt. Galunggung. All the engines of the aircraft suddenly stalled due to the ash cloud.
[2] KLM Flight 867 (also Boeing 747-400) made an emergency landing due to the eruption of Mt. Redoubt; this was the first experience of an engine stall due to the dispersion of volcanic ash.

2. Analysis Of The 2020 Taal Volcano Eruption

2.1 Outline of the 2020 Taal volcano eruption

On January 12, 2020, the Taal volcano eruption, which occurred approximately 70 km away from Manila Ninoy Aquino International Airport (MNL), resulted in the suspension of flights in the area. Fig. 1 shows the image that is described based on the information provided by the Himawari-8 satellite: it shows the ash cloud covering the airspace above the Philippines and quickly moving toward northeast (NICT Science Cloud 2020).

The eruption started at 16:00, and it generated an ash cloud that was growing and moving to the north. At 17:30, the cloud reached the middle of Luzon Island. The ash cloud continued northbound and reached a point at which the latitude was North 24.11 and longitude was East 126.35 (VAAC 2020).

Based on the ash cloud movement, aircraft close to the area with ash-contaminated air had to change their flight routes or needed to be canceled. Thus, understanding the characteristics of flight trajectories can help determine ways to ensure flight safety when a large eruption occurs.

2.2 Materials and method
As we analyze the flight trajectory, we used the flight trajectory data, which shows positions using longitude, latitude, and attitude information. We chose Flightradar24 (FR24) for our analysis. We randomly selected 120 flights that fly near or in the middle of the ash cloud when using regular routes.

Regarding the information of ash cloud movement, we used the data proposed by VAAC. Table 1 shows an example of the data.

Table 1. Example of information of ash cloud movement (the case of the Taal volcano).

<table>
<thead>
<tr>
<th>ADVISORY NR</th>
<th>Year, date and time</th>
<th>Observed volcanic ash cloud location (Decimal Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020/2</td>
<td>20200112/0754Z</td>
<td>14.00, 120.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.23, 120.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.23, 121.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.00, 121.03</td>
</tr>
<tr>
<td>2020/3</td>
<td>20200112/0900Z</td>
<td>13.93, 120.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.03, 120.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.43, 120.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.07, 120.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.12, 120.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.48, 121.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.02, 121.10</td>
</tr>
</tbody>
</table>


Note 1: this table is a summary of information based on the information by Tokyo VAAC.

Note 2: “ADVISORY NR” is the advisory number for this specific volcano; in this study, the target volcano is Mt. Taal.

Note 3: “Year, date and time” means the date and time of volcanic ash observation in UTC.

Note 4: Observed location shows latitude and longitude of the edge of ash cloud, respectively.

When analyzing the flight trajectories of each flight, classifying the trajectories is the most important work; in other words, finding the “regular” flight route is the key to understanding the features of the emergent situation, that is detour/rerouting and cancellation. For this aim, we adopt a hierarchical classification technology, hierarchical density-based spatial clustering of applications with noise (HDBSCAN). HDBSCAN (Corrado et al. 2020) is a family of density-based spatial clustering of applications with noise (DBSCAN), which is often used for classifying trajectories (Yuan et al., 2016; Olive and Basora 2019). HDBSCAN treats the classification by considering the stability of a hierarchy of clusters (Corrado et al. 2020), and it is useful for understanding the characteristics of each trajectory of the same flight. Therefore, we adopt this technology for classifying the flight trajectories.

HDBSCAN requires the information of the difference among trajectories. We focus on the difference considering the distance between trajectories. To identify the distance between trajectories, we adopt the idea of the Fréchet distance (Eiter and Mannila 1994), which is a distance metric that fully considers the location and sequential relationship of the point in trajectories while measuring their similarity. If the similarity is high, the value of the Fréchet distance is small. Fig. 2 depicts an example of trajectories and the values of the Fréchet distance. The figure shows the actual flight trajectories of China Eastern Airlines’ flight 715 (MU715) on January 10, 11, and 12 in 2020. The similarity between January 10 and 11 trajectories is very high, and the Fréchet distance of these two trajectories is 1.755. Conversely, the shape of trajectories of the 10th and 12th of January are quite different. The Fréchet distance of these two trajectories was calculated to be 8.412. Through the HDBSCAN algorithm, the trajectories of MU715 flying from Shanghai to Sydney in January 2020 are classified as three clusters: two regular routes and noise (irregular routes). The trajectories
of January 10 and 11 are classified as regular routes, while the trajectory of January 12 is classified as an irregular route. As mentioned before, we can use this information, including actual observations as well as data collected after 6, 12, and 18 h, and depict the frontier of ash cloud movement based on the information by Tokyo VAAC announced at 18:00 on January 12, 2020 to understand the characteristics of trajectories more clearly.

