Digital data behind ATSB 'MH370 path' from take-off from Kuala Lumpur until exiting radar coverage at 18h22 UTC.

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1 Presentation of the document

This document does not radically change our current knowledge of the trajectory travelled by MH370 between the IGARI waypoint and leaving radar coverage at 18:22 UTC. It provides evidence for almost perfect knowledge of this segment of the trajectory.

The objectives of this report are twofold: on the one hand, to present new, previously unknown digital radar data and to verify its purpose and quality; secondly, present a complementary study to our analysis where a fully piloted trajectory was reconstructed [1]. It should be understood as an update of the document on civil radar data published in [2].

With the help of trise5631, new information could be extracted, confirming our previous conclusion about manual piloting of the aircraft in the full geographical coverage of this digital data. In addition, this new data also makes it possible to infer a more precise, even still approximate, flight profile, leading to a conclusive estimate of FL320, or possibly FL300 as initially identified, in the Strait of Malacca. This is a slightly more precise update to our previous analysis [1], which does not impact its conclusions.

A video illustrating Geoscience data and the findings of this analysis is available at https://youtu.be/QTibtxZwaGc

2 Executive summary

2.1 The data

To some extent, this report fulfils the promise made by the Malaysian Defense Minister during the press conference to publish the radar data if it indeed concerns MH370 [3].

The analysis presented in this report goes a step beyond all previous studies on the specific segment of the trajectory of the MH370: the one that was captured by the radars from Kuala Lumpur until the exit from the radar coverage at 18:22 UTC (LSTRP). Until now only “paper or e-copy” images of this track were used or mentioned in a number of papers from analysts. The original image of this track has been published in figure 2 of the 2014 ATSB[1] report [4] and was used as a reference. It is reproduced in Figure 1.

The numerical data behind the reference map is available thanks to Geoscience Australia and has been retrieved for further analysis. It is presented in Figure 2.

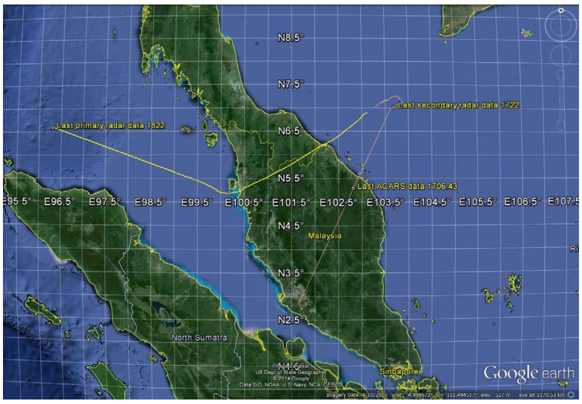

Figure 1: 2014 ATSB report reference map

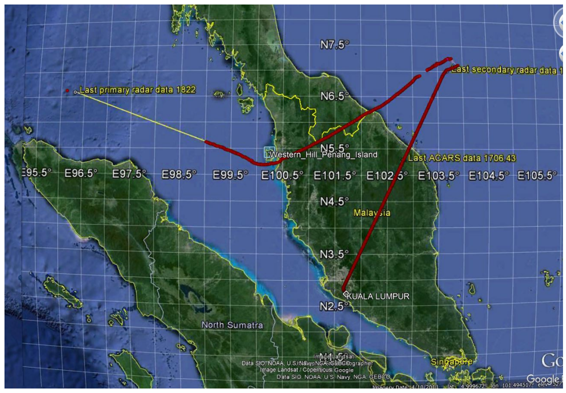

Figure 2: Geoscience points with digital coordinates

In the analysis below, it is shown that this numerical data is most probably the dataset given by Malaysian authorities to the ATSB.
With this data, knowledge switches from graphical to a substantial numerical content allowing for a more precise characterisation of the flight path from Kuala Lumpur to LSTRP.
The dataset includes geodetic coordinates for all provided points with an altitude information only for those from take-off until abeam IGARI. The track is not a continuous line but includes three holes, one during the U-Turn, one at halfway to Kota Bharu and one after Pulau Perak.
No time information is provided in the dataset. This makes any attempt to deduce speed information unfounded.
The points in the dataset are samples more or less regularly selected along the ground projection of path and in any case with a lower resolution than the digital data coming from the radar heads already published.

[1] *Australian Transport Safety Board*

2.2 The results

From take-off to IGARI, the aircraft demonstrated an excellent capability to fly a geometrically perfect trajectory controlled by the Auto Pilot LNAV function. The precision is remarkable. After IGARI, no such precision is visible. Even considering radar measurement errors, the trajectory presents the characteristics of a manually piloted flight (see Figure 3).

In particular, the reconstructed U-Turn simulated a year before recovering this data is matching perfectly the data. Thanks to this data, the U-Turn radius is now known numerically. It demonstrates that the U-turn could not be performed other than manually (see Figure 4).

Figure 3: Visual comparison of the Geoscience track with the KADAX LNAV path

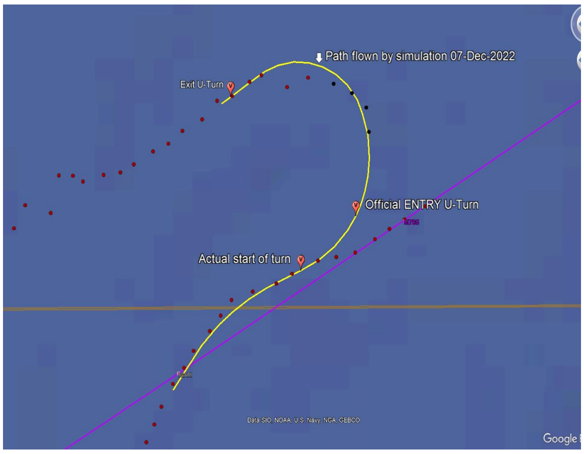

Figure 4: Simulation of the manual execution of the U-Turn with the Prepare-3D simulator (Yellow). Red points are the Geoscience track.

Furthermore, the data confirms the average speed between key points for which the actual geographical position is now known.

In several places, the geographic dispersion of the Geosciences data points as well as the absence of certain points provide very useful information. Using terrain elevation model and computed radar range including the refraction impact, we analysed which radar station was in visibility to track the aircraft and which was not. Cross-correlating the two allowed important aspects of the 3D profile of the travelled trajectory to be determined in many, but not all, locations. The shape of the two most consistent but indicative approximate profiles is shown in Figure 5.

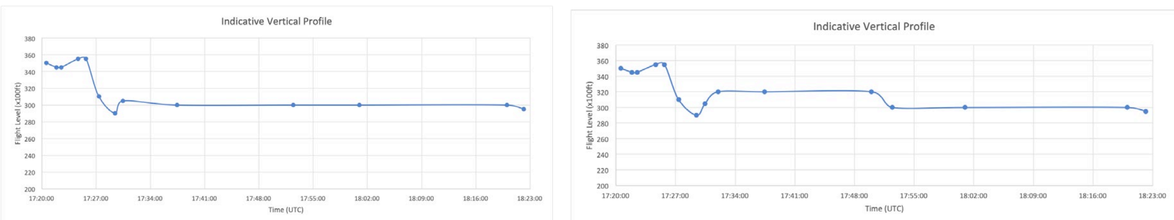

Figure 5: Most consistent indicative vertical profiles between IGARI and the Exit of radar coverage at 18:22 UTC

2.3 Conclusions

The data used on their website by Geoscience Australia to display MH370's trajectory from Kuala Lumpur to the exit from military radar coverage was shown to match the published reference map in Figure 2 of the 2014 ATSB report [4]. It is also coherent with the tracks published by the Australian Defence Science and technology Group (DSTG) and by Boeing.

The key information provided by this dataset is the numerical values of the geodetic coordinates of the points sampled along the track reconstructed by the military radar processor. The time intervals between points approximately follow a 9/9/12 second pattern. But the precision of the provisional time labels does not allow instantaneous values of the plane's ground speed to be evaluated.

No altitude information is provided after crossing IGARI. But before this waypoint, the altitude value is provided in full consistency with the known ADS-B data. After IGARI, the track is the projection on the ground of the actual flight trajectory.

A detailed analysis of the provided Geoscience track points was carried out in two parts. First, the lateral geometry of the actual trajectory was taken into account to verify the flight navigation performance. Second, a high-level geometric analysis using the radar coverage morphology was able to infer information about the relative vertical movements of the aircraft. An enhanced terrain elevation model has been enhanced with a horizontal angular accuracy up to 1/8°.

The analysis confirmed important aspects of the MH370 trajectory between IGARI and the exit from the radar coverage at 18:22 UTC:

- The aircraft was manually piloted as the lateral navigation characteristics of its trajectory do not match the LNAV capability of the auto-pilot.
- The average speed of the aircraft is confirmed at ~510kt.
- An indicative approximate vertical profile could be determined showing that the aircraft descended after the U-Turn and slightly climbed back at either ~FL300 or ~FL320 and ended at ~FL295 at 18:22 UTC.
- This means a quasi-levelled flight path after Kota Bharu if respecting RVSM rules.
- The exact level of refraction is unknown, our modelling with 17% refraction provides the only coherent full picture of the radar coverage and fits with the aeronautical constraints.
- The level of precision of this high-level vertical analysis is estimated at +/- 2000ft

This is in full coherence with the reconstructed trajectory described in our report in [1] where FL300 was identified as the most likely level.

3 Introduction

Until today the MH370 path from take-off at Kuala Lumpur until the exit from the radar coverage in the north of Sumatra at 18:22:12 UTC was only documented by figure 2 of the 2014 ATSB report [4], which is represented in Figure 6. The underlining source of information is not indicated. It could also come from the source indicated at the bottom of Figure 7 given as “ATSB, using Ministry of transport Malaysia”. It is basically graphical information on “paper” without numerical values attached to it. So far, all studies were obliged to work with this picture often overlaid on Google Earth globe in order to draw conclusions on the trajectory of the aircraft on the segment within the radar coverage. It represents the projection on ground of the path flown by the aircraft.

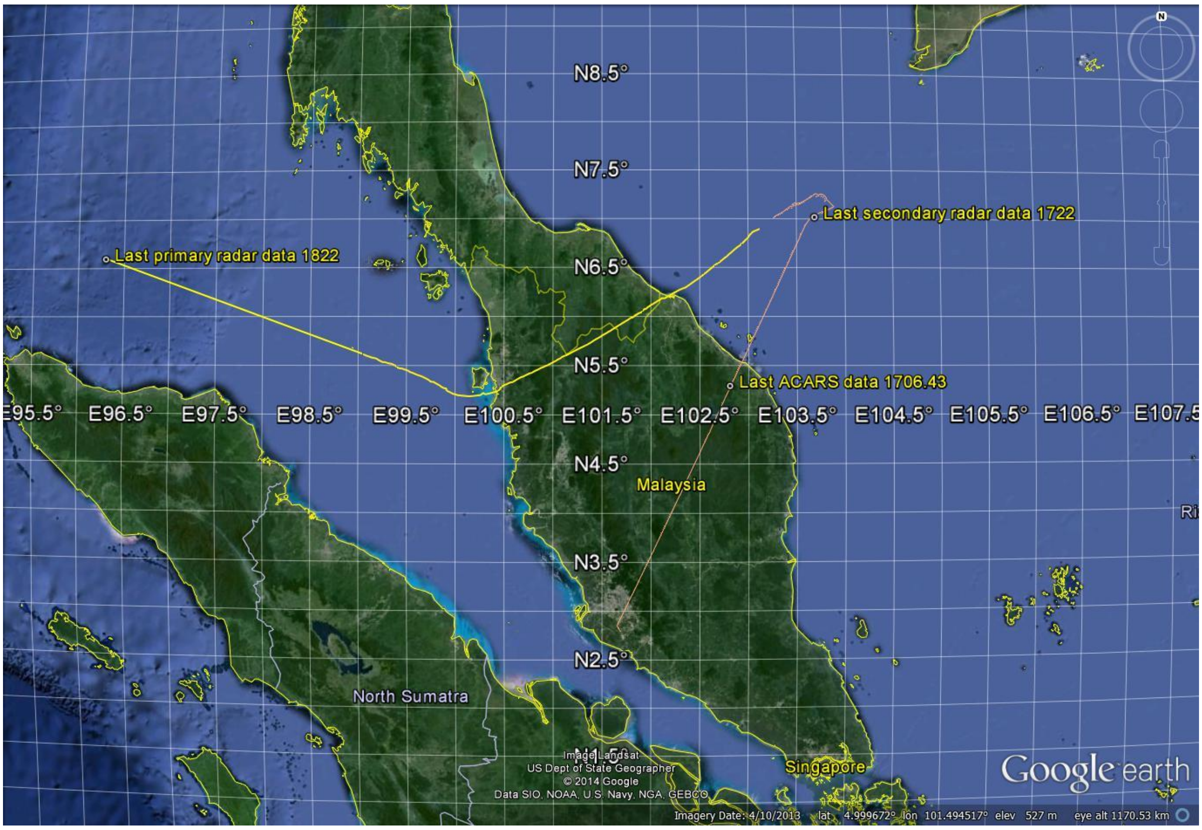

Figure 6: Unique reference picture provided in "paper" by Figure 2 of 2014 ATSB report [4]

Source: ATSB, using Ministry of Transport Malaysia data

Figure 7: History of recorded events (source Fig3 of ATSB report [5])

Until now, the only set of digital radar data provided came from the Independent Group [6] and was the data of the civilian primary approach radars located at Kota Bharu and at Butterworth. They had also published some digital data coming from the secondary surveillance radar (SSR) and the ADS-B messages [7]. We did use these sets for reconstructing the trajectory in our previous analysis [2].

Recently, we have been made aware of an existing digital dataset[2] which could be the one used to create the track illustrated in Figure 6 and in Figure 7. So far, several attempts to recreate numerical path in digitising the 2014 ATSB Reference map were made by using the zoomed image on the Geoscience website like in [8] for example. But actually, the Geoscience web picture is dynamically created at each click using digital data behind the scene to draw the track as vectors. The resulting track matches perfectly the representation given in Figure 7. We retrieved this genuine digital data fetched by the Geoscience Australia website which provides the digital geodetic coordinates of locations overflown by MH370 flight from take-off at Kuala Lumpur up to the vicinity of Pulau Perak Island with an additional isolated point at the exit from radar coverage at 18h22 UTC [9] called LSTRP.

The dataset has been made available on the mh370-caption.net web site [10] in the form of the original data in JSON format and the cleaned data, all grouped in an Excel file.

The purpose of the detailed analysis in this report is to present this digital data and to answer the mandatory questions: Did this data partially support the creation of the ATSB report reference map [4], as suspected? Does it include the actual military coordinates of the aircraft's locations along this 2-dimensional path? Can we use it for better characterising the flight during this time frame?

[2] *Direct communication from trise5631*

Important note: **Unfortunately, this data only provides altitude information up to abeam IGARI only. Additionally, it does not provide any temporal information either.**

Necessary steps must be completed before using the data with confidence. The first mandatory step is a technical review of the data to verify that it is what it is supposed to be. Then, different key events/locations and the subsequent segments will be analysed in detail using the data. A potential characterization of an indicative vertical profile will also be presented. An attempt to label the data with temporal labels is also reported but it was only made as a theoretical exercise because the data, being the result of military tracker processing, provides no clue to the temporal dimension.

Caveat1: ***Because of this last remark, the reader should be aware that any speed analysis performed on this data would be pure speculation. Thus, like any aviator, the speed must be evaluated as average speeds over the long segments between the 3 known locations with their known time label: The Exit from the U-turn, the detection of the co-pilot's cell phone at Penang and the Exit from radar coverage at 18:22 UTC. Any other attempt would NOT be based on solid ground.***

Caveat 2: ***The underlying assumption of the ATSB reference map and Geoscience dataset is that the aircraft flew directly towards the LSTRP from Pulau Perak Island. This is not correct. The final Malaysian report [11] clearly indicates: a direct 292° towards VAMPI, a turn at VAMPI then a true course at 285/286°. There were few navigation entries as visible from the Lido's image but no direct route as the Geoscience dataset suggests.***

4 Technical analysis

4.1 Source of the data

The digital dataset is actually the supporting source of information to dynamically create a public illustration on the Geoscience Australia site [9] as illustrated in Figure 8. This public website presents an animated page including a picture of a vector trajectory from take-off at Kuala Lumpur, via the U-Turn at IGARI and until the exit from the radar coverage at 18h22 UTC. This picture is not a still image created a priori but is recreated each time it is displayed.

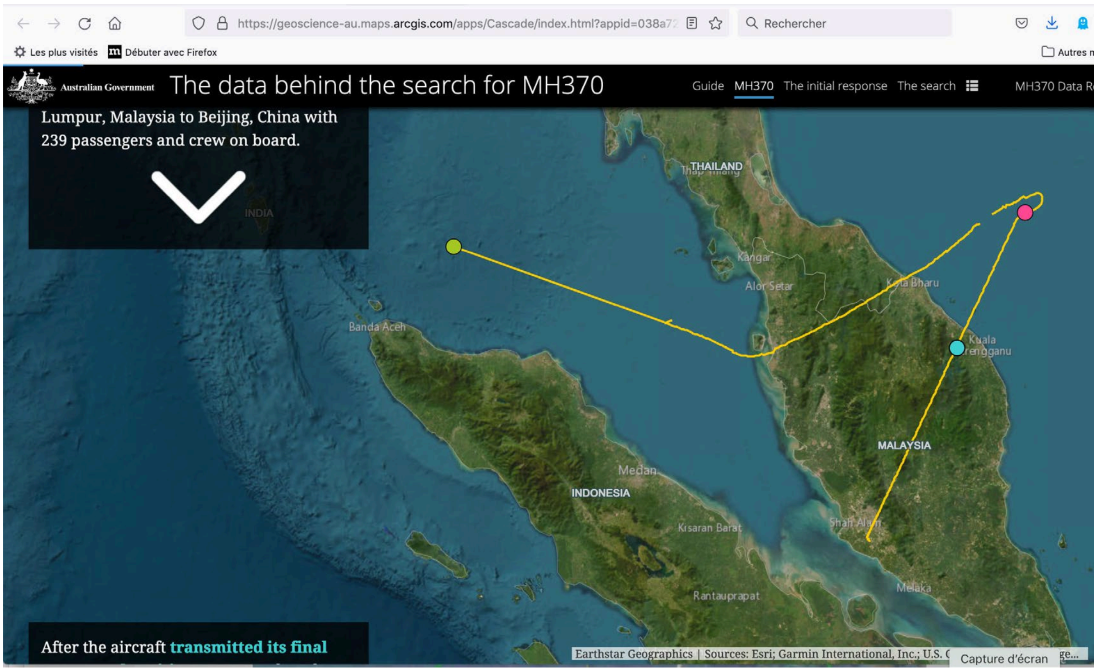

Figure 8: Geoscience Australia's illustration of MH370 path published on their site "The data behind the search for MH370"

4.2 Availability of the data

The original extracted data files are now available on our website at www.mh370-caption.net. They include the original JSON file, an Excel file containing just the numerical data, and an Excel file with an attempt to assign time labels to each of the points under the caveat1 above. All grouped in one Excel file.

4.3 Short Description

The data is available in digital format with the following information:

- SSR points with geodetic locations on the ground with altitude values from Kuala Lumpur to abeam IGARI (i.e. the climb phase and the start of the cruise phase)
- PSR points with geodetic ground locations with elevation value = 0 (meaning: no altitude data available)
- Some extra points probably added manually to aesthetically present a continuous, smooth U-turn that is actually unrealistic
- Several duplicated points and some points that make no sense

A more detailed description is provided in Section 4.4 below where the data is numerically analysed and cleaned.

Geoscience Australia takes data through ArcGIS platform services and dynamically creates the image shown in Figure 4. The ArcGIS platform is a service provided by ESRI based in Redlands, California.

It should be kept in mind that the exact origin of Geoscience data is unclear. The field "Credits" is filled with the value "ATSB". In addition, for figure 3 of the ATSB report [5], the source is indicated as "ATSB using Ministry of Transport Malaysia data". It will be demonstrated that in fact there is a high probability that indeed this data comes from the ATSB who used it to produce the single reference "paper" map in its ATSB 2014 report [4].

4.4 Cleaning of the data

4.4.1 At the U-Turn

The original JSON data file contains 229 SSR points (3D) with altitude values in meters and 271 PSR points (2D) in 10 segments without altitude information. The path they describe at ground level is illustrated in Figure 9.

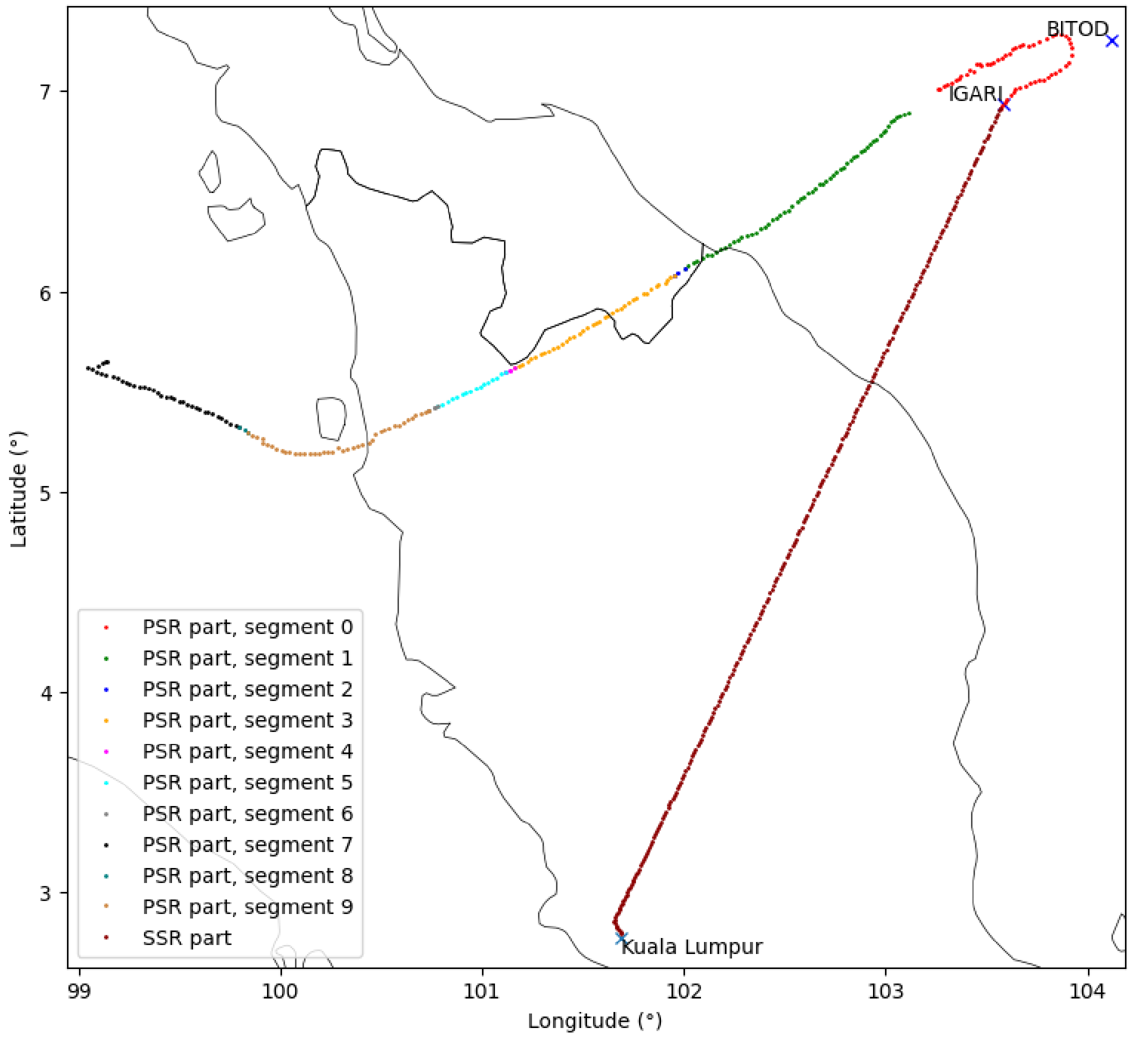

Figure 9: Geoscience Australia path at ground level

In the JSON file the different segments are not provided in the order of the flight. Thus, the segments were joined and arranged in chronological order. 12 points were removed because they were perfect duplicates of other points. Another five points were removed because they were considered duplicates due to their proximity, i.e., within 0.18 nm, of other points. The last 4 points were also removed because they clearly describe an unrealistic trajectory with almost instantaneous backward flight.