From Fig. 2, we can understand that the regular route of MU715 (January 10 and 11 routes) goes through the heavily ash-contaminated area (surrounded by the dashed lines), and the flight should take the emergent route (January 12) to avoid risks. Additionally, the departure time (coordinating universal time/UCT) was around 13:00—4 h had passed since the Taal volcano had last erupted—and therefore, the airline had a redundant route.

Another movement is shown in the case of JL37 (Japan Airlines) flying from Narita to Singapore (Fig. 3), of which the departure time was 1:50 (UCT). There are two regular routes; one is the route of January 11 and 12 (named route 1), and the other is that of January 13 (named route 2). Route 1 crosses through the heavily ash-contaminated area; therefore, route 2 can be taken. Because the departure time on January 12 was earlier than the time when the first eruption occurred, JL37 was not affected by the eruption; the eruption affected the next day’s flight instead. An interesting behavior of JL37 is that, after the eruption, they changed their route from route 1 to route 2 for two weeks. Comparing the cases of JL37 and MU715, JL 37 takes a route closer to the frontier of the ash cloud.

3. Results And Discussions

3.1 Summary of statistics

We randomly selected the trajectory data of 120 different flights from January 2020. When we selected the flight, we did not use flight data that had more than five non-flight days, except on January 12 and 13, because we needed to focus on flights that operated under a stable flight plan. Table 2 shows the summary of the data.

Table 2. Summary of data. FSC means full-service carriers; LCC means low-cost carriers.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>FSC</th>
<th>LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>To/from Manila</td>
<td>49</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>To/from the Philippines</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intra-Asia</td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of cancellations (January 12, 13, and both 12 and 13)</td>
<td>32, 10, and 4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regarding the airline category, 30% of the samples are of low-cost carriers (LCCs). Considering the share of LCCs in Asia-Pacific markets, the rate is almost like the market share, 29% (CAPA, 2019). Most of the samples are of intra-Asia flights, and 51% of them are from/to Manila flights. Thus, many flights of the samples are supposed to be affected by Taal volcano's eruption. The number of cancellations on January 12, 13, and both days are 32, 10, and 4 flights, respectively. This means that approximately 27% of the samples were cancelled or there was no flight on the day of the eruption.

3.2 Categorizing the flights

Applying the HDBSCAN algorithm can categorize trajectories of each flight. We mainly use a density of five; therefore, we can categorize two or three types of flights. However, some flights have more variable patterns. Consequently, we sometimes use a density of four or three; The choice of the density depends on the case.

Table 3. Example of results (HDBSCAN).
Table 3 shows the results of the HDBSCAN analysis on flight LJ63 (Jin Air), JL746, and 5J459 (Cebu Pacific). X means there was a cancellation/no flight. “0” appears in some columns; this means the trajectory cannot be categorized, and it is treated as “noise.” JL746 has two clusters, that is “1” and “2”, and it has no anomalistic trajectory; 5J459 has three categories; LJ63 has two categories, 1 and 2, but some uncategorized trajectories shown as “0” appear. From the table, LJ63’s trajectories in January 2020 were much various and unstable than other flights.

First, let us see the change in categories from January 11 to 15. Airlines are supposed to have cancellations/no-flight or changing route to avoid accidental events due to ash-contaminated air. There can be several combinations of decisions for flight cancellation, change of route, or flight-as-usual. Table 4 shows the results of the classification of routes.


<table>
<thead>
<tr>
<th>Category</th>
<th>No</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>21</td>
</tr>
<tr>
<td>II</td>
<td>29</td>
</tr>
<tr>
<td>III</td>
<td>22</td>
</tr>
<tr>
<td>IV</td>
<td>4</td>
</tr>
<tr>
<td>V</td>
<td>20</td>
</tr>
<tr>
<td>VI</td>
<td>10</td>
</tr>
<tr>
<td>VII</td>
<td>14</td>
</tr>
</tbody>
</table>

As Categories I and VII represent flights with “no change” on their flight routes during these days, 70% of samples had some route changes on January 12 and 13. Categories II and IV, which represent flights that took a special operation for one day, occupy 42.5%. From the results, we can say; they consider that a one-day special (anomalistic) operation is enough for avoiding accident risks owing to the ash-contaminated air. Category IV, V, and VI represent airlines that keep their special operation for a couple of days.

Fig. 4 shows the comparison of trajectories of Z29047 (Philippines Air Asia) on January 11, 12, 14, and 15.