A quick comparison of the data with the ATSB 2014 reference map [4] shows that the U-turn after IGARI has been significantly modified. It is believed that as this data was used to generate a public map depicting the known trajectory, points were removed and some added at the U-turn to display a more aesthetic continuous turn on the website image. Although points could be manually removed from the data by checking their consistency with the ATSB reference map, a more objective method was used to discriminate outliers.

The given coordinates are expressed with 12 decimal places in the data. However, most coordinates are multiples of 2.7777x10-4, or 1/3600. The coordinates therefore have a precision of one second of a degree. Only 13 points do not respect this pattern: 1 point shortly before IGARI, and 12 points in the U-Turn. This evidence was used to determine that these 12 points were the ones added to the map.

After removing them, the remaining points were visually similar to the ATSB data. The other point that does not follow the one degree second pattern appears to be a transition point between the SSR part and the PSR part. It has also been removed. The removed points (in red) and remaining points (in green) around IGARI are shown in Figure 10 in comparison with a grey scale version of the ATSB reference map [4].

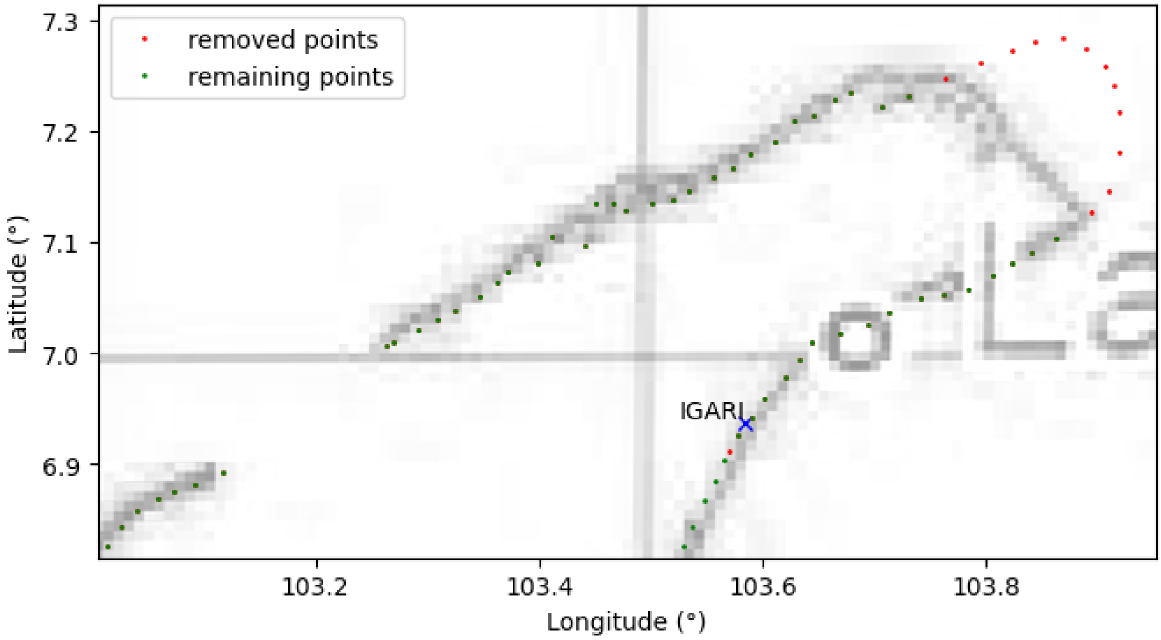

Figure 10: Comparison of the ATSB map with the remaining points after cleaning

In total and after this data cleaning, there remain 228 SSR points and 238 PSR points as illustrated in green in Figure 11. The red points are not retained as valid for the rest of the analysis.

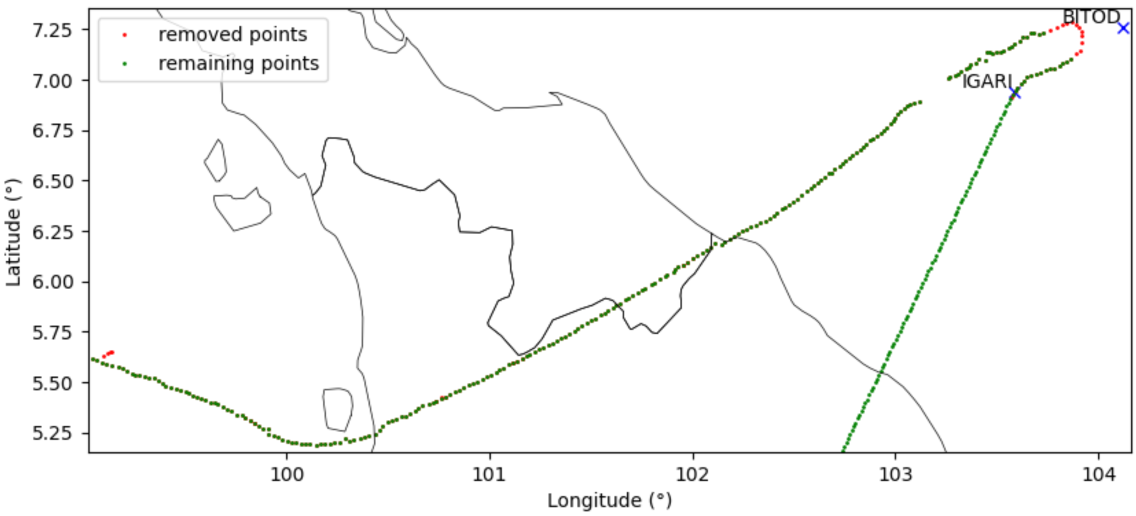

Figure 11: Geoscience Australia clean set of points retained for further analysis (green)

After this cleaning, comparing the cleaned dataset with the ATSB reference map shows that the Geoscience dataset is missing some points. Figure 12 shows that 5 or 6 points are missing in the U-turn. Two possible interpretations are possible: either the ATSB provided the dataset without them or they were not preserved by Geoscience for aesthetic purposes. They are highlighted by the blue arrow in Figure 12.

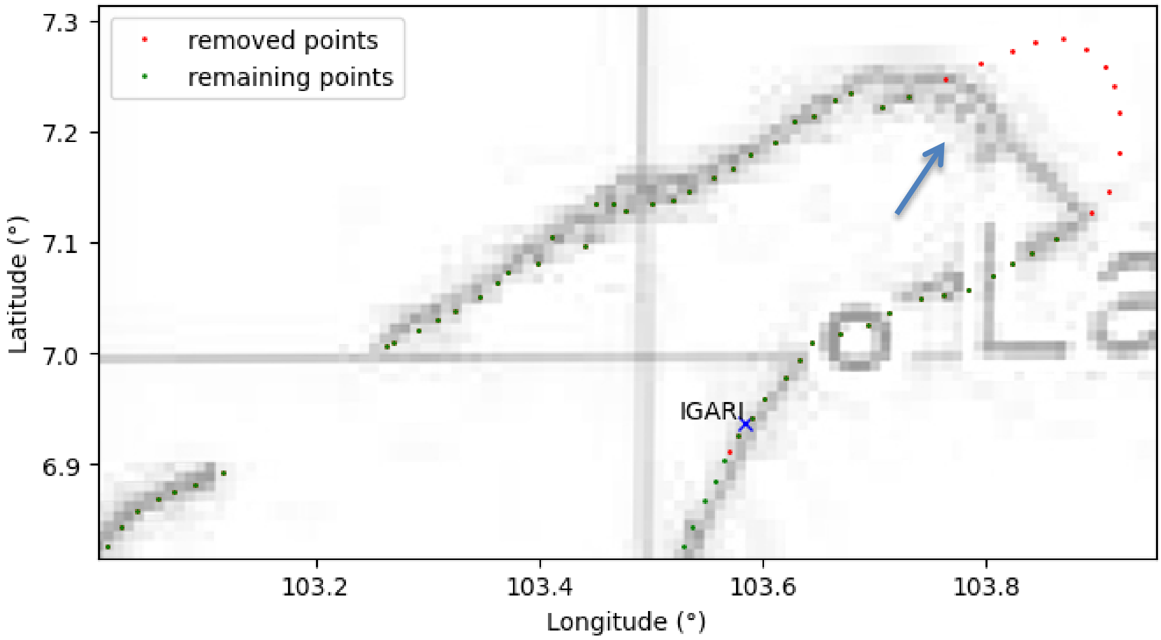

Figure 12: Highlight of missing points in Geoscience data set

4.4.2 Before Pulau Perak

At the end of the Geoscience track, which is near the island of Pulau Perak, there are 4 points, which obviously do not belong to the flight path because they suggest that the plane flew almost a U-turn instantaneously. This sharp turn is beyond the aeronautical capabilities of the aircraft and is not justified by any logical reason.

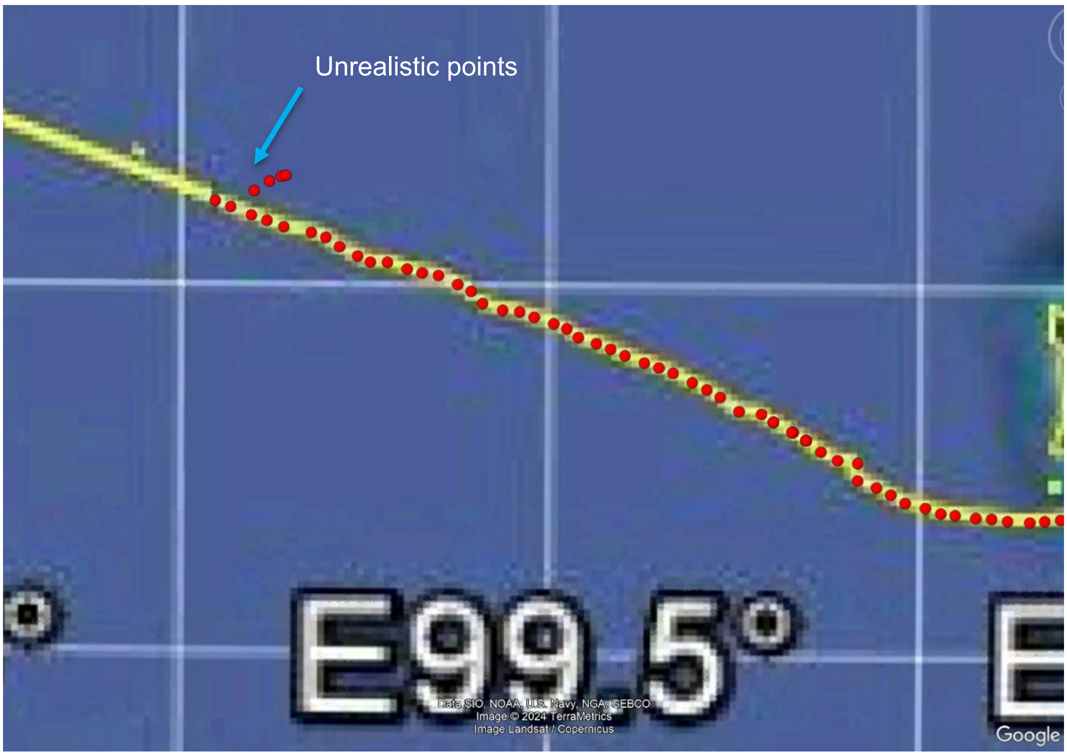

Figure 13: Geoscience dataset last outliers (4) near Pulau Perak

4.5 Visual Characteristics of the data

Figure 14 shows the overlay of Geoscience digital cleaned dataset in dark red over the previously presented ATSB reference map from the ATSB report [4]. The visual match is excellent.

However, some observations should be made:
- the Geoscience data does not cover the full yellow path of the ATSB reference map.
- three gaps are visible due to missing data (cf Figure 14):
    - Gap-1 is during the U-Turn i.e. after IGARI until the end of the U-Turn,
    - Gap-2 is starts some time after the Exit of the U-Turn at around 17:28:06 until 17h29:28 and is approximately 11Nm wide
    - Gap-3 starts few nautical miles before the Pelau Perak Island and finishes at the Last Radar Point (LSTRP) at 18h22:12 UTC.

Thus, one can conclude that the Geoscience data set is almost the full dataset output from the radar tracker except few points in the U-Turn. It includes 3 visible continuous segments and 1 final point:
1. Segment-1: from Kuala Lumpur to the loss of echoes after IGARI
2. Segment-2: starting somewhere towards the end of the U-turn for a length of 32 Nm
3. Segment-3: Starting after Gap-2 and finishing at about 7Nm before Pulau Perak Island
4. Final point: Isolated point (Last Radar Point called LSTRP) at the exit from the radar coverage in the northwest of the Strait of Malacca. The coordinates provided by Geoscience are at [96.311130957E; 6.599852522N]

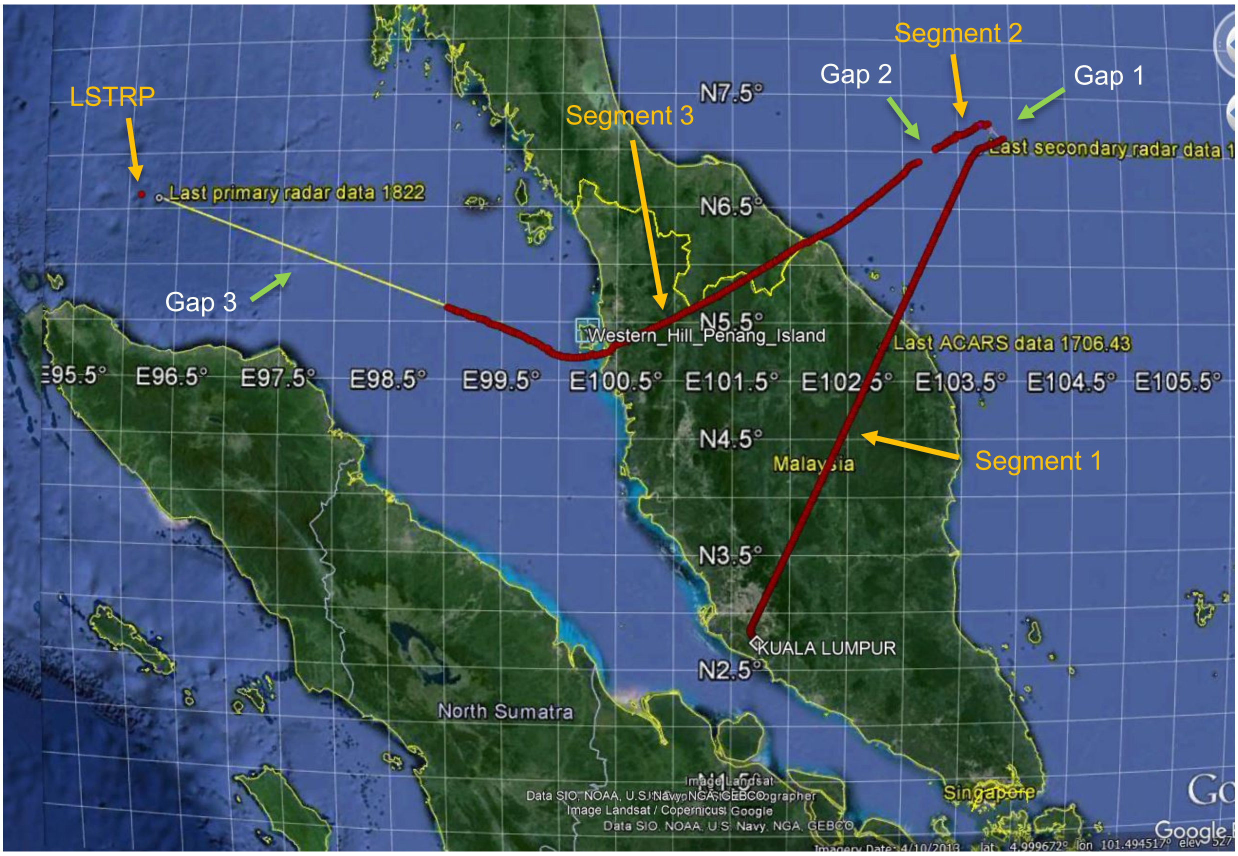

Figure 14: Overlay of the Geoscience points on the ATSB reference map with segments and gaps

4.6 Data checking

Despite the unknown origin of the Geoscience dataset, annotations in the original JSON file can be used for segment matching:

- "Flightpath": Segment 1 from Kuala Lumpur up to IGARI
- "Air Defense Radar Path": Segment 2 + Segment 3 from the exit from the U-Turn to near Pulau Perak Island
- "Path to Connect Updated Last Air Defense Radar Point to Air Defense Radar Data": Pseudo-segment 4 from Pulau Perak Island to the last radar point (LSTRP)

4.6.1 Checking by geodetic coordinates

In order to assess the confidence that can be placed in this dataset, it should be compared with available data from other sources where available and via numerical calculations where possible.

4.6.1.1 From Take-off to abeam IGARI

On Segment-1, Kuala Lumpur to abeam IGARI, SSR and ADS-B datasets are available. The latter provide data on a large part of this Segment.

Figure 15 illustrates ADS-B data provided by the Independent Group (IG) in green. 3584 3D-Points are available from the early stage of the climb phase up to IGARI at 17h20:34:55 UTC. Figure 16 illustrates Geoscience data in dark red including 228 available 3D-Points from take-off at Kuala Lumpur up to IGARI at 17h20:27[3] UTC.
The two data sets are not exactly covering the same time frame but this is sufficient to qualify their geographical correspondence.

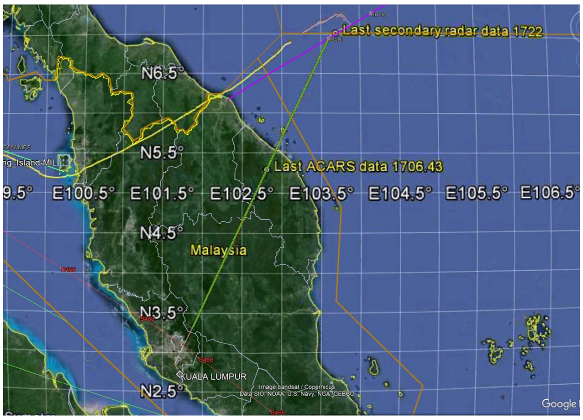

Figure 15: ADS-B points (source IG)

Figure 16: Geoscience points up to IGARI

A simple method was used to perform the quality check on this Segment-1: For each point of the two data sets, SSR and ADS-B, the closest distance between this point and the RMS[4] path defined by the Geoscience points was measured.

Figure 17 shows the evolution of the distance value during the time window starting at 16:49:45 UTC and ending at 17:20:27 UTC for ADS-B and at 17:06:12 UTC for SSR. The match is excellent since the distance is limited to 0.25 NM for most of the duration of each set.

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[3] *For practical reasons, the temporal labels assigned in Section 4.8 are used here in anticipation to identify each point.*

[4] *RMS: Root Mean Square is a distance minimization criterion*

For ADS-B, the distance increases rapidly from 17:20:15 UTC. It should be noted that approximately 25 seconds before IGARI, the Geoscience points gradually move slightly to the left. This is probably due to the tracking algorithm inertia showing some hesitation close to the IGARI waypoint probably coming from the SSR source, which is less frequently updated than ADS-B.

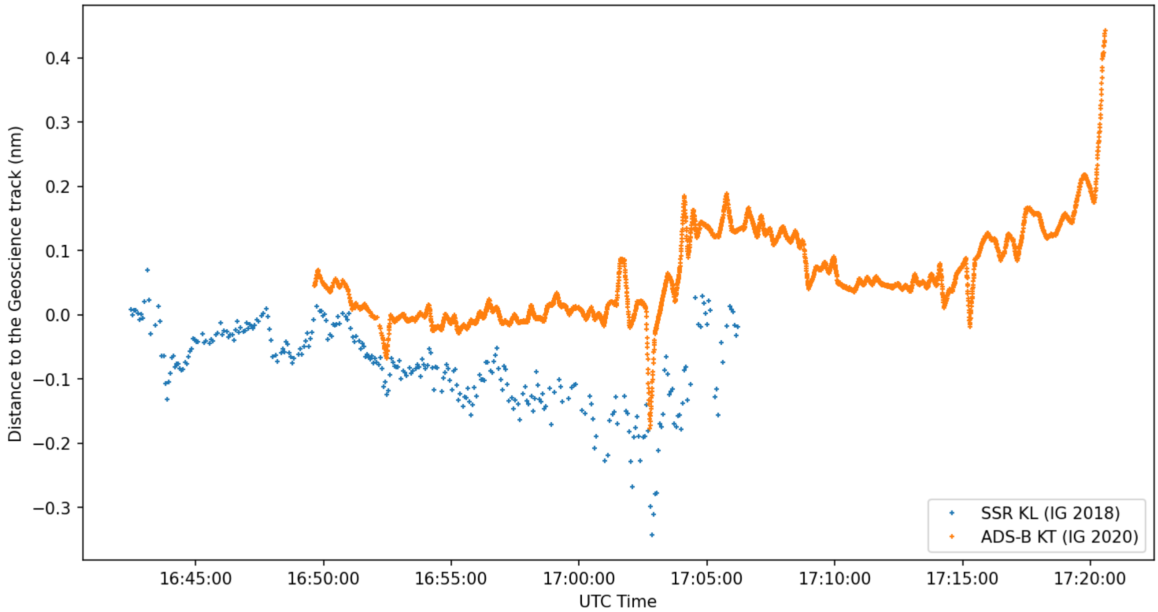

Figure 17: Orthogonal closest distance from SSR and ADS-B points to Geoscience path from 16:49:45 to 17:20:27 UTC

For completeness, Figure 18 shows the comparison between the altitude provided over time in the ADS-B dataset and the Geoscience dataset. They are identical.

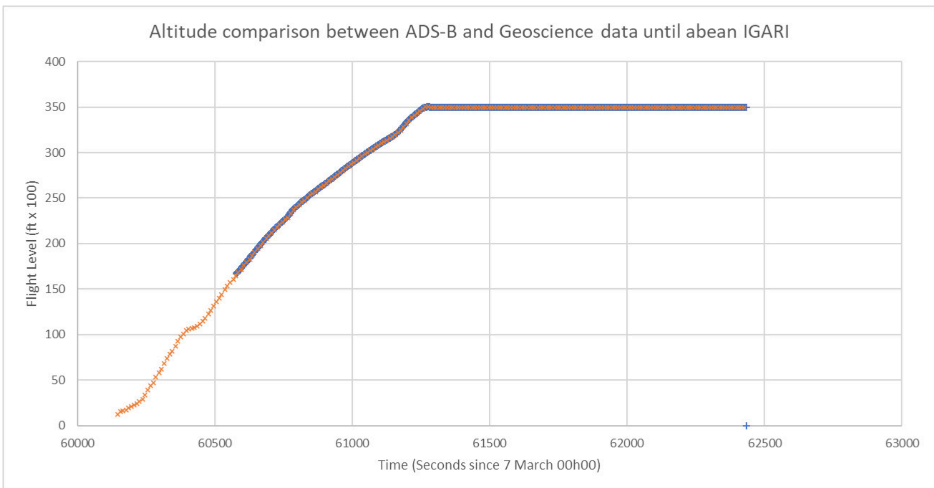

Figure 18: Comparison of ADS-B altitude versus Geoscience altitude from 16:49:45 to 17:20:27 UTC

After it passed abeam IGARI, no SSR (and thus ADS-B also) information was received by the ground. Coincidentally, the Geoscience altitude information is given as 0 from this precise moment.

The Geoscience dataset was constructed using SSR altitude information. A-priori ADS-B is not a primary source of the military operational system.

Figure 19 shows a zoom of the points positioned on the Google Earth map as IGARI approaches. Each Geoscience data point is in dark red with its alternate number in the ADS-B dataset in green until IGARI at 17:20:36. (Note: for the Geoscience point at 17:20:36, the altitude is given as 0).

This illustrates the impact of the data fusion algorithm (military processor software), which calculated the track using additional information in addition to pure geodetic information. In particular, the coordinates of the IGARI waypoint were used to "force" the track to fly over IGARI, because the software poorly imitates the real trajectory calculated on board and actually flown. Due to inertia and flight dynamics, an aircraft does not actually fly vertically over a waypoint where a turn must take place. But it is rather a slight shortcut along an arc tangent to the two segments of the route.

This is only visible once in the entire dataset, i.e. only here at IGARI. But the consequence is that, at the start of the turn, the plane was actually flying a short distance on the east side of the trajectory reconstructed by the radar data Processor. Fortunately, this has almost no impact on the ability to analyse the trajectory.

Figure 19: Discrepancy between Geoscience points (red) with ADS-B points (green) abeam IGARI waypoint

4.6.2 Checking by visual matching

In the remaining data between 17:20:36 and 18:22:12 UTC, no altitude values are provided.

It should be noted that there are no other data sources containing altitude information, except for the last point when exiting radar coverage at 18:22:12, as noted in the Malaysian Final Report [11]. The only method available to verify the data is to visually compare the Geoscience points with the official ATSB 2014 reference map [4] through careful examination. The test consisted of looking at the pattern of white (and sometimes fuzzy) dots in the ATSB reference image and seeing if a match was possible with the Geoscience points.

4.6.2.1 U-Turn after IGARI

The ATSB 2014 reference map [4] being a reproduction of an unknown projection made on Google Earth, it was cut into 2 parts to compare the doublets of points first for the U-Turn Entrance path then on the output path.

Figure 20 provides a zoom of the U-turn and demonstrates the excellent visual match of the Geoscience data with the reference map from the 2014 ATSB report. Figure 20 is a combination of two images: one for the track around IGARI and one for the track starting just before the Exit of the U-turn.

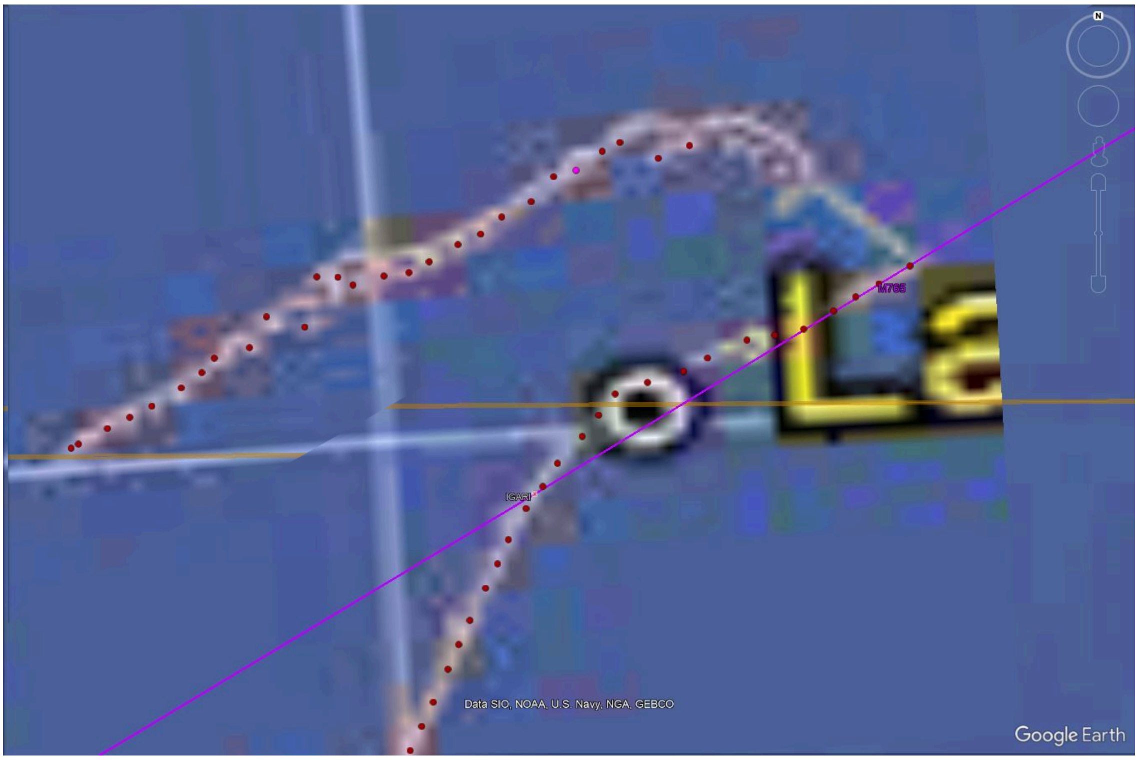

Figure 20: Visual comparison of Geoscience data and the ATSB reference map (images combination)

Interestingly, the Geoscience data shows excellent correlation with the ATSB reference map. Remarkably, the last 5 points of Segment-1 are exactly aligned with route M765 between waypoints IGARI and BITOD.

Additionally, some points matching some white dots are still missing at the start of Segment-2 at the top right of the path as already highlighted in Figure 12 above.

Graphically, it is possible to suggest substitutes for these missing points that were visually most likely available but perhaps with low confidence. The time labels indicate that there is a delay of approximately 1 minute between the last point in Segment-1 before Gap-1 and the first point in Segment-2 after that gap. Approximately 5 or 6 echoes are therefore missing, as highlighted in green in Figure 21.

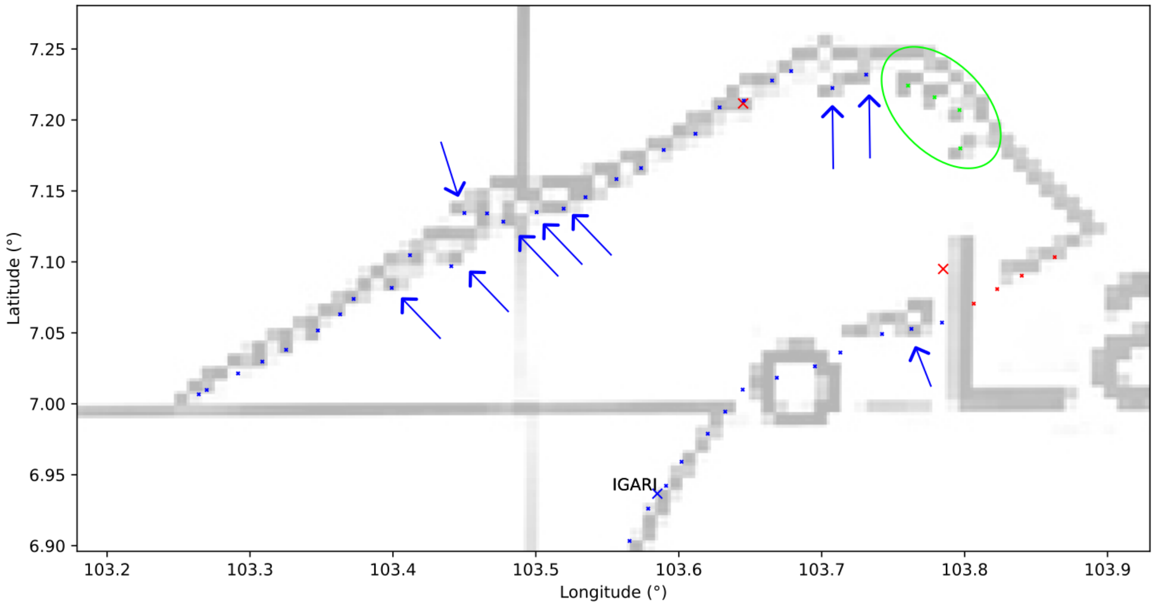

Figure 21: Identification of the missing points by best point alignment on the Exit Branch

It appears here that the creation of the ATSB reference map [4] probably used two slightly offset images during the merging process leading to these double lines, which should actually overlap.

By correctly positioning the ATSB reference map, a near-perfect match appears close to the pixel resolution. Thus, without taking too many risks, it is possible to identify and propose additional points. These points are illustrated in green in Figure 21 and in black in Figure 22.

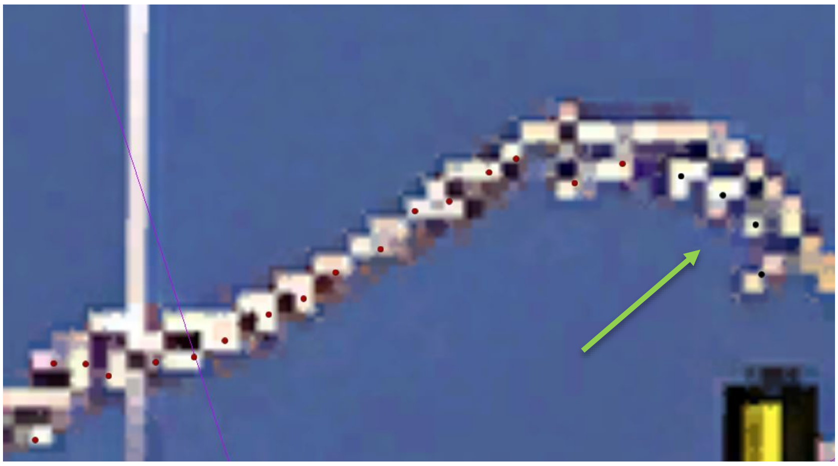

Figure 22: Identification of missing points in the Geoscience dataset

4.6.2.2 After the U-Turn to Pulau Perak

In this paragraph, the visual inspection focuses on the yellow path from Gap-2 to the location pointed by the green arrow towards Pulau Perak Island in Figure 23. It should be noted that this yellow line is visually different from Segment-1 and Segment-2 going from Kuala Lumpur to the exit of the U-turn. Its texture and colour differ from previous segments. The origin of this difference in display is not known. One interpretation is that they could come from two different radar trackers and were merged into a single image.

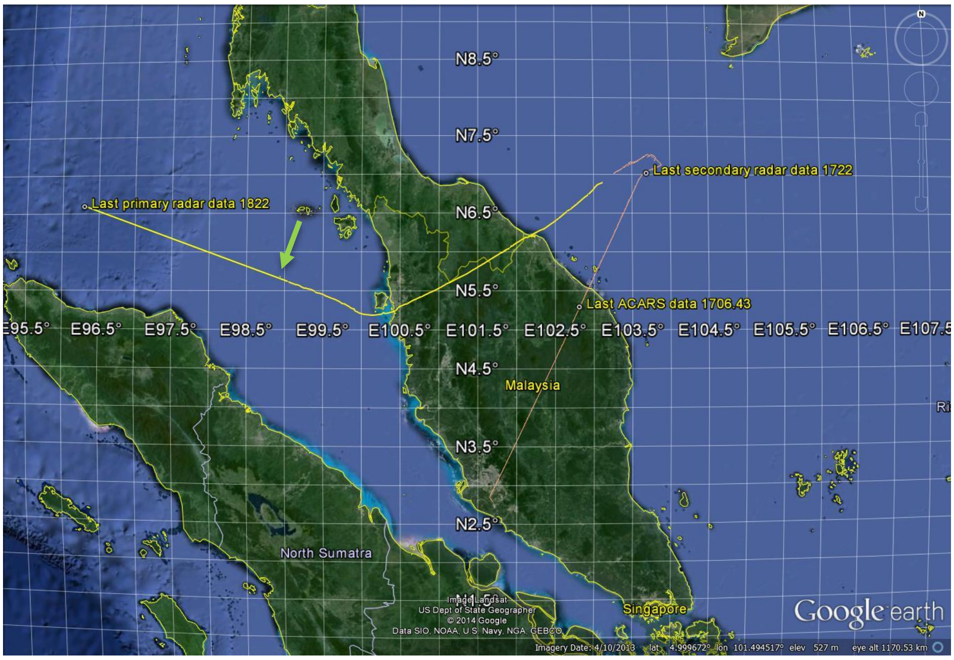

Figure 23: In yellow: Last segment of ATSB reference map [4]

At high level as illustrated in Figure 24, the track formed by the red points of the Geoscience dataset corresponds perfectly to the yellow track presented in the 2014 ATSB report reference map [4].

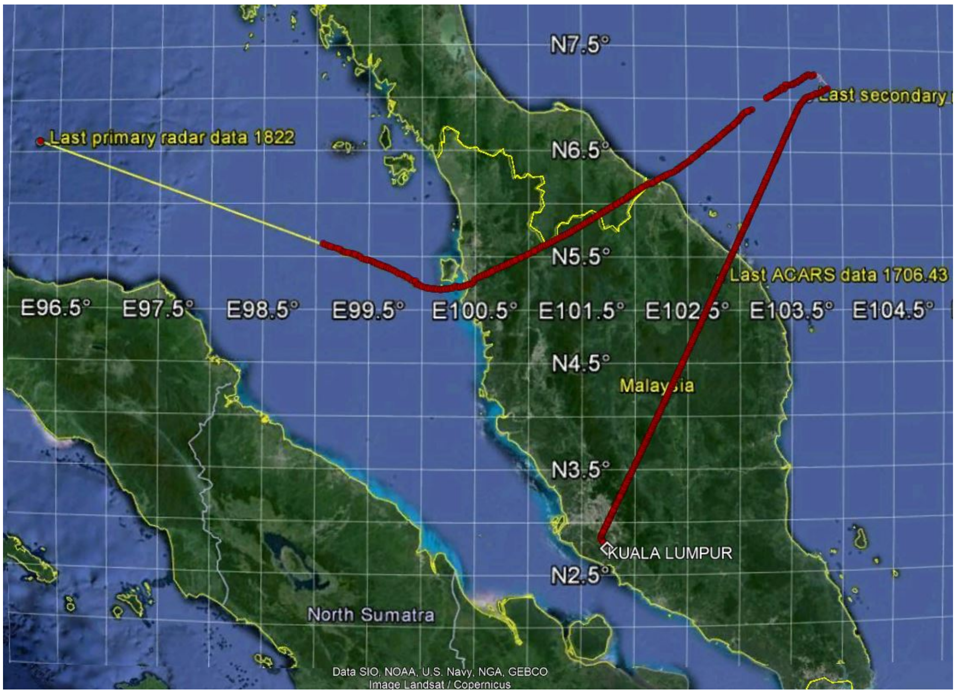

Figure 24: Geoscience dataset (red points) compared to the ATSB Reference map (yellow)

In terms of detail, the Geoscience points even overlap perfectly with the yellow line. Some specific locations are enlarged to illustrate this in Figure 25 and Figure 26.

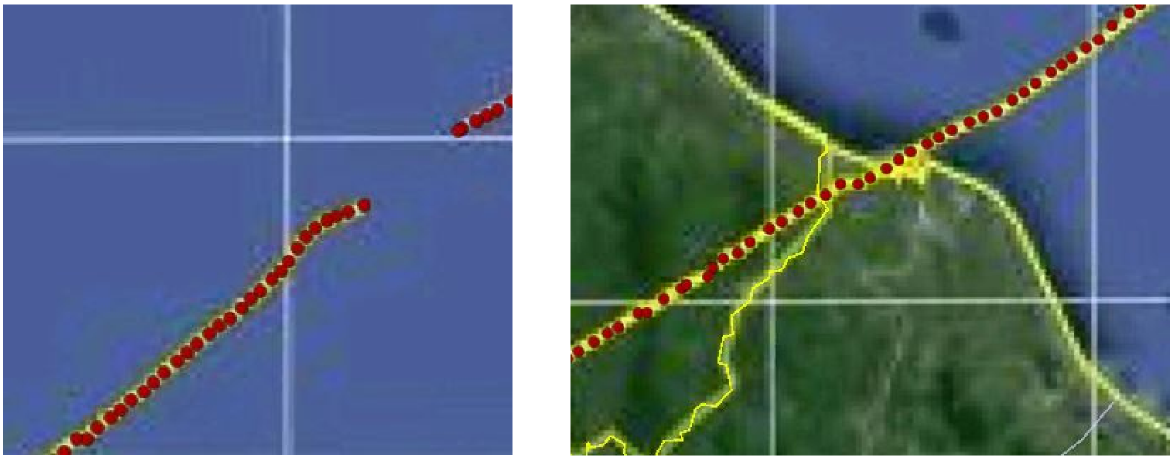

Figure 25: Details of the comparison of the Geoscience dataset (red) with the ATSB reference map (yellow) - I

Figure 26: Details of the comparison of the Geoscience dataset (red) with the ATSB reference map (yellow) - II

4.6.2.3 Last Radar Point (LSTRP)

The Geoscience dataset does not provide data from near the island of Pulau Perak to a very last point corresponding to the last radar echo (LSTRP) received at 18:22:12 UTC as shown in Figure 27. Coincidentally, the ATSB reference map [4] displays a perfect geometric straight line between the last radar echo in Segment-3 before Gap-3 and the given very last radar point (LSRTP). As this straight line is not supported by any other data source, it shows that intermediate radar data was either missing or considered not reliable enough to be used. This will be linked (cf below) to the information provided by the Lido image.

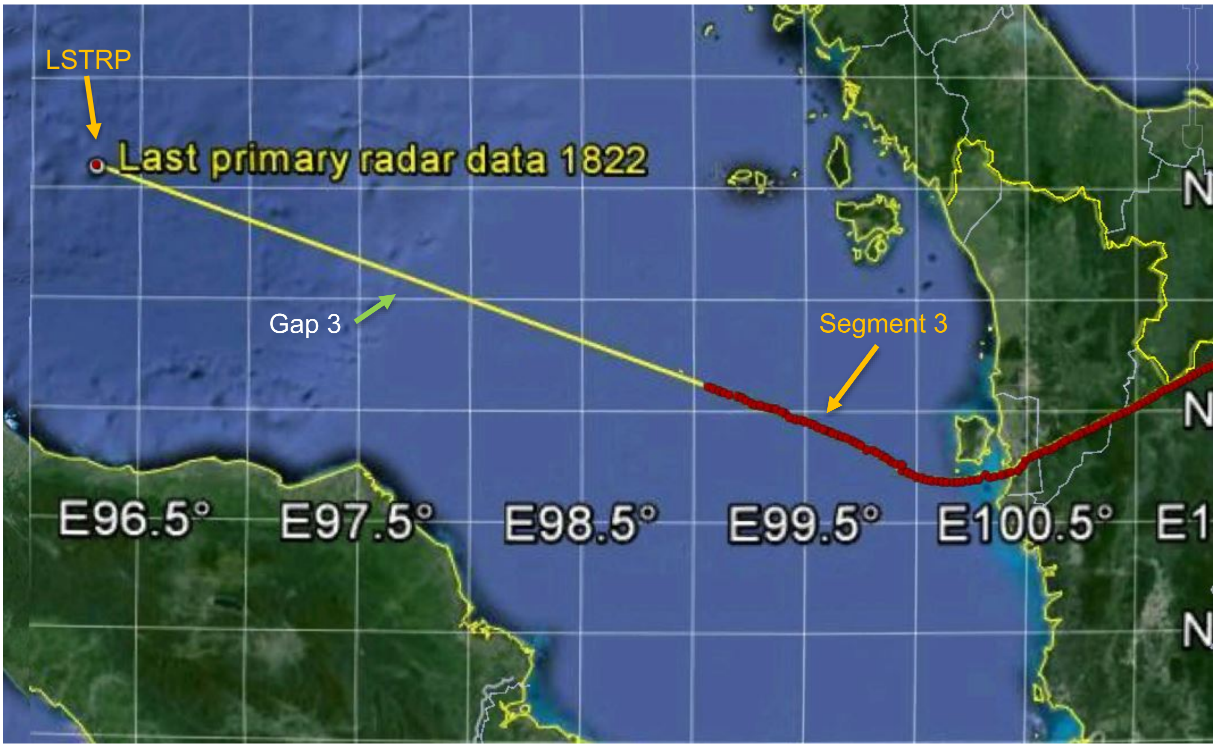

Figure 27: Missing data from ~18:01:49 UTC (after Pulau Perak Island) until 18:22:12 (LSTRP)

This point is further analysed in Paragraph 6.3 below.

4.6.3 Comparison with IG's Butterworth civilian approach radar data

The comparison of the Geoscience dataset and the data provided by the two civilian approach radars at Kota Bharu and Butterworth should be worth doing.