The regular route of Z29047 ran through the area where the ash-contaminated air remained. Thus, they changed the route drastically, far from the area of the ash-contaminated air. The next day, they canceled the flight. On January 14,
they kept their irregular route to avoid the accident risks due to the ash-contaminated air; however, that route was a bit closer to the regular route (January 11 and 15 routes) because the major part of ash cloud moved out from the area relevant to their regular route. From this behavior, Z29047 seemed to take “more risk-averse” behavior. As Z29047 is an intra-Asia flight, considering the behavior of 96 intra-Asia flights would be meaningful to understand whether the behavior of Z29047 is unique. Sixty-seven flights from 96 samples are classified as “irregular” routes on January 12 and/or 13. Thirty-eight out of 96 flights that had irregular routes took a special operation for one day; its rate was 39.6%. Consequently, the behavior of Z29047 can be a more risk-averse action as an intra-Asia flight.

Another aspect is observed between intra-Asia flights and Manila-based flights. Sixty-six out of the 96 intra-Asia flights are Manila-based flights. Fifty-three flights out of the 66 Manila-based flights are classified as having “irregular” routes on January 12 and/or 13. Thirty flights are classified as Category II or III flights, that is, special operation for one day. The rate of special operation for one day reached 56.6%. In this context, there is no difference in the rate of special operation for one day between intra-Asia flights and Manila-based intra-Asia flights.

Regarding the long-haul flights[3], we have 23 flights in the sample. Seventeen flights were classified as having “irregular” routes on January 12 and/or 13. In 17 flights, 13 flights took special operation for one day, and their rate reached 76.5%; thus, five flights were supposed to take more risk-averse behavior. Fig. 5 shows the comparison of trajectories of KE112 (Korean Air) from January 11 to 14, 2020. On the 13th, KE112 took an irregular route, but the following day it got back to its regular route because the major part of ash cloud moved out (or was forecasted to move out) from the area relevant to their regular route.

Comparing the rate of intra-Asia flights to that of long-haul flights, we can say that intra-Asia flights can more risk-averse behavior than long-haul flights. However, in each case, the trajectory of irregular flights is close to the edge of the ash cloud (or the expected movement area of the ash cloud); this suggests that the flight path of irregular routes could heavily depend on the information provided by the VAAC.

Another discussion point is about the departure time. Fig. 6 shows the comparison of departure times (UTC). Looking at the figure of Category II (left side chart), no flight is found from 0:00-6:00. Conversely, 0:00-12:00 flights occupy the majority in the pattern of Category III (right side chart). This means that “special operation for one day” can be taken for the flights of which departure times were between 9:00 on January 12 to 12:00 on January 13. An interesting point is that there is no observation at the time range 12:00-15:00 on January 13. Fig. 7 suggests its meaning.

In Fig. 7, half of the observations, that is ten flights, are categorized as the flights with a departure time of 12:00-15:00. More importantly, six of the ten flights are bound for the Philippines. Therefore, one hypothesis can be proposed: based on the VAAC information, flights that were destined for the Philippines and had a departure time of 12:00-15:00 could be affected by the ash-contaminated air if one day had passed since the eruption; therefore, they kept their special operation. Because the last eruption was on the 12th of January (UTC), the decision made after 24 h could be critical; in other words, 24 h later, the airlines (or flight operators) should have a decision of “keeping the special operation” or “back to the regular” in the case of the 2020 Taal volcano.

From above discussion, we have the following possible actions about flight cancellation or rerouting in the case of the 2020 Taal volcano.

1. The airlines choose flight cancellation or at least rerouting for the flights that fly through or near the heavily ash-contaminated area within 24 h.
2. After 24 h, airlines can have two options for flights that depart within a couple of hours; “keeping the special operation” or “back to the regular”, in the case of the 2020 Taal volcano.
3. After 27 h, airlines can turn the schedule back to normal and reduce the number of cancellations and irregular routing drastically.

Action 1 would be rational because airlines should focus on the movement of the volcano after the large eruption to avoid further risks from imminent eruptions. After 24 h (Action 2), their decision would be critical. If the airline is (more) risk-averse, they can keep their special operation (cancellation or rerouting); otherwise, they try to get back to “regular.” This depends on the characteristics of the airline and/or route. In subsection 3.2, we suggest that intra-Asia flights would be more risk-averse than flights that take the long-haul routes. In other words, long-haul flights can be regarded as “more optimistic.” The exact reason is unclear so far, but one possible reason may be the travel time. As long-haul Pacific flights have a long travel time (10-12 h), the airlines may expect the “better situation” several hours later judging from the information from VAAC. However, this hypothesis must be proved with other information. This is our next research target.

[3] We define the flight as long-haul when the flight requires more than eight hours.