As an example, the plot of the Geoscience data along with the Butterworth data for the altitude 0ft is shown in Figure 28. Obviously, the visible match and discrepancies need more detailed analysis.

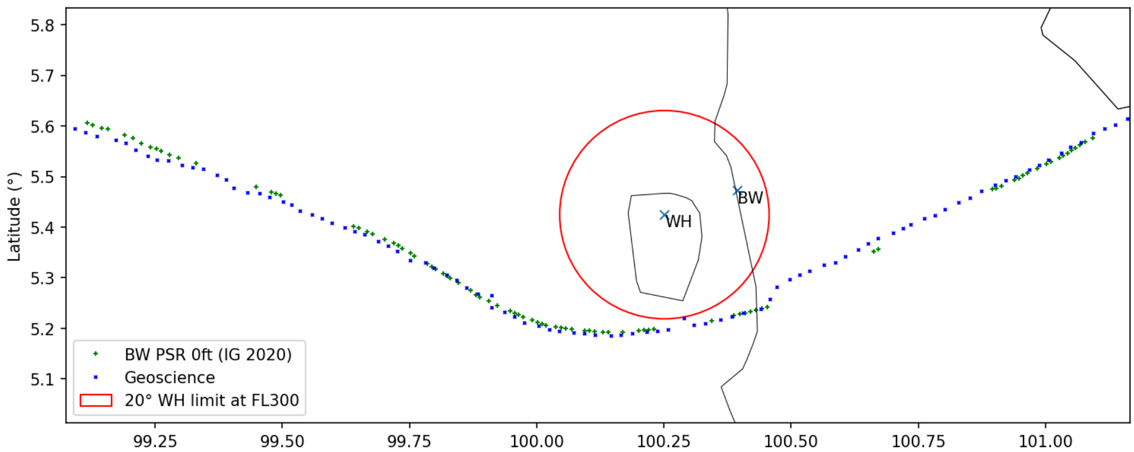

Figure 28: Comparison of Geoscience (blue) data with Butterworth civil radar data (green) at altitude 0ft

It is clear from Figure 28 that Butterworth data has been used from reconstructing the military track. Remember that this radar station is located in an Air Force base an operated by the military for the DCA. The use of civilian data and their comparison with the Geoscience dataset will be the subject of a detailed analysis subsequent to this report as it is a demanding area.

4.6.4 Conclusions

The geoscience data numerically matches the ADS-B available from 16:49:45 to 17:20:27 UTC and visually matches perfectly with the ATSB 2014 report reference map [4] through 18:22:12 UTC.

Subsequently, it can be concluded that the Geoscience dataset is most likely almost the entire authentic dataset produced by the data fusion algorithm that supported the creation of the graphical track in the ATSB reference map reported in the 2014 ATSB report [4].

At this stage it is interesting to note the correspondence with other references like the Boeing maps, the DSTG maps, the Royal Malaysian Police report (partial) map, the map in the Malaysian report "MH370 – Search Radius for MH370" and the Lido photo. The latter is all the more interesting because it does not include the "Last radar point updated" but the "Last radar point".

Therefore, the Geoscience dataset is a solid basis for a more detailed analysis, which is presented below.

4.7 Data fusion and coasting

Despite multi-site radar coverage, the presence of gaps in the dataset reveals that the production of the ATSB track in the reference map image [4] encountered difficulties in using some data, or even missed some. It is clear that several sources provided data as described in Section 5 below.

Data fusion allowed the creation of the track by taking the most appropriate information to produce the most reliable continuous track when enough data was input. But the presence of discontinuities actually illustrates two things: the lack of sufficient information and the presence of coasted points.

Coasting is a predictive algorithm that "creates" substitution points when echoes are no longer received, resulting in missing data, and places these substitution points in their calculated predicted locations. Usually between 4 to 6 substitution points are coasted. It is not uncommon for radar to not receive echoes for a short period of time. Coasting allows to "fill the gap" with a probable trajectory until the next confidence echo is received to ensure the continuity of the display because an aircraft does not "stop" in flight. But coasting ends after a predefined number of missing echoes. In our analysis, we determined that the maximum number of coasted points is five.

In the Geoscience dataset, coasting was detected in several locations. At least 5 locations have been clearly identified where coasting could have taken place, as highlighted by the arrows in Figure 29. Additional candidate points are visible in other locations, but they are the result of our own "coasting detection" algorithm, which relies on the predictability of the position of a point based on the previous ones. For example, SSR data produced false positive results.

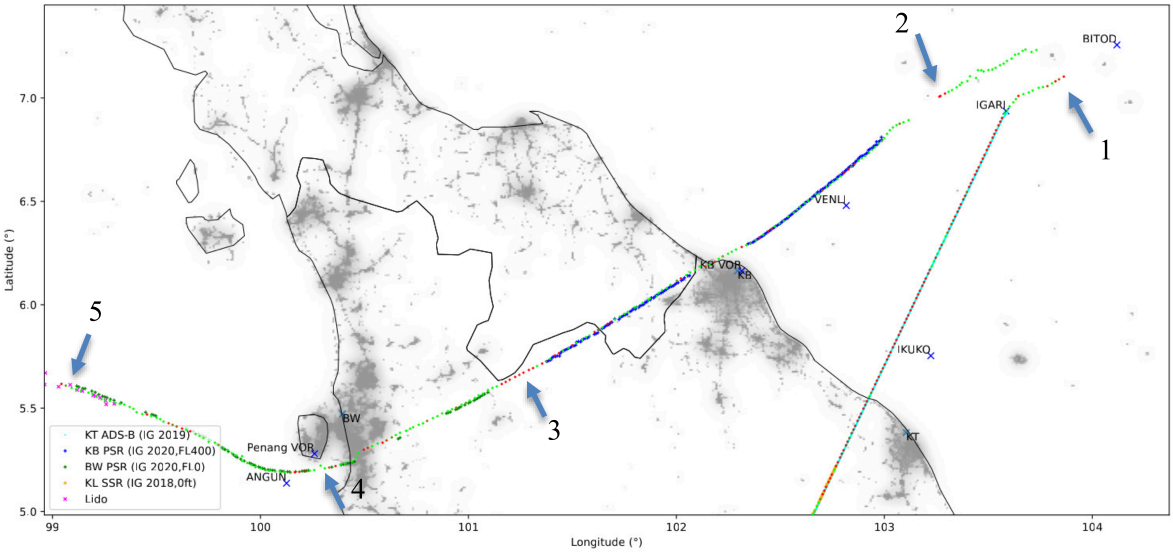

Figure 29: Locations of detected radar trackers' coasting

The following paragraphs address each of the 5 locations where coasting seems to be detected.

Note: For clarity of presentation, time labels are sometimes referred to to identify specific points and their likely time. This is done in anticipation of the time labelling attempt made in section 4.8 below.

4.7.1 Coasting after IGARI

Considering the start of the U-turn just after IGARI at the end of Segment-1, Figure 30 illustrates the behaviour of the algorithm, which coasted 5 points and continuously reconstructed the track.

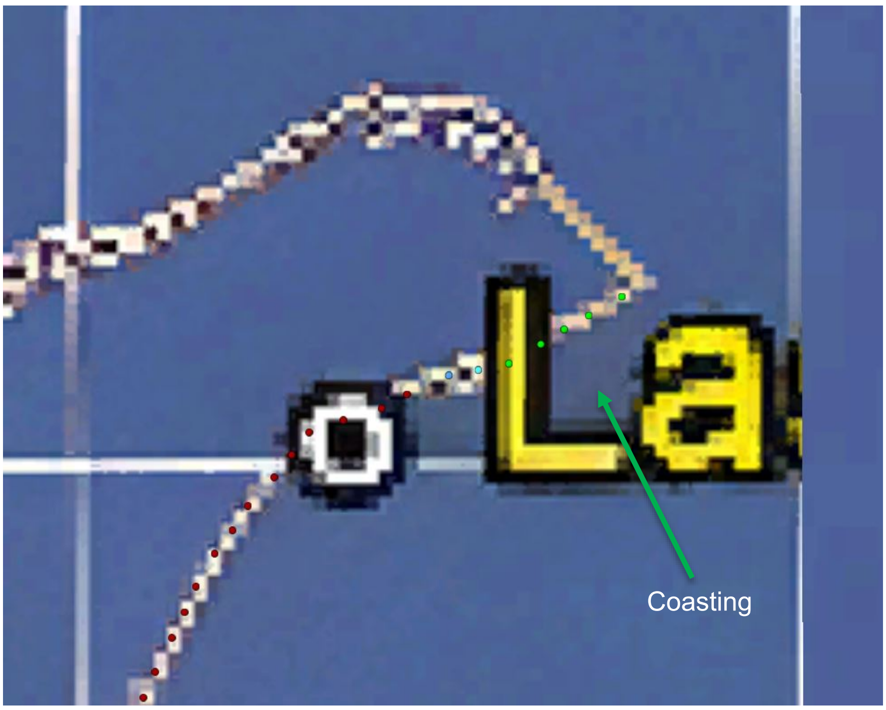

Figure 30: Coasting after IGARI at the beginning of the U-Turn (green points)

As shown in green in Figure 31, the last five points are exactly aligned with Route M765 segment from IGARI to BITOD supposedly followed by the aircraft. But in reality, the aircraft is known to have turned left and was indeed detected north of these five points. Therefore, these points cannot be real flown-over points.

In fact, these are fictitious points that were created and placed here by the data fusion and coasting algorithm. Furthermore, the two previous ones, in blue, seem to serve as a sort of conjunction to the previous point probably created thanks to an echo actually received.

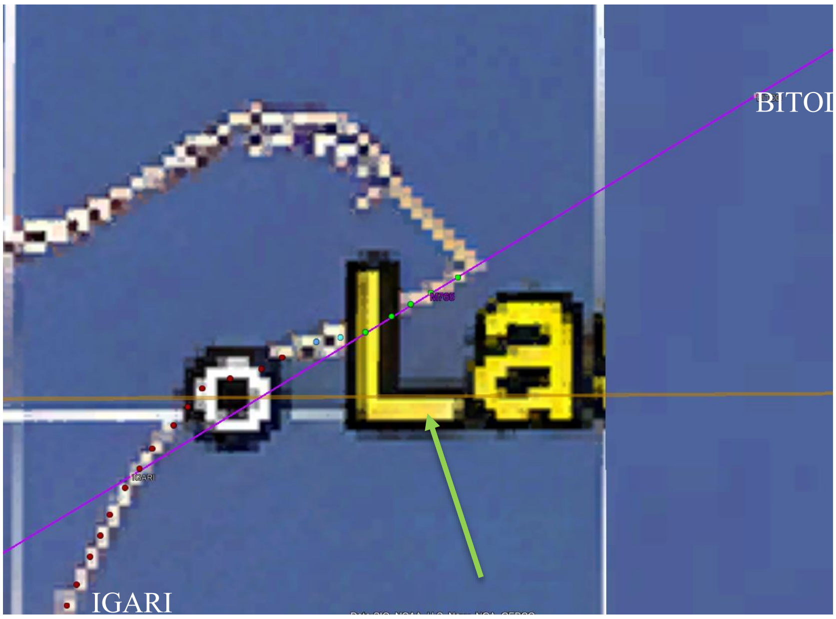

Figure 31: The 5 coasted points (green) are exactly on Route M765 from IGARI towards BITOD (purple)

Where did the information necessary for coasting come from? The most likely answer is "from the flight plan filed by the pilot/company", which was the only digital information available at that time.

For the record, the pattern identified during this undisputable coasting is summarised in Table 1.

Table 1: Coasting points characteristics after IGARI

Coasted point	Distance interval (Nm)	Supposed Time Interval (Sec)	Calculated ground Speed by the coasting algorithm (kt)	Geometry
1				Perfect straight line at true track 59.4°
2	1.54	12	460	
3	1.15	9	460	
4	1.17	9	468	
5	1.58	12	474	

Later, when reception of reliable echoes resumed, the radar data processor algorithm plotted the new points thanks to the echoes measured geographic location. To ensure the necessary continuity of the track display, a direct line was drawn connecting the last "predicted" position to the newly acquired position of the first new reliable echo. Subsequently, the track displays a sort of 90° turn to the left, fictitious and unrealistic because it is impossible to fly by such an aircraft.

Note: At this stage, another possible coasting could have taken place just after having passed IGARI. This will be detailed in a separate follow-up detailed analysis as previously announced.

4.7.2 Coasting after the U-Turn before Gap-2

This paragraph deals with coasting detected approximately 3 minutes after exiting the U-turn and before Gap-2 in the track as indicated by arrow 2 in Figure 29 and also highlighted by the red circle in Figure 32. Coasted points are in green. Here again, there are 5 five points which also display straight-line geometry like the previous coasted points before the U-turn. They are summarized in Table 2. However, the last point raises questions. It is perfectly aligned with its predecessors but it is ~3s apart only, at a distance consistent with the estimated speed (to precision). Why did the coasting algorithm create such a point? No clear answer was found.

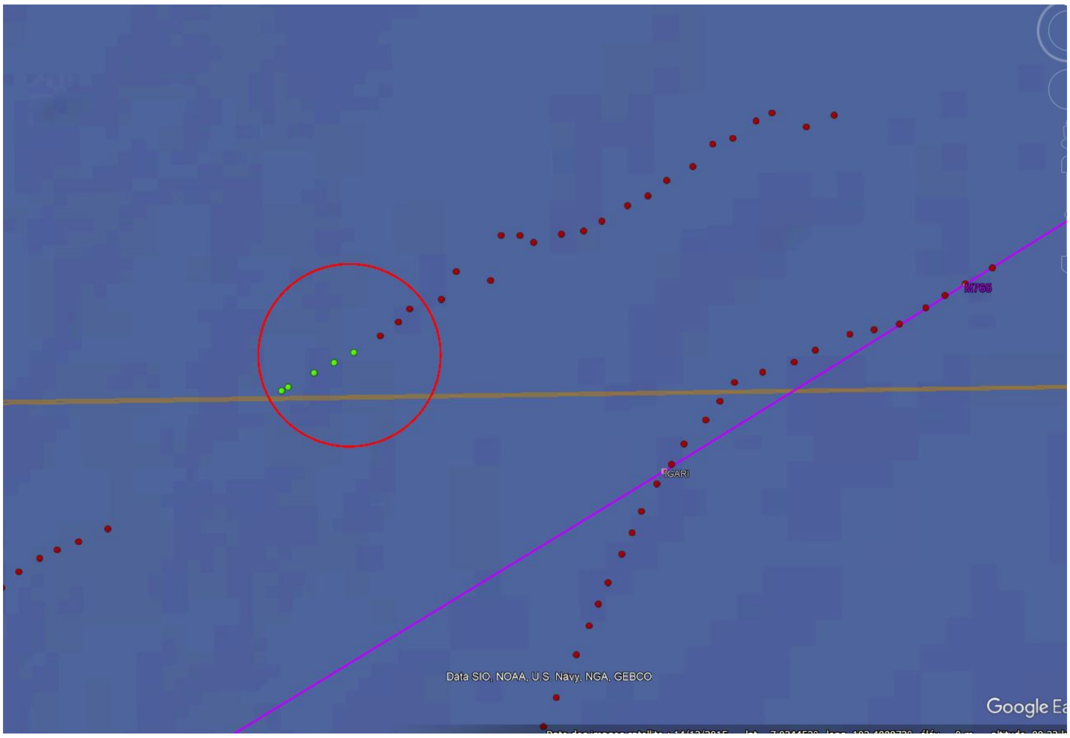

Figure 32: Coasted points (green) after the Exit of U-Turn before Gap-2

Table 2: Coasted points characteristics after the Exit of U-Turn before Gap-2

Coasted point	Distance interval (Nm)	Supposed Time Interval (Sec)	Calculated ground Speed by the coasting algorithm (kt)	Geometry
1				Perfect straight line at true track 242.7°
2	1.11	9	444	
3	1.12	9	448	
4	1.49	12	447	
5	0.38	3	456	
			447	<- average

4.7.3 Peculiar points detected between Kota Bharu and Butterworth radars coverage

This paragraph addresses the points identified and pointed by arrow 3 in Figure 29 and highlighted by the red circle in Figure 33.

This gap is the result of reaching the limits of the Kota Bharu civilian approach radar and the lack of data from the Butterworth Air Force Base radar (providing civilian approach radar services). Butterworth presents incomplete data with many missing points creating many gaps.

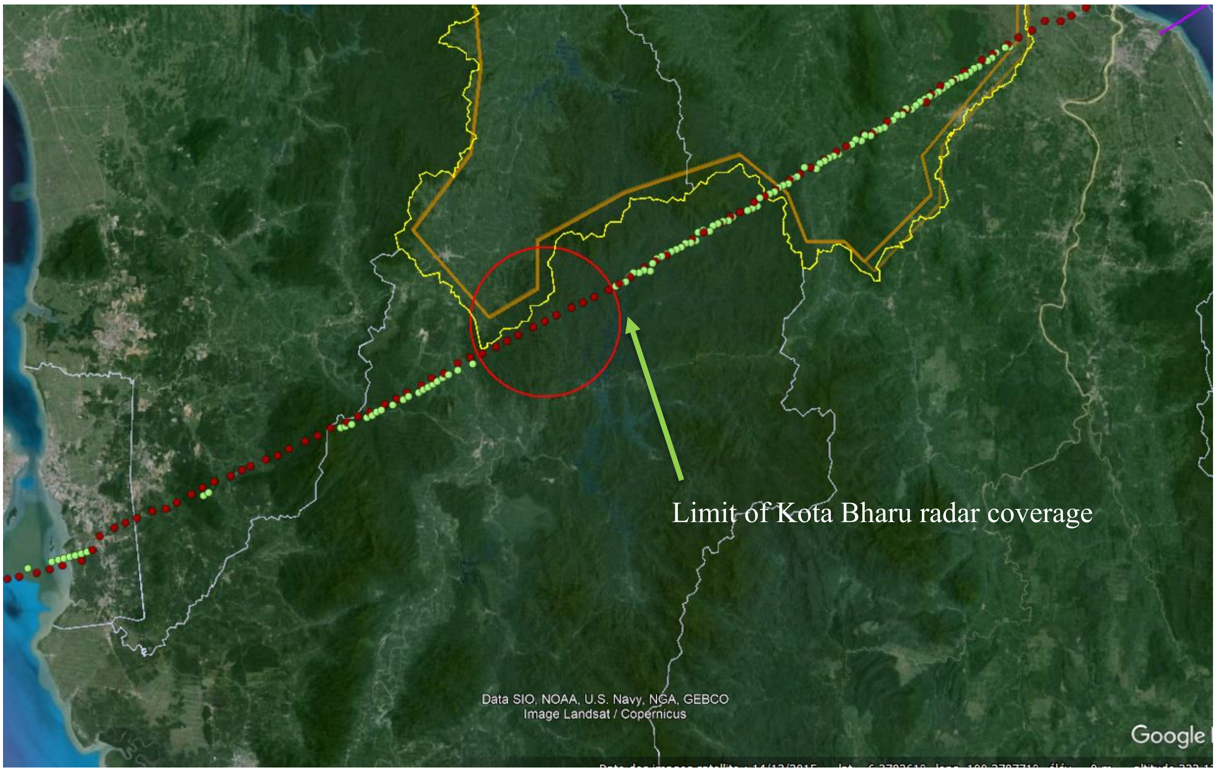

Figure 33: Peculiar points between the two radar coverage areas of Kota Bharu and Butterworth

These points are well aligned. But as there are 11 points, talking about coasting is not realistic because the algorithm would not follow its behaviour already shown in the two previous cases, i.e. 5 points maximum for ~ 42 s.

But it is known also that before plotting the start of a new track segment, the RDP "waits" few new echoes to be received and validated as reliable information. Thus, it possible that 5 points were coasted and the remaining 6 came from these new echoes, which were available as Butterworth, is part of the military system.

They are summarised in Table 3.

Table 3: Peculiar points between Kota Bharu and Butterworth coverage areas

Peculiar points	Distance interval (Nm)	Supposed Time Interval (Sec)	Calculated ground Speed Supposed time tags (kt)	Geometry
1				Quasi-Perfect straight line at true track 243°
2	1.66	12	498	
3	1.28	9	512	
4	1.30	9	520	
5	1.74	12	522	
6	1.35	9	540	
7	1.34	9	536	
8	1.76	12	528	
9	1.32	9	528	
10	1.28	9	512	
11	1.57	12	471	
			515	<- average

The difference in geometry from the previous and subsequent points, which are not aligned in a perfect straight line, highlights the influence of the lack of information from other sources. The most likely conclusion is that the RDP tracking algorithm compensated for this.

This also raises the question: which of the military radars had the aircraft in visibility in this area.

4.7.4 Coasting in the South of Penang Island

This paragraph addresses the 5 Geoscience points identified and pointed by arrow 4 in Figure 29 and highlighted by the red circle in Figure 34.

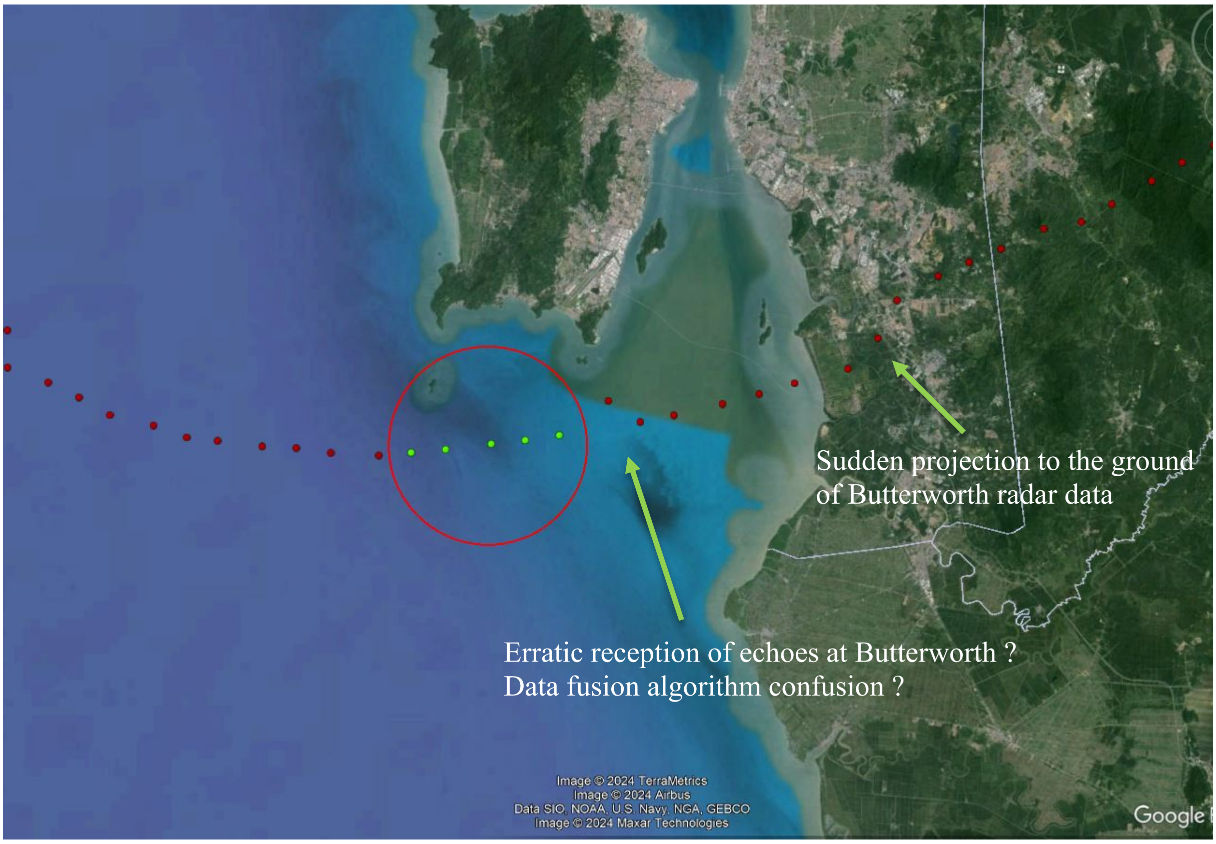

Figure 34: Coasted points (green) in the south of Penang Island

The actual reason for having coated points at this location will be further looked at in some details below in this report. At this stage it appears that the "misbehaviour" of Butterworth radar provoked some malfunctioning of the data fusion algorithm. This is clearly visible in Figure 97 in section 7.7.1 below.

For the record, the pattern identified during this undisputable coasting is summarised in Table 4.

Table 4: Coasted points characteristics in the South of Penang

Coasted point	Distance interval (Nm)	Supposed Time Interval (Sec)	Calculated ground Speed by the coasting algorithm (kt)	Geometry
1				Perfect straight line at true track 263.6°
2	1.29	9	516	
3	1.30	9	520	
4	1.72	12	516	
5	1.30	9	520	
			518	<- Average

4.7.5 Coasting just before Pulau Perak

The Geoscience dataset is running out of points before the very last isolated point at 18h22 UTC (LSTRP). This is a huge Gap-3 that begins a few nautical miles before the island of Pulau Perak.

A gap means data loss. A loss is usually followed by a temporary coasting of points before finally finishing producing track points. As expected, the last five points before the gap have the characteristics of coasted points (in the red circle in Figure 35). They line up perfectly on track 291°.

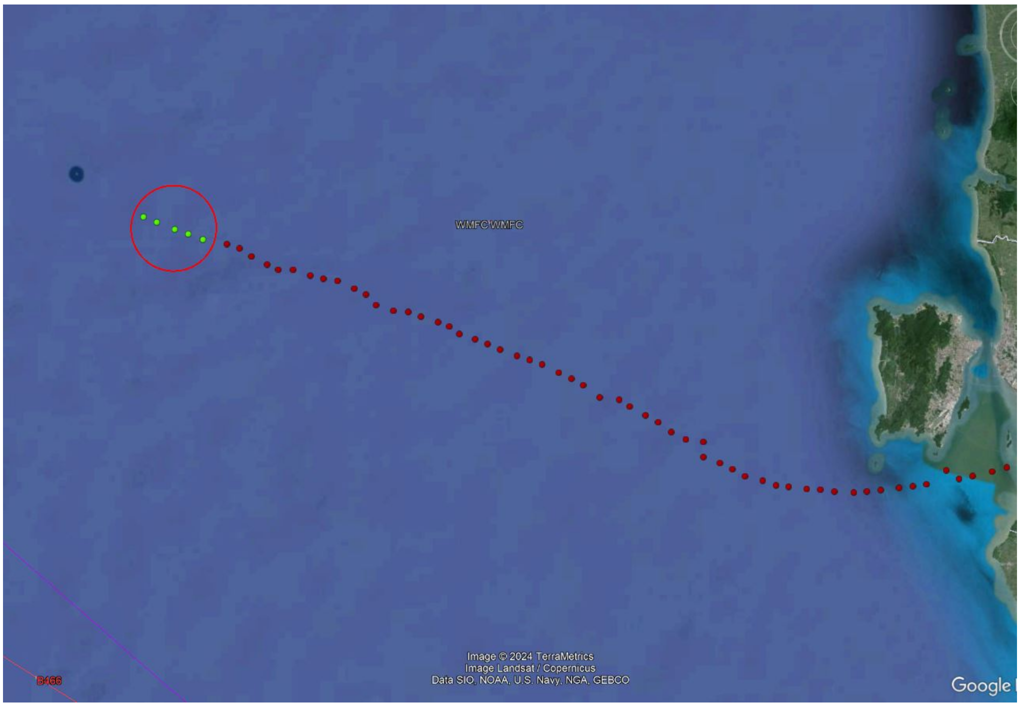

Figure 35: Coasting the last 5 points before the large Gap-3 starting before Pulau Perak until LSTRP at 18h22 UTC

Figure 36: Five coasted points perfectly aligned at 291°

For the record, the pattern identified during this undisputable coasting is summarised in Table 5.

Table 5: Coasted points characteristics before Gap-3 at Pulau Perak Island

Coasted point	Distance interval (Nm)	Supposed Time Interval (Sec)	Calculated ground Speed by the coasting algorithm (kt)	Geometry
1				Perfect straight line at true track 291°
2	1.45	9	580	
3	1.34	9	536	
4	1.80	12	540	
5	1.33	9	532	
			546	<- Average

These last points demonstrate that the military radar data processor (RDP) was no longer provided with enough reliable data and was no longer able to produce a reliable track.

4.7.6 Conclusions on coasting

Coasting was identified at 4 locations while a fifth location is a false positive in our analysis. They provide valuable information as their location will be used in the attempt to extract vertical profile information in Section 7 below.

Important note: Ground speed information has been shown to be unreliable, due to the anticipated use of approximate time labels assigned to each point in Section 4.8 below.

4.8 Attempt to assign temporal tags

Geoscience data file contained no time labels, but as it appeared to have visual similarities to the data used by the DSTG, it was first analysed as having approximately 10-second intervals between points as in [5] and compared to other radar data published. By manually shifting the points in time, the data appeared to coincide closely with previous radar data.

After aligning the Geoscience data with other radar data, the resulting start and end times matched the given times in the DSTG report, 16:42:27 and 18:01:49 UTC, by less than 10 seconds, therefore these times will be used as reference points to generate the time labels that have been removed from the authentic data.
By considering the distances between successive points, it appears that one point in three is further from the previous one, by approximately a third of the distance. This is particularly clear in the SSR data up to IGARI, but still visible in the PSR parts thereafter. In fact, it appears that the points are not separated by 10-second intervals, but by a repeating pattern of 9s/9s/12s intervals. The same pattern seems to appear in PSR dataset as well.

As shown in Figure 37, in the SSR part (the first 227 points) the distance between each point and the previous one, points 3n+2 is further away than the others. In the PSR data, the differences are less clear but visible enough to confirm that this trend is still present.

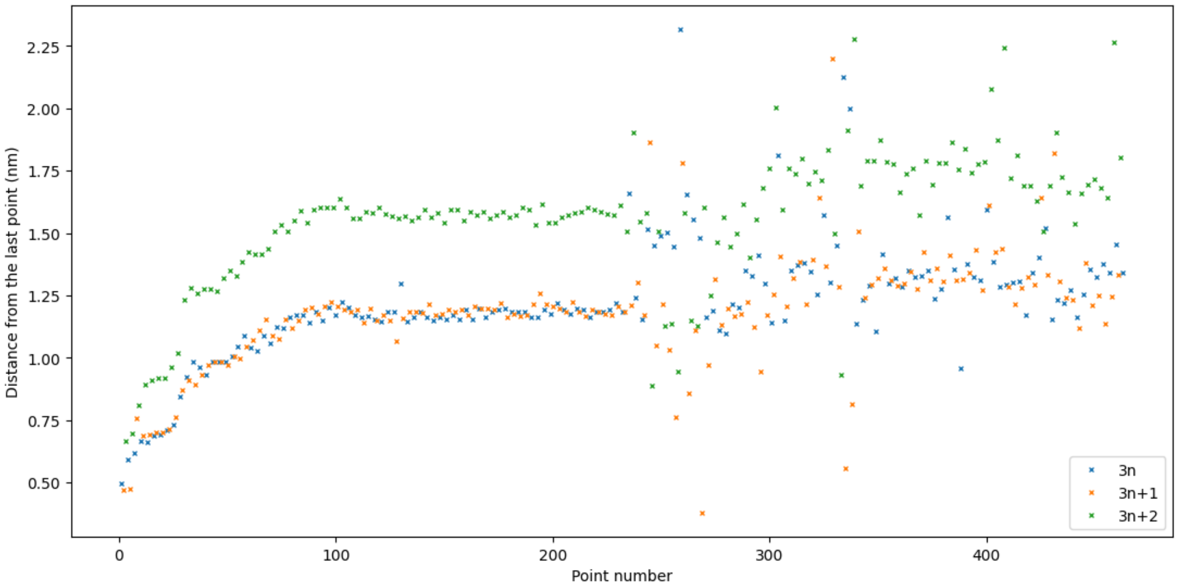

Figure 37: Distance between successive points in the Goescience dataset

By using these intervals in the SSR data, the calculated speed between two successive points becomes much less erratic. Figure 38 shows the results of calculating the speed between successive points using 10 s intervals and using 9 s/9 s/12 s model intervals against ADS-B and Kuala Lumpur SSR data.

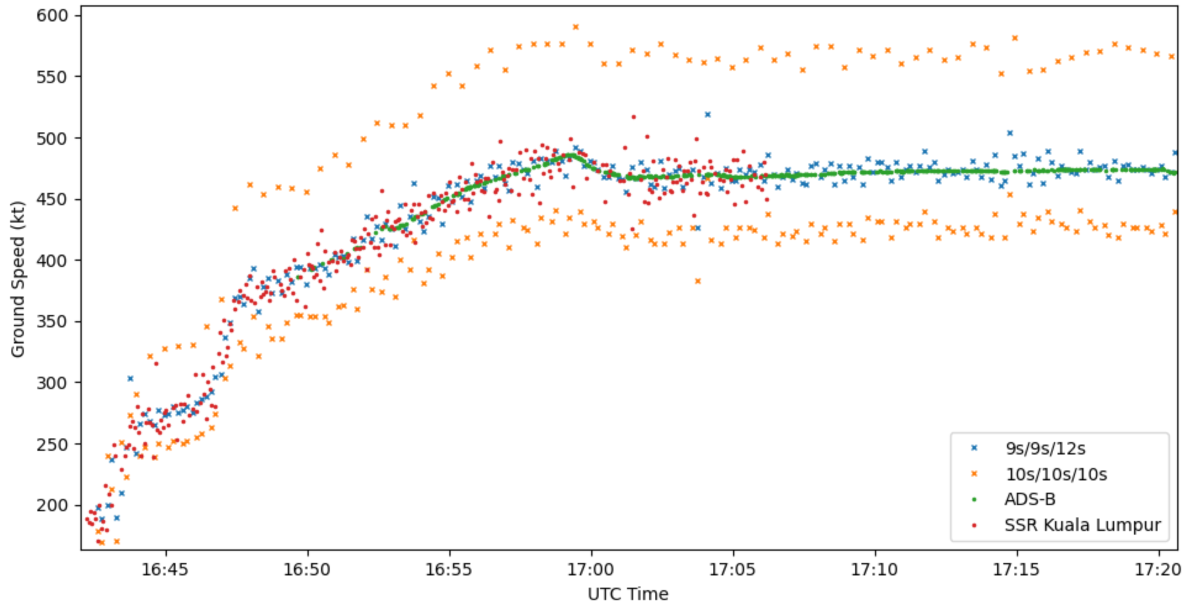

Figure 38: Supposed speed between successive points using 10s intervals (orange) and 9s/9s/12s pattern intervals (blue) , compared with ADS-B and Kuala Lumpur SSR data (green and red)

Caveat1: Around 17:04 UTC, two points appear to have a time interval different from 9 or 12 seconds, the first appears to follow an interval of 10 seconds, and the next an interval of 8 seconds. These points demonstrate the limits of time label generation. Other points also might not follow the pattern of the PSR data. But without the original time labels it is impossible to know.

Caveat2: It appears that even the distance intervals between points are clearly not constant the track may have been provided to the ASTB and to Boeing with constant time labels at 10s intervals.

The only point that clearly does not seem to correspond to the 9/9/12 pattern is the last point before the Gap-2 (also called "break" by Boeing), after the U-turn. The distance and the time interval between the two previous points were used to estimate the interval between this last point and its predecessor, i.e. 3 seconds.

The PSR portion of the dataset between U-turn and break could not be directly linked to DSTG start/end times, but could be aligned using data provided by a table from the analysis of Boeing performance in Table 3 of the appendix. 1.6E [19] reproduced here in Table 6. The information provided in row 2 leads to an estimated duration of the break (Gap-2) of approximately ~82 s. Subsequently, the temporal labels of this part could be estimated as presented in Table 7.

Table 3: Flight Segment Details and Fuel Burn

Segment	Travel Time (hours)	Distance (nm)	Assumed Flight Level	Average Wind Component (+headwind/ -tailwind)	Average True Airspeed (knots)	Mach	Ending Fuel Weight (lb) (Beginning Fuel Weight = 96,563 lb)
1	0.36	175.3	FL350	-14	478	0.829	91,242
2	0.023	11.1	FL350	-19	470	0.815	90,911
3	0.54	282	FL300	-13	510	0.865	81,104
4	0.34	173.5	FL300	-14	502	0.852	75,425
5	0.092	46.4	FL300	-9	494	0.838	73,908

Table 6: Boeing Performance Analysis Table provided in Appendix 1.6E [19]

Table 7: Estimation of the duration of the Boeing segments using the measured distances and estimated average speeds

Segment	Travel Time (s)	Distance (nm)	Average wind component (kts)	Average True Air Speed (kts)	Estimated Ground Speed (kts)	Estimated Travel Time (s)
1-Last ACARS to break	1278-1314	175,3	-14	478	492	**1282,7**
2-Break	81-84,6	11,1	-19	470	489	**81,7**
3-Break to Pulau Pelak	1926-1962	282	-13	510	523	**1941,1**

A schematic representation of the different parts of the track, with the corresponding Boeing segments is illustrated in Figure 39.

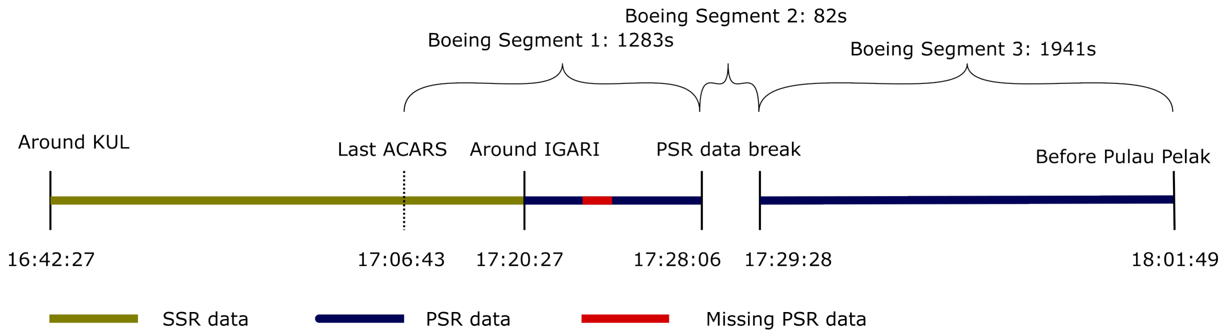

Figure 39: Mapping of the Geoscience dataset with Boeing-defined segments

Using the first row of Table 6 and Table 7, which are dedicated to the segment between the last ACARS transmission at 17:06:43 UTC and the break (Gap-2), the start time of the break is calculated as ~17:28:06 UTC. This is the same time obtained using break duration of 82 seconds.
Using the third row of these tables, which deals with the segment between the break and the end of the track, a travel time of 1941 seconds is obtained. This is in agreement with previous time label calculations and confirms break duration of 82 seconds.

Using these approximate time labels, a comparison with ADS-B data provided by the IG in April 2019 provides an interesting high-level cross-check. The results are presented graphically from Figure 40 to Figure 42.

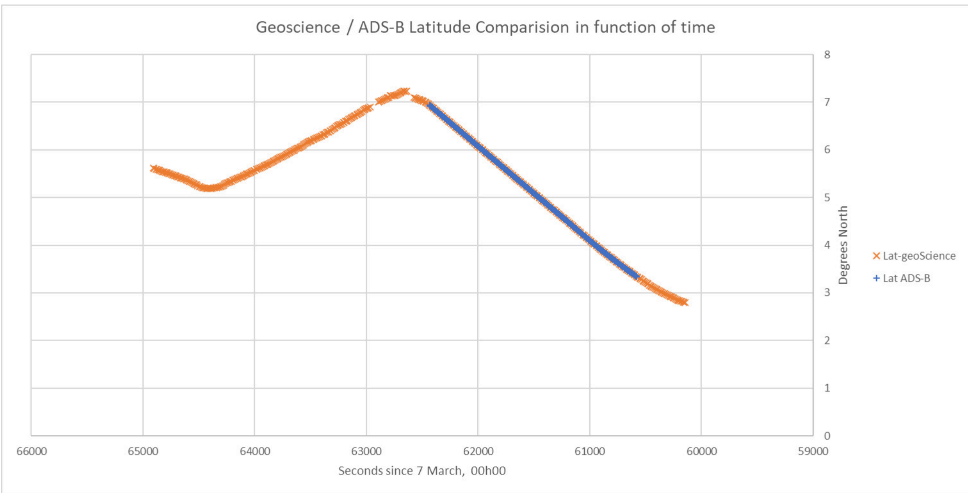

Figure 40: Latitude comparison Geoscience / ADS-B (Source IG) versus time

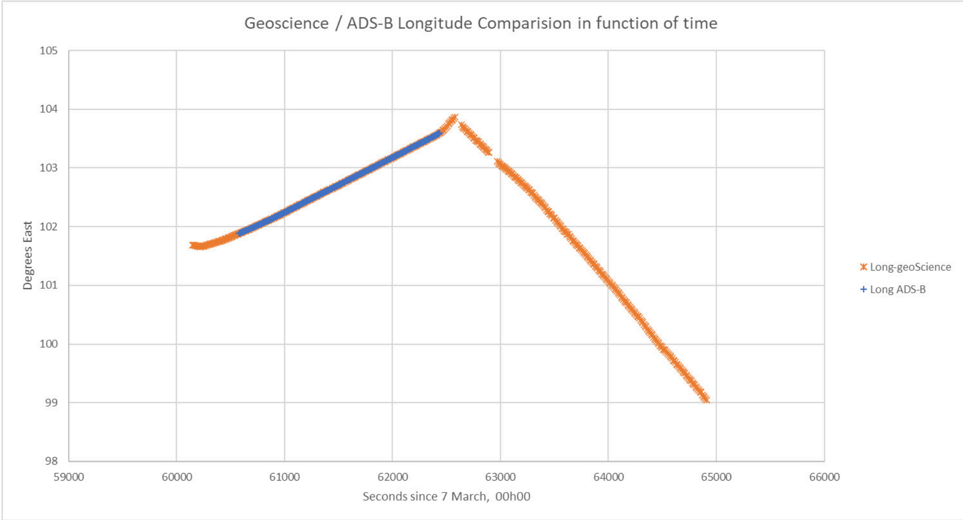

Figure 41: Longitude comparison Geoscience / ADS-B (Source IG) versus time

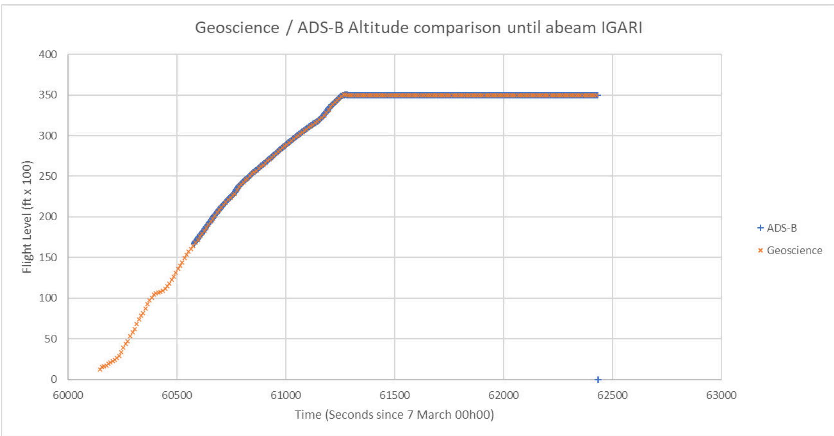

Figure 42: Altitude comparison Geoscience / ADS-B (Source IG) versus time

4.9 Aeronautical analysis of speeds deduced according to flight level

4.9.1 What do mean the deduced speeds?

The high level of uncertainty in time labels in this dataset - and the questions on the Kota Bharu and Butterworth civilian approach radars data - has always led to serious difficulties in estimating the speed characteristics of the plane between the U-Turn until 18h22 UTC. Numerous attempts have been documented, for example [13] & [14], but have never provided satisfactory answers and computed speed values were almost systematically outside the flight protection envelope.

Additionally, Figure 1.1B of the Malaysian Final Report [11] raises serious questions about the "flyability" of such a profile with such calculated speeds.

Thus, this paragraph aims to verify the displayed speeds at which the estimated time labels lead. The airline pilot method is used to calculate speed encompassing aviators' procedures and data. The calculation below is based on the Wintem charts of that day (March 7, 2014) at 18:00 UTC for flight levels FL240, 300, 340 and 390 with the corresponding delta ISA and on the flight path measured on the ground.

As the Geoscience dataset shows that the aircraft flew very close to KADAX, the following waypoints were used to define the study segments: official Exit from the U-Turn, KADAX, detection of co-pilot's mobile phone (GSM) and VAMPI.

From the pilot's point of view, these estimated ground speeds are somewhat inconsistent with the aircraft's flight envelope. Let us now refer to Table 8. The upper and lower limits of the speeds are underlined in green while the calculated values outside these limits are underlined in red. The reference average ground speed between the Exit of the U-Turn and the south of Penang is calculated at 510kt. Between the south of Penang and the Last Radar Point (LSTRP) it is calculated at 511kt.