4. Conclusions

This study analyzes the influence of a large volcanic eruption on flight routing, by applying the trajectory clustering technology (HDBSCAN with Fréchet distance) and finding ways to avoid risks due to the volcanic ash. For the case of the 2020 Taal volcano, we have three possible actions discussed in the previous subsection. In three actions, we should highlight that Action 2— after 24 h, airlines can have two options for flights that depart within a couple of hours— suggests the airlines’ critical decision-making situation. Of course, this can depend on cases, but “24 h” can be one strong threshold for deciding their behavior. The aviation sector can have a guideline for critically deciding “flight or not” considering this threshold. Considering details about deciding the threshold will be needed for fruiting the useful guideline for avoiding the trouble due to the ash-contaminated air; however, our three possible actions will be a good first step for this goal. Notably, the information from the VAAC, which is based on highly reliable satellite observations, has a more critical effect on flight decisions. In addition, accurate forecasting of ash cloud movement would be crucial for decision making by airlines.

The case of the Taal volcano was a relatively big eruption, which means its ash plume almost reached the stratosphere. Thus, as we analyzed, this eruption caused the special operation for aviation[4]. Although the Taal volcano’s case was classified as VEI=3[5] class, the impact on aviation cannot be regarded as small. If a larger eruption— VEI=4 class or larger— occurs in this area (Asia-Pacific), the impact will be crucial. This means more cancellation/special operations will be needed and the decision for getting back the regular route/flight plan will be much more important. Policy makers should provide a suitable guideline for making the “flight or not” and “keep the special operation or get back to the regular” Decisions. For this aim, a more detailed analysis about the timing of a decision at flight would be demanded.

This study has some limitations. First, our analysis is based on sampling data, of which the number is limited. We took care of non-bias sampling and our results captured the outline of the emergent behavior of the flights, but expanding the number of observations would be desirable to improve the stability of results. Second, we have a hypothesis that the airline may expect the “better situation” for long-haul flights several hours later judging from the information from the VAAC. However, it is obtained from a very limited number of observations. This study deals with the case of Mt. Taal 2020, but for reinforcing the rationality of our hypothesis, we need to catch other cases. In the Asa-Pacific region, some serious eruption occurred; Mt. Semeru of Indonesia in 2021, Mt. Manam of Papua New Guinea in 2022, and Hunga-Tonga-Hunga-Ha'apai of Tonga in 2022. In the next study, we will collect the data of these eruptions and discuss the rationality of our hypothesis.
[4] Taal volcano erupted in 2021 and 2022, but these eruptions were not so harmful because its ash plume did not reach the stratosphere.

[5] VEI (Volcanic Explosivity Index) is defined by the volume of the eject and plume height (Newhall and Self 1982). Takebayashi et al. (2021) mentioned that a large eruption with VEI=4 class or larger will cause a serious transnational crisis on air and other transport modes.

**Declarations**

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**Author contributions**

Aleksandra Solodova: Data Collection, Methodology, Formal Analysis, Writing Original Draft (Introduction, methodology, data description, and trajectory analysis)

Mikio Takebayashi: Conceptualization, Data Collection, Methodology, Formal Analysis, Writing Original Draft (All part)

Masamitsu Onishi: Formal Analysis, Writing Original Draft (Discussion part)

Masato Iguchi: Writing Original Draft (Volcanic disaster part)

**Competing interests**

The authors have no relevant financial or non-financial interests to disclose.

**References**


Figures
Fig. 1. Movement of an ash cloud (January 12, 2020).

Note 1: Based on the Himawari-8’s information the authors described.

Note 2: ▲ shows the location of the Taal volcano. The lines from inside to outside mean the approximate frontier of the ash cloud at 16:00 (thin), 16:30 (dotted), 17:00 (broken), and 17:30 (thick).

**Figure 1**

See image above for figure legend.
Figure 2

Flight trajectories of MU715 (January 10-12, 2020). In the legend, “Ash cloud” means the movement of the frontier of the ash cloud based on the observation at 18:00, on January 12, 2020. Circles in the ash cloud lines are the points where the edge of the ash cloud (forecasted to) is observed.
Figure 3

Figure 4

Trajectories of Z29047 (January 11, 12, 14, and 15, 2020)
Figure 5

Trajectories of KE121 (January 11, 12, 13, and 14, 2020).

Figure 6
Comparison of observed flights by departure time (Left: Category II; Right: Category III).

Category II: Cancel/no-flight or irregular route on Jan 12, and on Jan 13 back to the regular.

Category III: Cancel/no-flight or irregular route on Jan 13, and on Jan 14 back to the regular.

**Figure 7**

Comparison of observed flights by departure time (Category V: Cancel/no-flight or irregular route on Jan 12 and 13; on Jan 14 back to regular.)