Table 8: Average speeds relative to flight level based on assigned time labels

Waypoint	***Average ground speed (kt)***	***ISA (°)***	***Wind Velocity (°/kt)***	***True Airspeed TAS (kt)***	***Mach***	***IAS (kt)***	***Comments***
U-Exit							
FL240	477	+16	056/15	462	0.740	317	
FL300	477	+14	072/15	463	0.763	288	
FL340	477	+11	073/20	458	0.772	267	
FL370	477	+9	073/20	458	0.782	**253**	**Below Minimum holding speed = 258kts**
FL377	477	+9	073/20	458	0.782	**249**	**Below Minimum holding speed = 256kts**
FL390	477	+2.5	072/20	458	0.793	**246**	The IAS would be below the Holding speed flaps retracted **(-6kts)** as recommended by Boeing (cf Table 9)
FL405	477	0	085/20	460	0.802	**240**	The IAS would be below the Holding speed flaps retracted **(-9kts)** as recommended by Boeing (cf Table 9)
KADAX							
FL240	530	+19	056/15	515	0.820	**354**	The IAS would be above the maximum operability velocity VMO **+24kts**
FL291	530	+14	072/15	515	0.845	329	Minimum realistic flight level (max VMO reached)
FL300	530	+14	072/15	515	0.848	324	VMO -6 kts
FL340	530	+11	073/20	510	0.859	301	
FL370	530	+10	073/20	510	0.869	285	Maximum possible flight Level (maximum MMO reached)
FL390	530	+2.5	073/20	510	**0.884**	277	The Mach would be above the flyable Mach M0.870
GSM							
FL240	511	+18	090/10	502	0.801	**345**	The IAS would be above the maximum operability velocity VMO IAS330. : VMO + 15 kt
FL300	511	+14	046/5	509	0.838	320	= VMO – 10kt
FL340	511	+12	081/20	494	0.830	290	≈ LR 0.827
FL390	511	+2.5	085/20	493	0.855	264	> LR (0.84)
VAMPI							

If at the end of the U-Turn the plane were to climb above its optimal altitude (FL370), the pilot should at least respect the “minimum and reasonable” speed recommended by Boeing called “Holding speed flap up” or “minimum drag speed” or “minimum clean speed”. This corresponds to the speed indicated in the manufacturer's B777-200 ER FCOM tables and which at these altitudes corresponds to an approximately constant Mach of M 0.81. Flying below this speed would significantly reduce the margin left for manoeuvring in flight. Additionally, a B777-200 no longer has any thrust reserve as it approaches its maximum altitude. In the event of destabilization, the only solution would be to descend. It would be surprising if a pilot frankly climbed above his “optimal” flight level, and found himself in a situation close to instability, while also experiencing an increase in consumption, without having a valid technical reason.

Pilot’s perspective: *It would be very surprising that here, in the highly likely scenario of a hijacking of this aircraft, the person in command would choose to climb to a very high altitude close to its maximum flight level, with a low remaining available thrust. This would slow down the aircraft to an extremely low speed - below the minimum recommended by Boeing - and jeopardize the good control of the plane. In addition, from a physiological point of view, it would be extremely complicated for the human body as well as the brain to function properly for long minutes at extremely low temperatures (we are talking here about -54°C outside temperature). An airline pilot would not take that risk especially with the objective to escape and not be spotted… lower speed and higher flight level? For these reasons, from a pilot’s point of view, climbing high is not an option.*

Exert form Boeing FCOM: PI 28.6 **"**Holding"
Target EPR, indicated airspeed and fuel flow per engine information is tabulated for holding with flaps up based on the FMC optimum holding.
Speed schedule. This is the higher of the maximum endurance speed and the manoeuvring speed for the selected flap setting

Some comments on Table 8:

At FL240, the Indicated Air Speed (IAS) would be higher than the maximum operating speed (VMO) by +15kt and +24kt on the last two segments.

At FL390, in one segment the IAS would below the recommended holding speed by -6kt while in another segment the Mach would be at 0.884, which is well above the maximum Mach operating speed of 0.870.

All of the above between U-Turn and KADAX should be considered in the perspective of Boeing's recommendation to maintain speed below the minimum manoeuvring speed **+15 kt** (yellow speed tape) in flight when below M0.82, which means a speed greater than **258 kt** (see FCOM PI 28.5). This leads to a maximum flight level around FL370 according to Boeing's table.

At FL340, getting to KADAX is still within the flight envelope and getting to "GSM" is also just below MMO (0.870) at M0.859. But in Penang, the co-pilot's mobile phone would not be detected because it was above the maximum capacity of the ground antenna at the actual altitude of ~32,000 feet. Additionally, it would also not meet the reported altitude of 29,500 feet at 18:22:12 UTC. This also applies questions a level of FL320 in this location. Remember that when flying west, RVSM flight levels are even numbers to avoid collisions (with no TCAS in use) and the procedure is to stay levelled.

At FL390, on arrival at KADAX, the deduced IAS of 246 kt is much lower (-6 kts) than the flaps retracted holding speed estimated for a mass of 216 t, as interpolated from Table 9 at 252 kts. It is unusual for a pilot to slow down so much at this flight level. It would be below the Minimum clean speed and would shift into the region of reverse command. This would then mean accelerating to reach ground speed of 530 kt between KADAX and GSM. This would than mean a Mach greater than 0.885, which is well beyond the flight envelope.

The plane's control laws protection would cause the plane to pitch up to slow it down while the auto throttle (ATHR) **if used** would reduce thrust.
Given the force feedback on the B777 controls, the pilot would have to "fight" against the machine if it remains as is. From a pilot's point of view, there is no logic in slowing down to a very low speed and then accelerating to "over speed" immediately afterwards.

Table 9: Holding speeds of a B777-200ER with the Trent Engines (source: PMDG FCOM identical to Boeing's FCOM)

777-200ER/TRENT892
FAA
Category A Brakes

DO NOT USE FOR FLIGHT

777 Flight Crew Operations Manual

Performance Inflight
All Engine

Holding
Flaps Up

WEIGHT (1000 KG)		PRESSURE ALTITUDE (FT) 1500	5000	10000	15000	20000	25000	30000	35000	40000	43000
300	EPR										
	KIAS										
	FF/ENG										
280	EPR										
	KIAS										
	FF/ENG										
260	EPR										
	KIAS										
	FF/ENG										
240	EPR										
	KIAS										
	FF/ENG										
220	EPR								1.167	1.357	
	KIAS								266	249	
	FF/ENG								3310	3590	
200	EPR								1.138	1.249	
	KIAS								253	249	
	FF/ENG								2950	3130	
180	EPR										
	KIAS										
	FF/ENG										
160	EPR										
	KIAS										
	FF/ENG										
140	EPR										
	KIAS										
	FF/ENG										

This table includes 5% additional fuel for holding in a racetrack pattern.

4.9.2 Conclusions

As explained above, flying up and down at speeds outside the aircraft's flight envelope does not make sense for a professional pilot, even under extraordinary circumstances of his own creation.

It must therefore be concluded that, in order not to jeopardize his plan, the person in commands kept the aircraft within the limits indicated in Table 8. That is to say between the minimum FL290 and the maximum FL360 if RVSM rules have been followed, which means FL300, FL320, FL340 or FL360.

Moreover, the Geoscience data shows a sort of S-shaped deviation located just before crossing the mainland seashore before 17:52:00 UTC. Several interpretations are possible and today none is definitive. The more likely explanation from the digital analysis is that the radar data processor selected or was suddenly fed by a different data source, causing some sort of abrupt shift in the reconstructed track during data fusion processing i.e. Butterworth data at the altitude of 0ft in particular. Another possible explanation is an offset coming from an incorrect altitude misleading the tracker. Section 7.8 below will provide an overview on this.

Furthermore, it is striking that the average ground speeds on the two segments "Exit of the UTurn-to-GSM" and "GSM-to-Last radar contact at 18:22:12 UTC" are quasi-identical: 510 kt and 511 kt respectively. Using these two figures for FL300 and FL320 flight levels, the resulting calculated flight parameters display the values shown in Table 10 and Table 11. These two flight levels are those for which no major problems have been identified above and follows in anticipation of the analysis detailed in section 7 below.

Table 10: Average speeds based on the 3 officially known time tags using Airmen practices for FL300

Waypoint	***Average ground speed (kt)***	***ISA (°)***	***Wind Velocity (°/kt)***	***True Airspeed TAS (kt)***	***Mach***	***IAS (kt)***	***Comments***
U-Exit							17h24:40
FL300	510	+14	072/15	496	0.817	311	
GSM							South of Penang 17h52:31
FL300	511	+14	046/05	509	0.838	320	
LSTRP							Exit radar coverage at 18h22:12

Table 11: Average speeds based on the 3 officially known time tags using Airmen practices for FL320

Waypoint	***Average ground speed (kt)***	***ISA (°)***	***Wind Velocity (°/kt)***	***True Airspeed TAS (kt)***	***Mach***	***IAS (kt)***	***Comments***
U-Exit							17h24:40
FL320	510	+12.5	063/13	497	0.828	302	
GSM							South of Penang 17h52:31
FL320	511	+12.5	053/12	505	0.841	308	
LSTRP							Exit radar coverage at 18h22:12

Summarizing the results so far: no timestamps in original data, noisy radar data, and surrogate time labels. This only provides an approximative and certainly no decisive conclusion about instantaneous speed.

These average values correlate with the values obtained during simulations carried out with our Prepare-3D simulator.

So, for now, the 3 officially known time labels and their locations are the best numerical figures to use to estimate the average aircraft behaviour. Additionally, this is also supported by the fuel consumption, which lasts until 00:19 UTC. This allows reconstructing this part of the trajectory of the "fleeing plane".

5 Potential radars

Unfortunately, no information is provided on the data fusion algorithm that created the Geoscience dataset that we might also call the Malaysian Military Data Track. Additionally, no information is provided about the data source used at a particular time and place. The only meta information provided by the Geoscience JSON data file are the labels "Air Defense Radar Path", "Flightpath" and "Updated Last Air Defense Radar Point", which is very general.

In fact, there are not many possible sources of flight path information in Malaysia. Namely these are:

- Primary civil and military radars (PSR)
- Secondary Surveillance Radar (SSR)
- Automatic Dependency Monitoring Broadcasts (ADS-B)

SSR and ADS-B data were received until 17:20:34 UTC when the transponder stopped transmitting because it had been manually switched on standby. Until then, the track "Flightpath" is well known with its corresponding time labels.

The reference map in the 2014 ATSB report [4] is likely based on a fusion of these sources feeding a fusion algorithm in the military radar's data processor, likely similar to civilian SASS-C for example. It is impossible to know which particular source was specifically used for each point in the dataset. But, throughout the journey, the availability of data depends on the visibility of the aircraft for each source, that is, when it was in line of sight.

In 2017, the ATSB report [5] said that Malaysian authorities provided them with two tracks. The first covers from somewhere at 16:42 UTC after take-off to Gap-2 located after the U-turn. It is referred to as SSR: Malaysia Air Defense Secondary Surveillance Radar data, Track BD764 from 7 March 2014, 16:42:07 to 17:28:37 UTC, recorded at 10 second intervals. It includes more data than the SSR. The second track provided covers from Gap-2 to near Pulau-Perak and is called PSR: Malaysia Air Defense Primary Radar Data, Track BE144 7 March 2014, 1729:09 – 1802:59 UTC, recorded at 10-second intervals.

5.1 Military Primary Surveillance radars (PSR)

5.1.1 Introduction

A detailed description of the Malaysian military surveillance capabilities was provided in [12] reporting that a Sentry Command and Control system (Sentry C2) had been procured to integrate their legacy system and to augment it with proven technologies. This enhanced radar surveillance provides a coherent picture of Malaysian airspace. It became operational at the end of 2012.

Several military PSR radars could have captured echoes from MH370. Considering the technical specifications of their range, they are:

In Malaysia:

- Western Hill, Penang Island
- Bukit Puteri, Jertih, Terengannu
- Bukit Ibam, Muadzam Shah, Pahang

In Thailand:

- Kohk Muang, Songkhla
- Ko Samui Island

In Vietnam:

- Ca Mau

As no mention was made of possible cooperation with Thailand and Vietnam in tracking MH370, we assume that Malaysian military authorities did not request or use data from Thailand and Vietnam (in fact, this assumption is supported by the analysis below).

5.1.2 Malaysian Military radars

Interesting Malaysian military radar coverage is shown in Figure 44, the example is taken at an actual altitude of 40,100 feet (FL380 on that day) for the maximum of coverage to consider.

Western Hill is grey, Bukit Puteri is blue, and Bukit Ibam is near-white. Depending on its altitude, these three radars received the primary echoes from the plane but not necessarily simultaneously.

In this analysis, the radar coverage limit calculation is based on the model used by www.HeyWhatsthat.com [15] with a refraction of 17% slightly higher than the standard 14% using the USGS SRTM (Shuttle Radar Topography) data files from USGS.gov. Radar horizon limits were calculated based on this website horizon data with a horizontal angular accuracy of 1/8°.

A geographical view of the terrain is shown in Figure 43 to illustrate potential obstacles in Malaysian radar lines of sight.

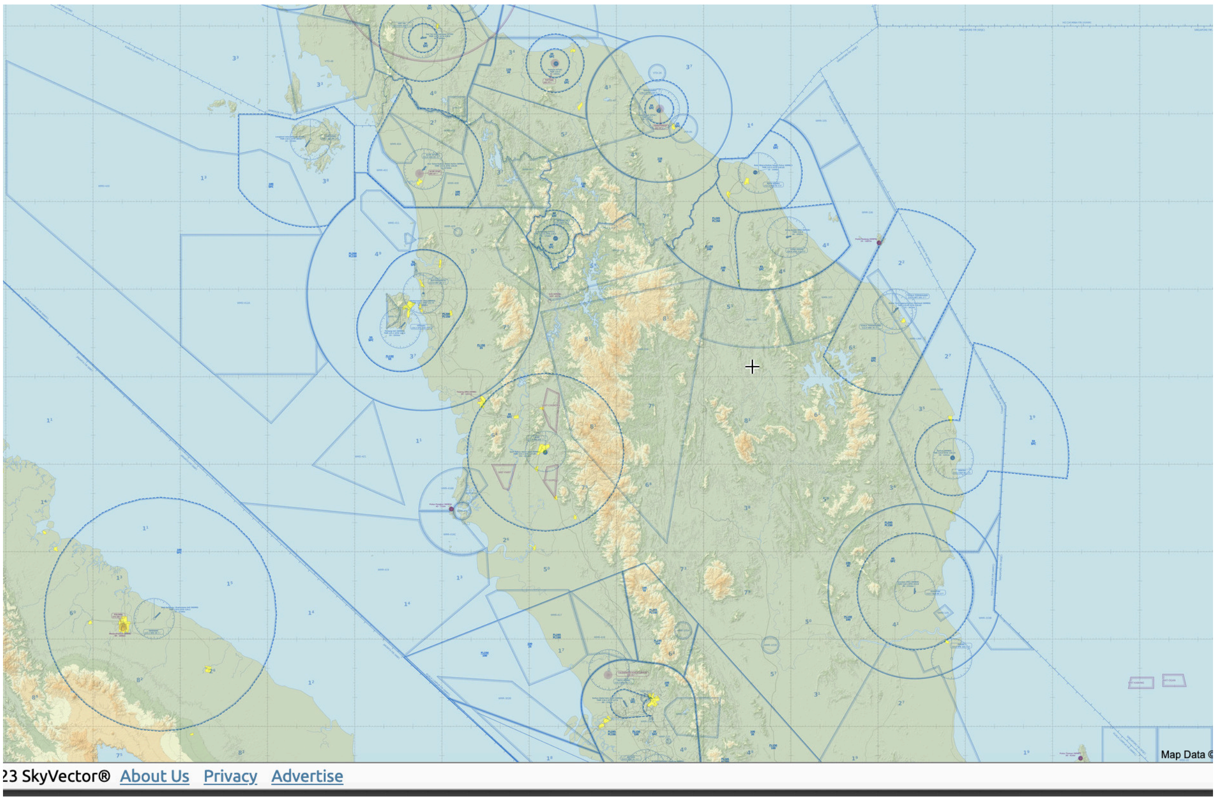

Figure 43: Geographical view of the terrain illustrating the possible obstacles in Malaysian radar lines of sight

On this day, it is impossible to know with precision the exact level of refraction. One might assume that the order of magnitude is sufficient for the high-level analysis performed here. A lower refraction level shortens radar coverage, thereby “shifting up” the minimum visible flight level at the particular location being scanned. A higher refraction level extends radar coverage, thereby “shifting down” the minimum visible flight level at the same location.

Caution: As a result of the above, the analysis cannot provide precise values but rather ranges and trends based on a morphological study of radar coverage.

The question of simultaneous visibility by several radars is important. Already, Figure 44 gives us the clue that the points in the Geoscience dataset were only provided **if at least two of these three radars had the aircraft in their line of sight simultaneously** in the absence of additional information from SSR or ADS-B systems although with some exceptions when civilian radar were available. This will be confirmed later in Section 7 below.

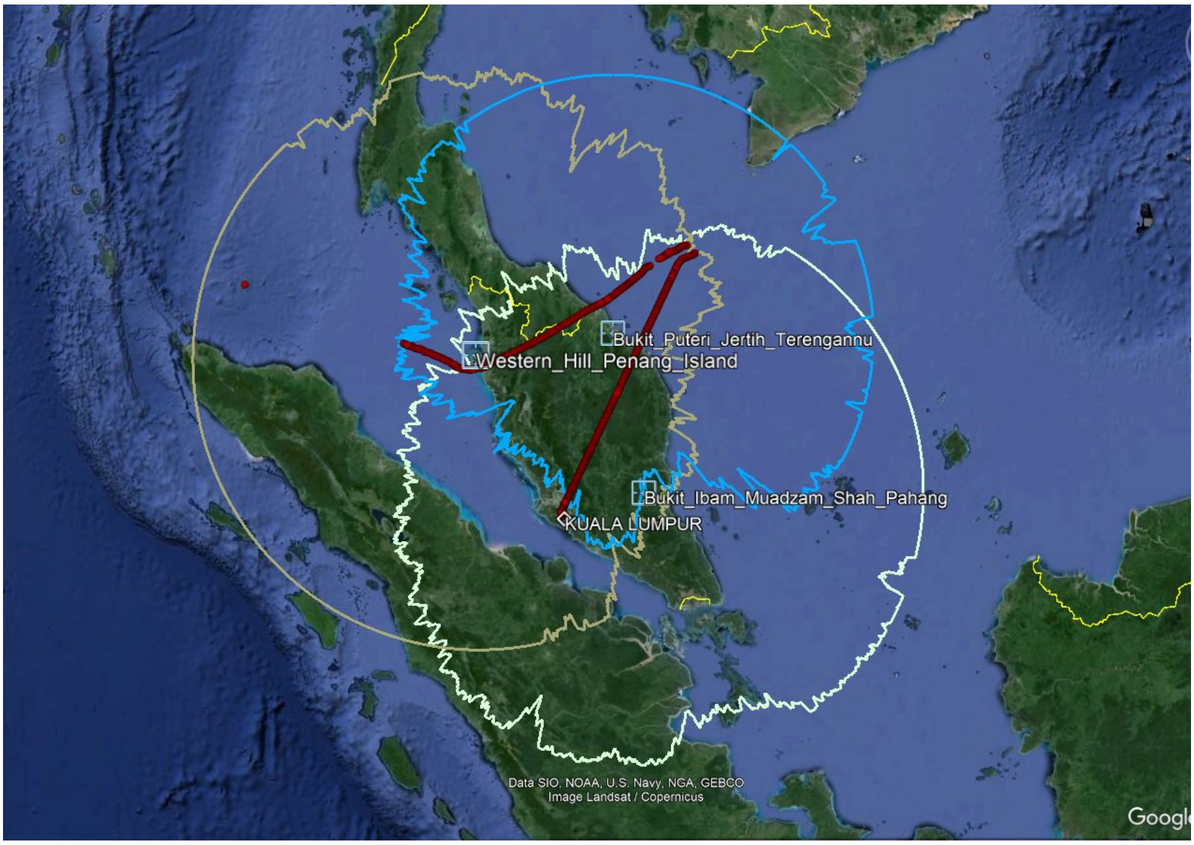

Figure 44: Malaysian Military PSR radars coverage at FL380 (14% refraction)

Remember that points are missing in three subsets of Geoscience data: after IGARI during the U-turn (Gap-1), shortly after exiting the U-turn (Gap-2), then from somewhere not far before Pulau Perak to the last point radar (LSTRP) at 18:22:12 UTC (Gap-3).

5.1.3 Refraction modelling

A key factor when considering radar coverage range is wave propagation. Refraction was the most influential factor as we found that no ducting had taken place that day. These factors are strongly linked to the weather conditions of the day.

Figure 45 illustrates the isotropic modelling of refraction for increasing levels from 5% (inner circle) to 26% (outer circle). The thickest curve is at 14%, which is generally considered the standard value.

Using the weather balloon data from Kota Bharu, the actual refraction was determined to be higher than average, comparable with a 26% value. But real propagation is influenced by local variations in temperature and humidity around the radars which were not modelled as the model used is a simplified one and the analysis showed that the refraction level at 17% is the correct “parameter” value calibrated at key locations to obey the constraints of aeronautical flight levels where these are known.

Thus, the refraction level must be considered as a simple tuning parameter of the high-level isotropic model we used. Actual refraction is not isotropic, but this approximation is considered sufficient for the level of the analysis performed here.

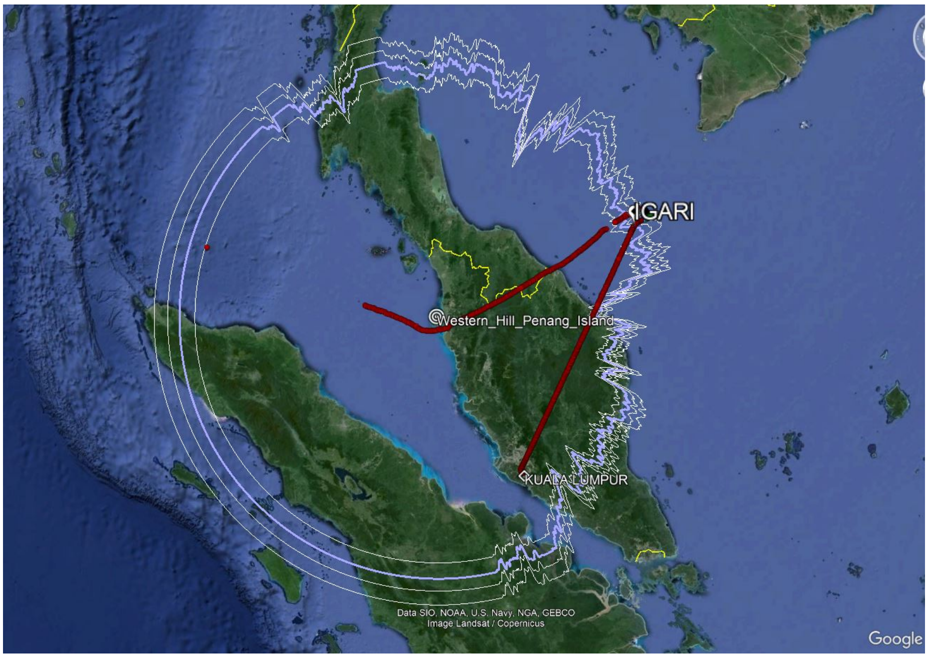

Figure 45: Modelling of different levels of refraction for Western Hill PSR (5%-14%-20%-26%)

5.1.4 Thai Military radars

For verification, Figure 46 illustrates the radar coverage of the Thai Kohk Muang site for a true height of 41,000 feet at 14% refraction. This radar would have provided valuable information for the three portions of the track for which data is missing. But the actual lack of data supports the conclusion that the Malaysian military did not use Thai military data at that time, otherwise there would be no gap in the track, at least until halfway between Pulau Perak and LSTRP.

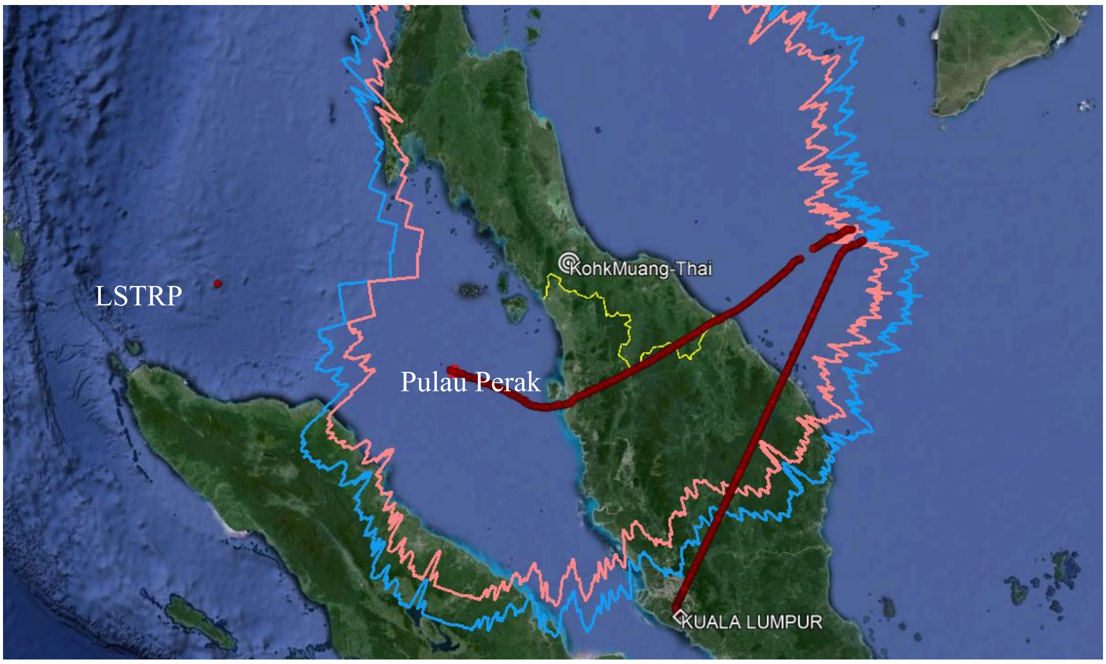

Figure 46: Thai radar coverage at Kohk Muang (FL300 and FL390) most certainly not used for reconstructing the track

5.2 Civilian approach radars

Data from civilian radars in digital format was given to the Independent Group and kindly published on their website [15]. Two data sets were provided: one from the Kota Bharu Airport civilian approach radar and the other from the Butterworth Air Force Base civilian approach radar (actually military) used for the approach to the airport from Penang. We also need to mention here the SSR data provided up to IGARI.

Data sets have gaps with no clear or no explanations. Structurally, their coverage areas are contiguous to each other. Kota Bharu misses few points, particularly at each beginning of the two half-tracks, probably due to the delay necessary for confirmation of a real target detection. However, Butterworth misses many points, mainly on the Malaysian mainland and in the south. These missing points could not be explained apart from a technical problem probably at the hardware level.

For each radar location, the data includes the measured slant distance, that is, the distance along the line of sight between the radar head and the target, the azimuth, and a time label for each measurement. Thus, to calculate the 3D location of the origin of the plots it is required to make an a priori hypothesis on the altitude, which is in reality unknown. For each assumed altitude, a different projected track on the ground is obtained.

Figure 47 illustrates the points of the possible trajectory (in light green) calculated with the data available for a true altitude of 37000ft (~FL350). Gaps are visible in this green track indicating that they could not cover the entire route (cone of silence, loss of data etc.) in their coverage area. Comparing with Geoscience data, Figure 48 shows that these gaps are all filled with red dots from other sources, i.e. military data.

Thus, it can be assumed that Geoscience data constitutes a superset of civil approach radar datasets.

To the question: were the two civilian datasets actually used by the military to reconstruct the track within the limits of their coverage? The answer is definitely yes. In the press conference hosting the Minister of Defence and his Chief of the Defence Staff, the latter clearly indicated they worked jointly with DCA (Direction of Civil Aviation) on Kota Bharu radar data [3]. On the other hand, Butterworth is an Air Base of the Royal Malaysian Air Force. It is actually military radar providing approach control services for the DCA at Penang airport. Its data has been used because it is part of the military network feeding the Sentry C2 system.
This will be taken into consideration when specific locations are analysed in detail below.

In Figure 49, the Geoscience track starts with points ahead of the Kota Bharu civilian radar data when the aircraft was en-route to Kota Bharu. This is a very useful data in the profile analysis further below.

The systematic shift of Butterworh points to the east of Geoscience points appears to come to the low precision of the radar angular estimation which shows to be not better than 1°.

Could they really be correlated? The best result today is obtained when assigning an altitude 0 to the civilian data.

But this will be the subject of a more detailed analysis in a separate report.

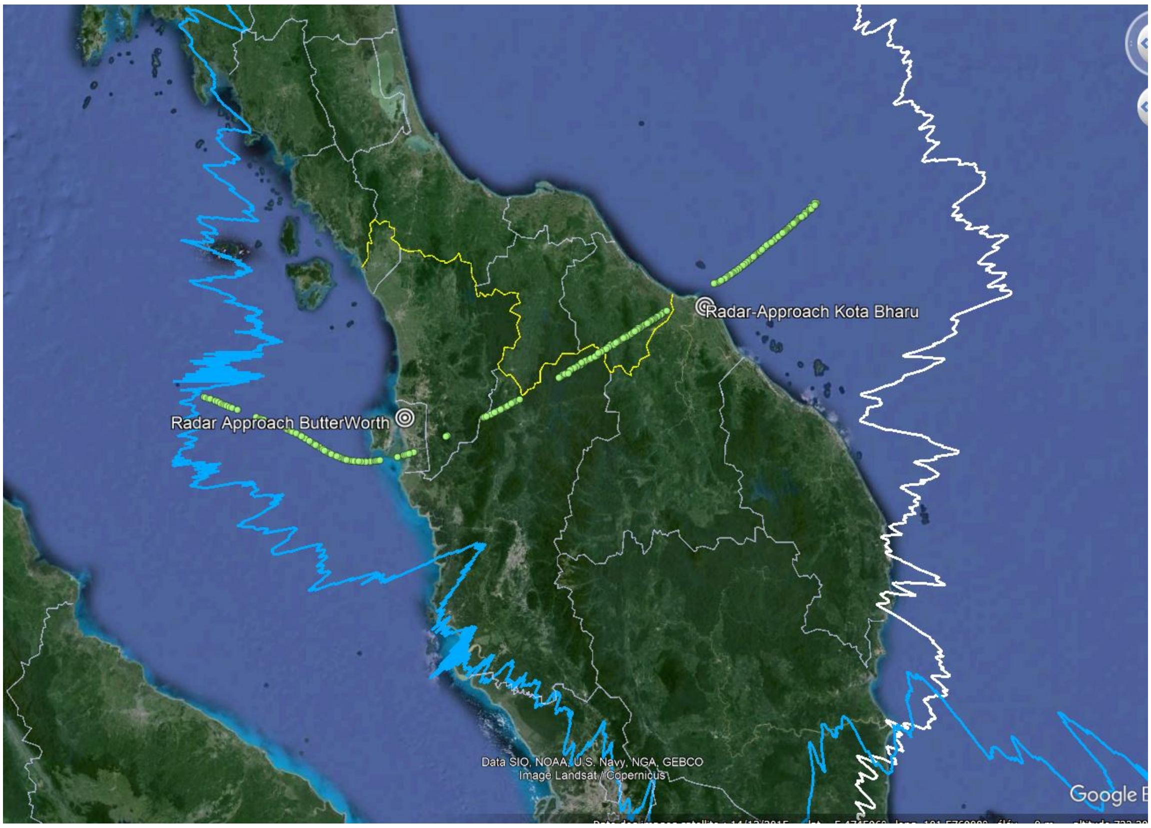

Figure 47: Civilian Approach radar echoes (light green dots) received at Kota Bharu and Butterworth stations

Figure 48: Merged tracks with Geoscience data and Civilian approach radar data

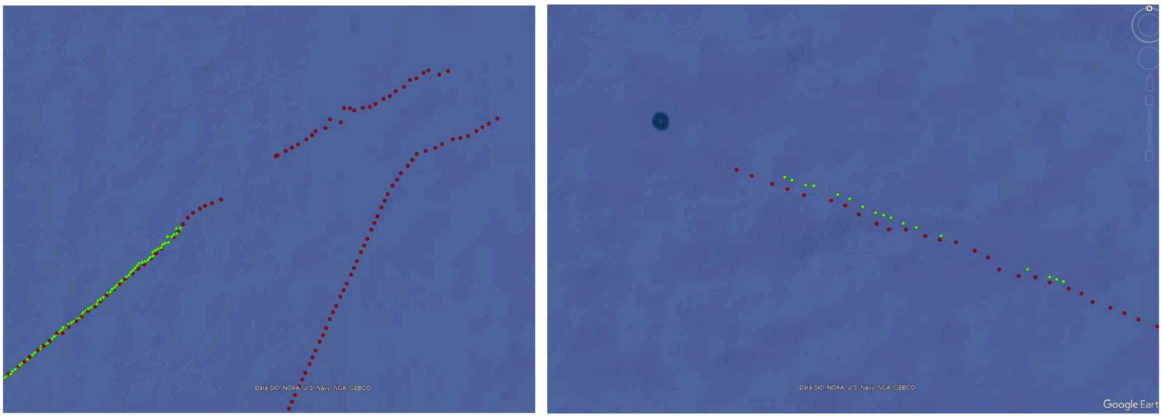

Figure 49: (left) Military track (red) and Kota Bharu Civilian radar data (green) and (right) systematic eastward shift of Butterworth RMAF Air Base radar data (right)

6 Key locations in details

6.1 Introduction

The Geoscience dataset includes information that can be used to analyse how the aircraft flew between IGARI and the LSTRP at 18:22 UTC. The information is in 2 dimensions only (projected on the ground), thus the analysis will be done in projective geometry. Despite this limitation, it is possible to produce pieces of evidence in the "horizontal plane" regarding the lateral navigation of the aircraft.

We will provide an answer to certain assertions made here and there about the fact that the plane was controlled by the LNAV function of the autopilot. But this was not the case.

In the section below, the analysis will review key locations in detail, providing important factual information.

6.2 Manual Half turn after IGARI

6.2.1 Aeronautical considerations and limitations at IGARI and during the U-Turn

The first key location is the U-turn manoeuvre in the part of the flight after the IGARI waypoint until the U-turn exit as shown in Figure 50. With the new knowledge of the numerical values of the track point coordinates, it is possible to situate them well with their environment and with respect to Route M765 and the Thai military ADIZ not to be trespassed.

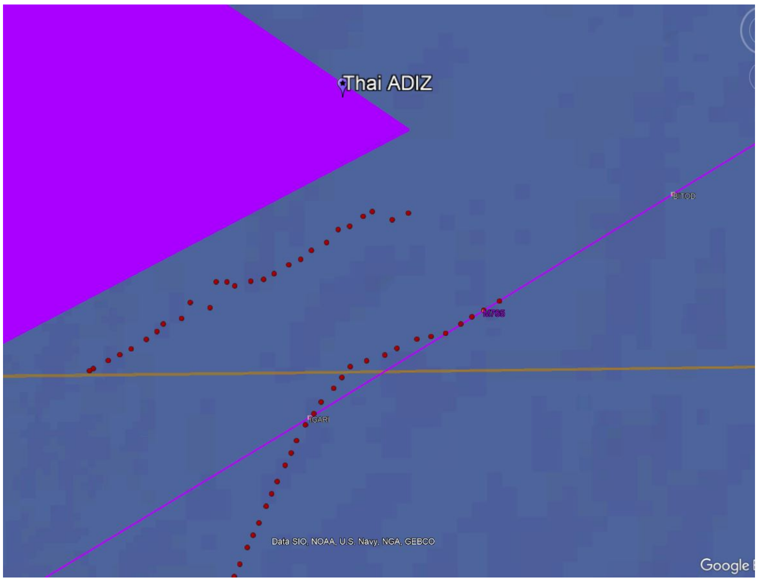

Figure 50: Zoom of the Geoscience before, during and after the U-Turn at IGARI (red dots)

At IGARI, the aircraft was at FL350 (true height ~37,000 feet) with a ground speed of 474 kt and its mass was 217 tonnes.
Considering Boeing's buffet limit charts for the 217t and Trent engines characteristics, the maximum possible flight altitude indicated is ~FL405, or true 42,000 feet.

So, as a pilot would never climb to this limit for control and safety reasons, he would take a margin and consider that ~FL380 is the maximum acceptable which corresponds to the true height ~40100ft. As underlined above, FL370 would be the safety limit.

6.2.2 Auto-pilot option versus manual option

In our report [1] from March 2023, we reported the results of our simulations demonstrating that the U-turn was performed manually and not with autopilot. Several simulations carried out twice on the SkyWays professional simulator in September 2022 and November 2023 in Nantes, France also confirmed this.

Figure 51 illustrates the trajectory travelled manually in our simulator with an increasing banking angle up to 38° (yellow curve) and starting a little earlier than the official entry point. It is remarkable that our simulated trajectory in March 2023 flies very well over the actual trajectory points before we obtained digital Geoscience data. **This independent determination of the U-turn trajectory constitutes a compelling additional piece of evidence.**

The orange circle (Figure 51) represents the theoretical, hypothetical trajectory if the aircraft had a constant inclination of 31° from the official entry point. But it is not possible to initiate a turn instantly at 31° therefore the inclination had to develop gradually before. Thus, the start of the round turn must necessarily be earlier. However, it serves as a reference to show that the bank angle must have been well outside the capabilities of the autopilot, which is limited to a maximum of 25° (in green in Figure 51).

This limitation is illustrated by the green circle in Figure 51 which represents the radius of the simulated U-turn carried out by our FsX simulator with the autopilot with the characteristics of the aircraft at this moment: mass, speed, FL, wind, etc.

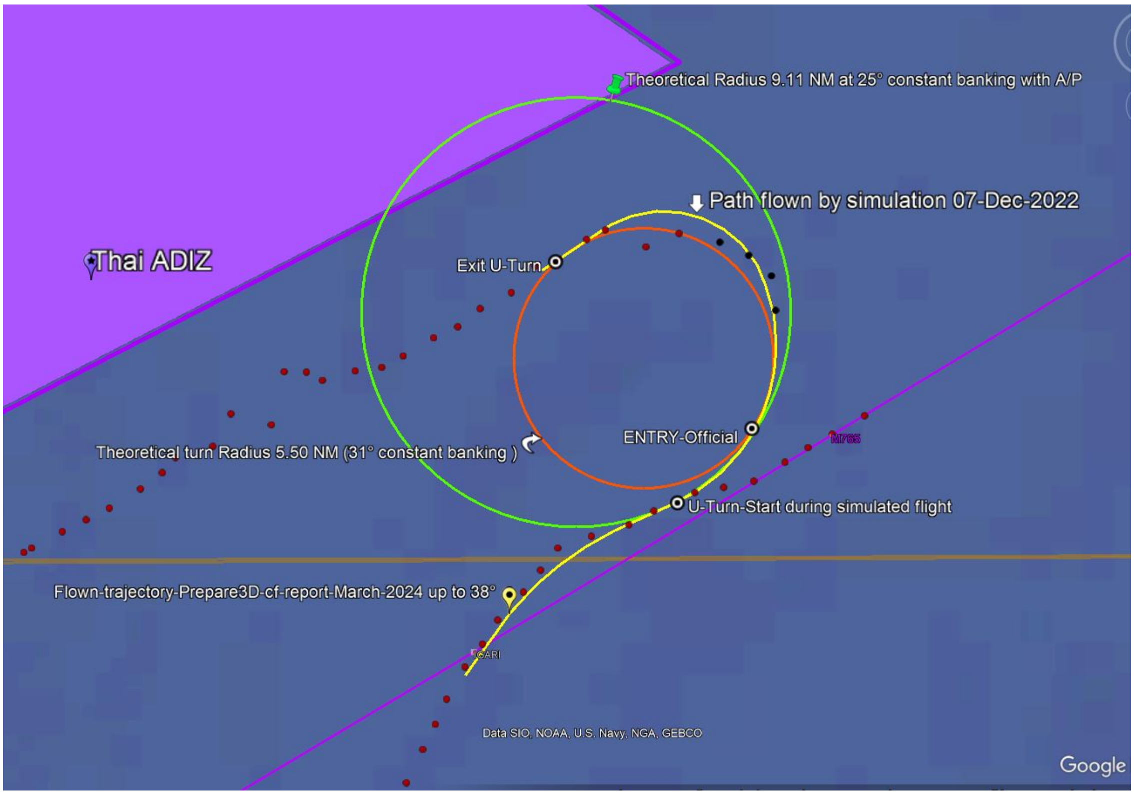

Figure 51: Comparison of U-turn execution with autopilot (green) or manual (yellow)

Figure 52 presents in detail the results of the simulations carried out with the Prepare-3D simulator on a PC home computer. The correspondence with the Geoscience points (red) is very good as well as with the additional points (black) deduced earlier in this study. For the record, the simulation was carried out respecting the officially announced timing, i.e. 2min10s. This was also the case for the SkyWays simulator.

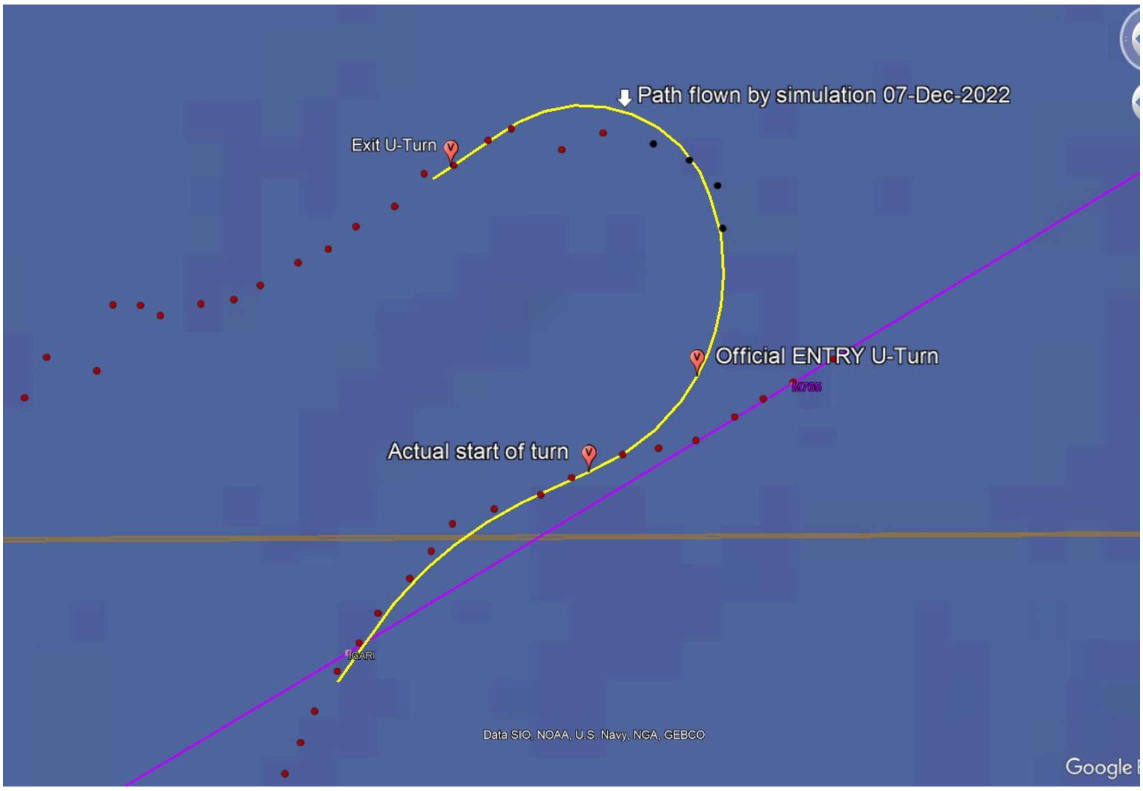

Figure 52: Simulation of the manual execution of the U-Turn with the Prepare-3D simulator

6.2.3 Conclusion

Knowing the numerical coordinates of the flight path in dark red in Figure 51 and Figure 52 clearly demonstrates that the U-turn was performed manually because the small turn radius of approximately 5.5 NM on average is unfeasible for the LNAV function of an aircraft with this mass and this speed at this flight level.

6.3 Manual Flying after the exit of the U-turn

6.3.1 Overall considerations

A first simple visual inspection of the digital data of the actual trajectory (see Figure 53) before IGARI shows the perfect linearity of the flight from the right turn just after take-off until just before reaching IGARI which illustrates the capability of the aircraft to fly in a near-perfect straight line when controlled by the automation of the autopilot's LNAV function.

First of all, this should be compared to the visual appearance of the trajectory flown on the return to Malaysia (upper part of the route in Figure 53), which presents numerous irregularities. It could be argued that before IGARI, data was produced from SSR/ADS-B information, whereas after IGARI, this data came only from the PSR. Maybe, but it is therefore worth making two points here: 1) two radar sources were used at different line-of-sight angles to produce the points and 2) the eye is a very good visual low-pass filter thus capturing the main trends and not the roughness of details.

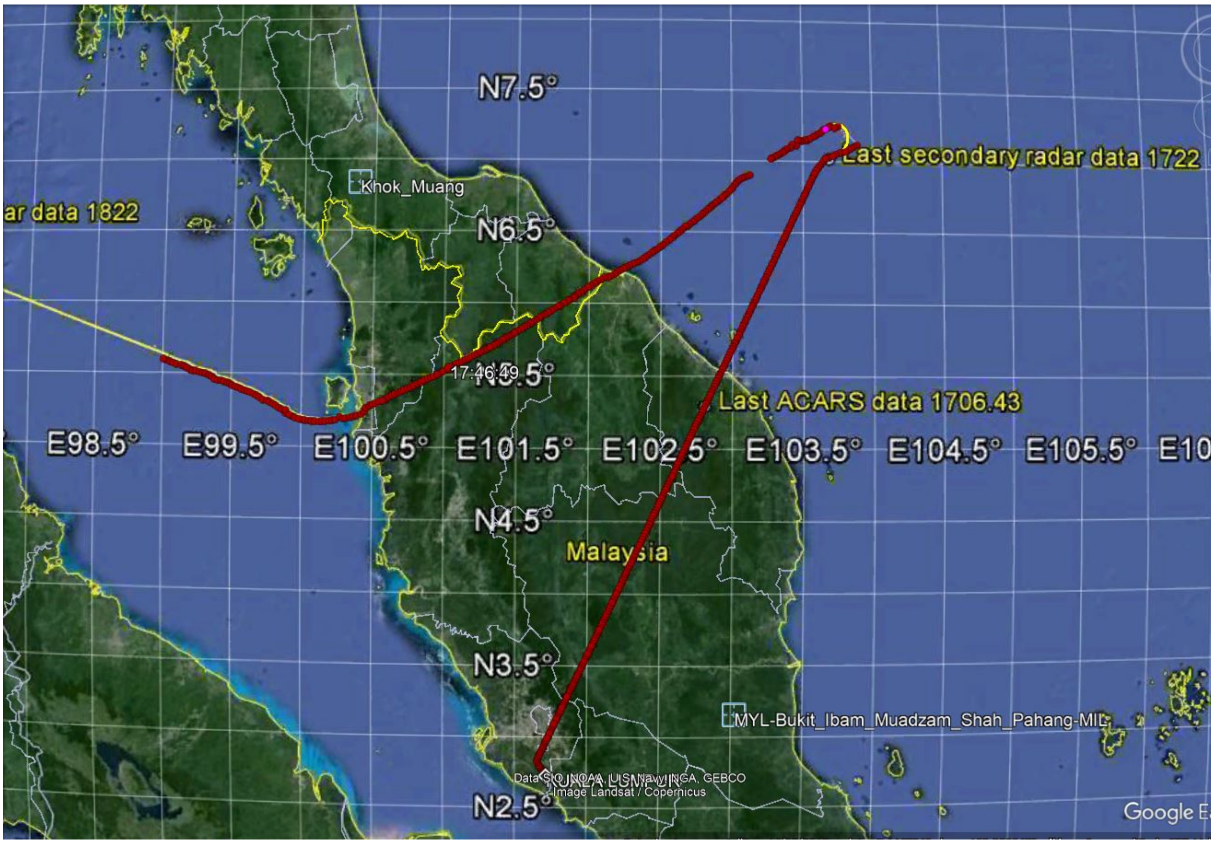

Figure 53: Full Geoscience dataset mapped on the 2014 ATSB report reference map

In any case, to reach a conclusion, further analysis of the data is necessary. And, it is presented below starting from the “past” before IGARI for the sake of demonstration.

6.3.2 Characteristics of the flown path before IGARI

Figure 54 illustrates the ability of the autopilot's LNAV function to fly the aircraft in a straight line. This is confirmed by the correlation factor R^2 value of the plotted trend line showing a perfect match. This high flight accuracy will serve as a reference when comparing flight paths further below.

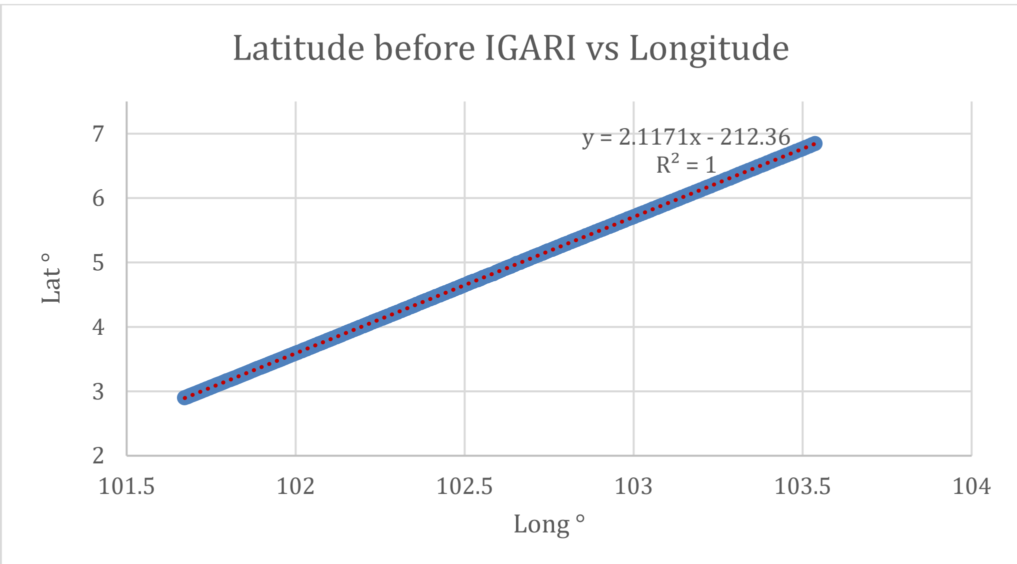

Figure 54: Geometric digital analysis of the path “Direct to IGARI” perfectly flown with the autopilot

6.3.3 Characteristics of the flown path after exiting the U-turn

It was demonstrated in Section 6.2 above that the U-turn was performed manually. But what about the following steps, were they also done manually?

If the aircraft had been flown with the LNAV function of the autopilot, a reference heading or reference waypoint would have been entered into the MCP. In such a case, the path must be a sort of broken line composed of straight-line sub segments.

6.3.3.1 After the Exit of the U-Turn until approximately after 17h28

The segment before Gap-2 of approximately 3.5 minutes of flight covered here is underlined in Figure 55 by the red oval. In the middle of this segment, a slight right turn is visible. This segment is clearly not a straight line; it is therefore not necessary to evaluate it numerically. The first part that could be considered a short straight line is on the 238° trajectory (orange segment). The same goes for the second part also on track 238° (green segment). But since they are not aligned, the small adjustment in the middle necessarily had to be done manually since no autopilot would behave that way. In addition, it is logical that this part is carried out manually in the same way as a continuation of the previous U-turn carried out manually.

Figure 55: Geoscience points from the Exit from the U-Turn to the beginning of the gap

6.3.3.2 From approximately 17h27 until Kota Bharu after 17h37

The focus now shifts to the next segment, shown in the red highlighted area in Figure 56. It covers the U-turn exit to near Kota Bharu on the east coast of Malaysia.

Figure 56: Geoscience points from approx. 17h27 until approx. 17h37

Assuming that this portion was flown with the autopilot, either a heading had been entered into the MCP or a reference waypoint had been entered in the aircraft's LNAV function via the MCDU. Figure 57 shows that the aircraft passed abeam the KADAX waypoint at a distance of approximately 0.6 Nm, which is the closest waypoint before going around Kota Bharu. Thus, KADAX will be used as a hypothetical waypoint to compare potential paths.

But before that, it should be emphasized that 0.6 Nm does not respect the 0.5RNAV capability of the B777 demonstrated at 17h20 UTC where the aircraft passed exactly 0.5Nm through IGARI according to the specifications of its navigation system. At that time, it was turning which is not the same situation as at KADAX. This is further evidence supporting the hypothesis that the plane was manually piloted.

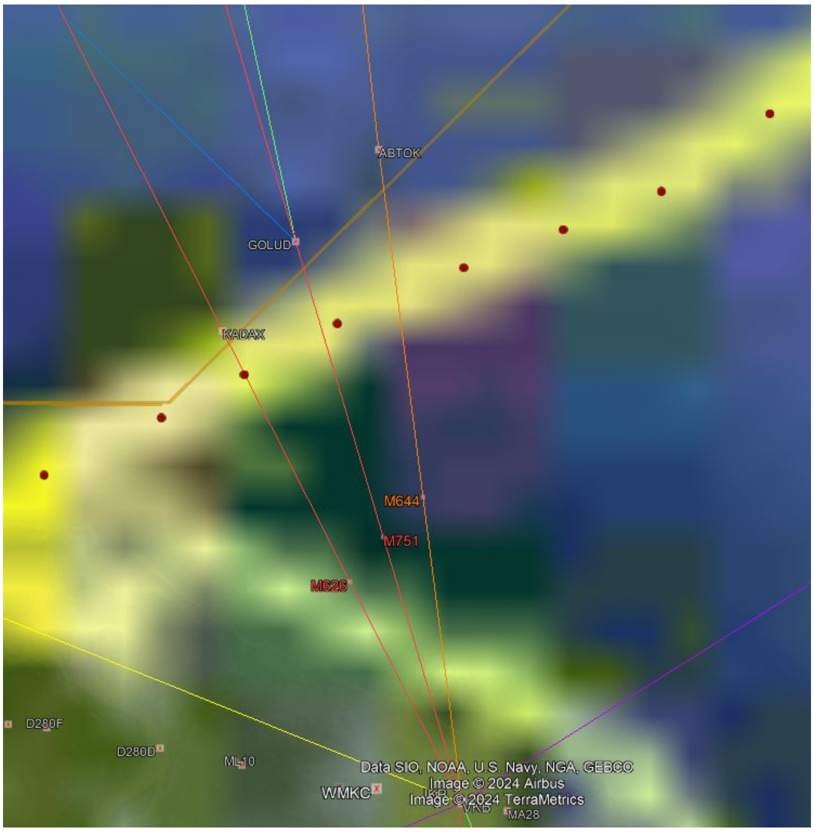

Figure 57: KADAX is would have been most probable direction if flown with the LNAV function

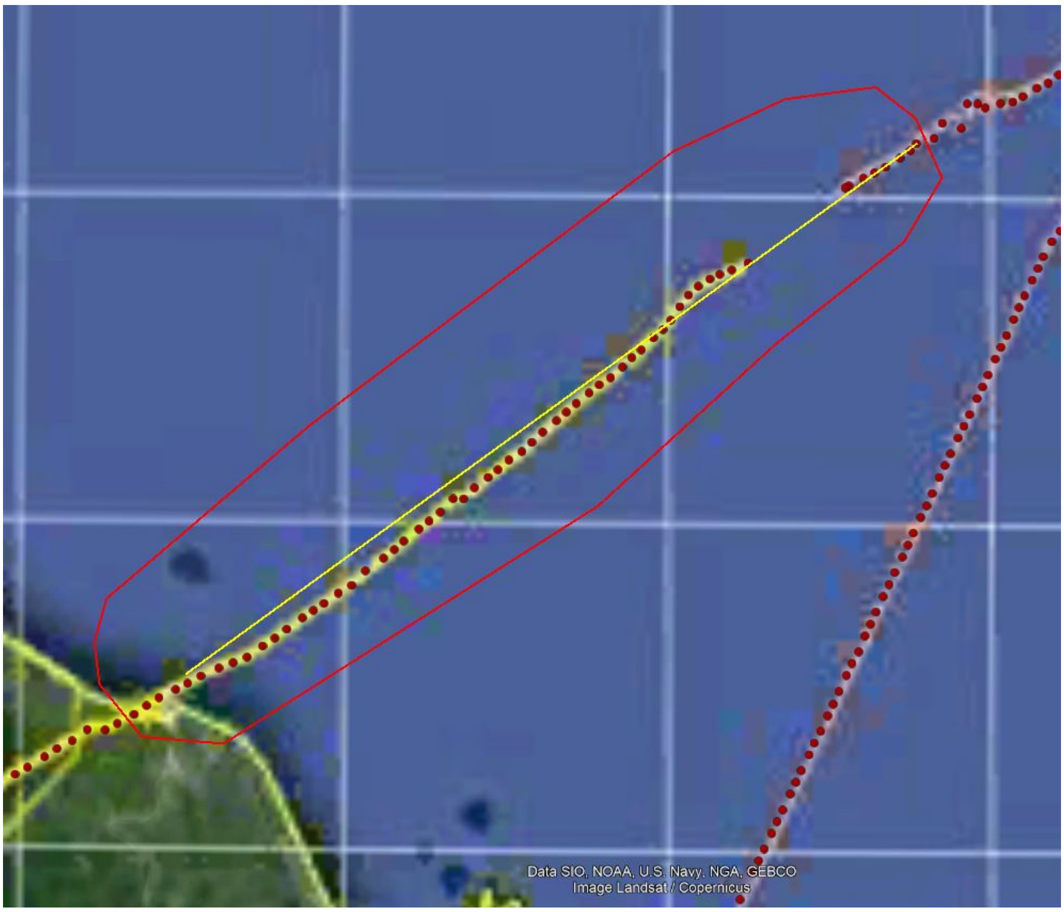

Figure 58: Visual comparison of the Geoscience track with the KADAX LNAV path

Taking KADAX as the LNAV reference waypoint, the trajectory is at 234° as illustrated in Figure 58. It is visually clear that on its own, the (im)precision of the radar does not fully explain the differences between the two tracks. The Geoscience track is far from executed with the aircraft's LNAV capability demonstrated before IGARI. This is also another compelling piece of evidence that the aircraft was manually controlled at that time.

If we now consider a true track (the best would actually be to take a heading), then the best direction would be ~233° as provided by the Geoscience trend line and as illustrated in Figure 59. This trajectory is shown in Figure 60 in yellow, which confirms that the plane did not follow a direct route on this segment.

If we consider that several headings were entered successively in the MCP, then this would have been done at least half a dozen times, which is … manual piloting. But we did not detect such successive linear segments.

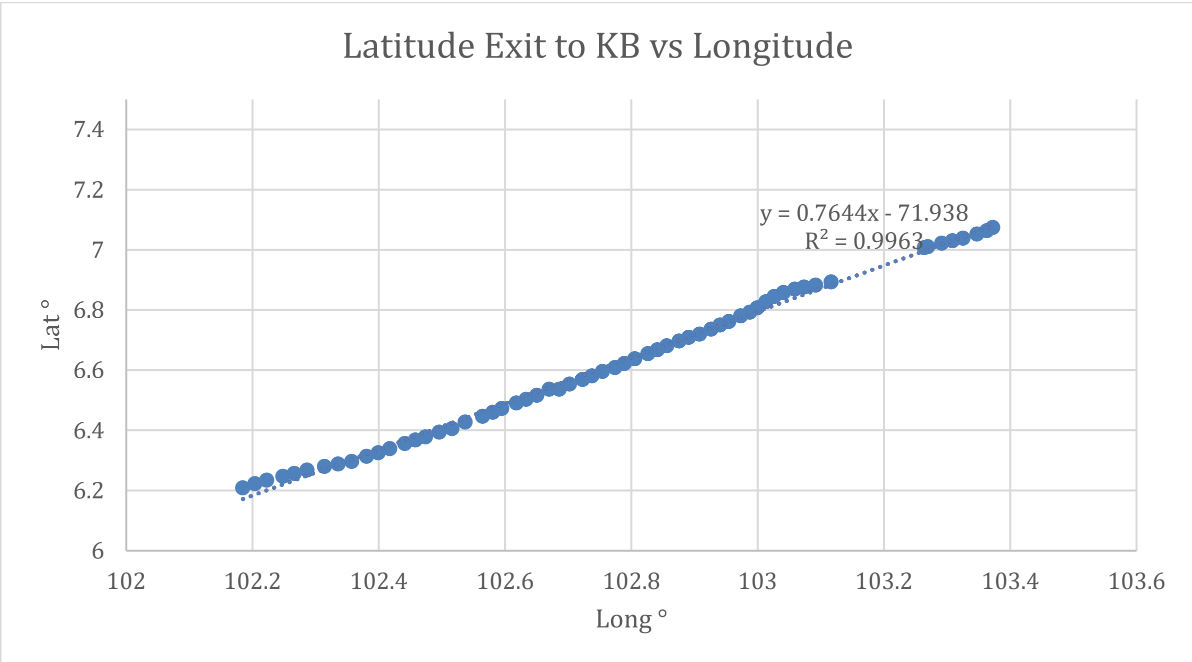

Figure 59: Trend line of the Geoscience path (at 233°)

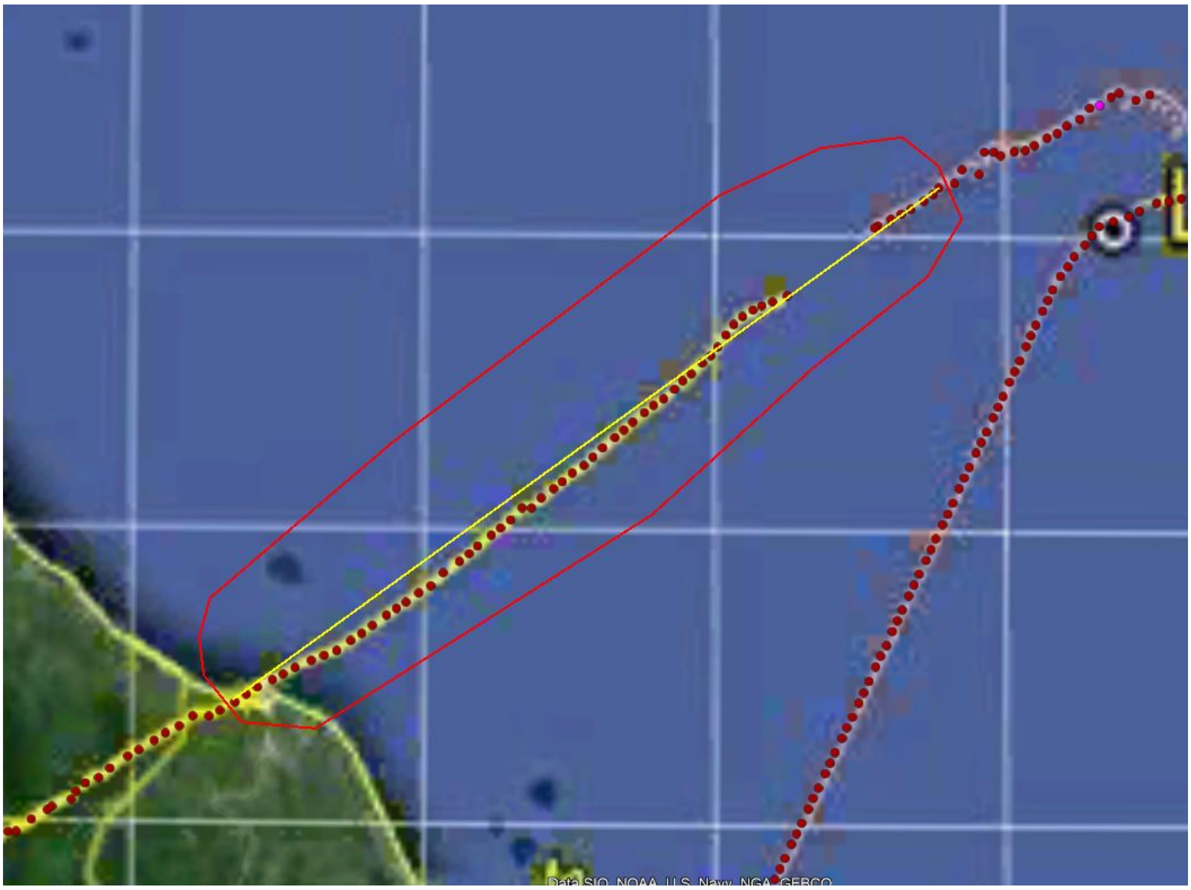

Figure 60: Visual comparison of the Geoscience track with the path at true track 233°.

6.3.3.3 From Kota Bharu to vicinity of Penang

The next segment to consider is shown in Figure 61 in the area highlighted in red. It extends from Kota Bharu to the vicinity of Penang Island on the west coast of Malaysia.

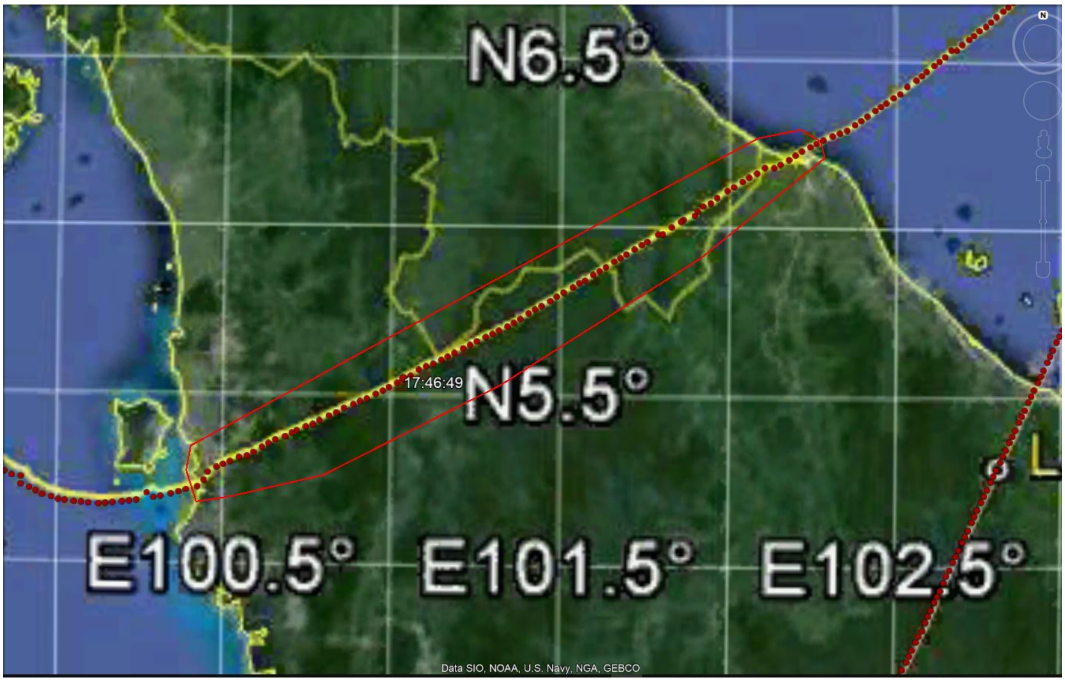

Figure 61: Geoscience track from Kota Bharu to near Penang Island

Along or near this path, there are only a few possible navigation items: Route B219 and its waypoints. The aircraft did not follow this route but crossed it before LOSLO waypoint. Abeam LOSLO, the distance was approximately 2 Nm. Subsequently, the LNAV function could not have controlled the aircraft on this segment. In addition, the logical waypoint for the upcoming turn at Penang would have been VPG (Penang Airport), the track does not pass north of VPG but south of it which is not a normal automatic behaviour. VPG is the only upper airspace IFR waypoint there.

The other possibility was to fly the aircraft with a reference heading input on the MCP. Figure 62 provides us with the value of the best resulting trajectory at true track ~241°. This trajectory is shown in Figure 63 in yellow, which confirms that the plane did not follow a straight-line route on this leg.

Moreover, the weather was well within the aircraft capability to maintain a quasi-perfect linear trajectory.

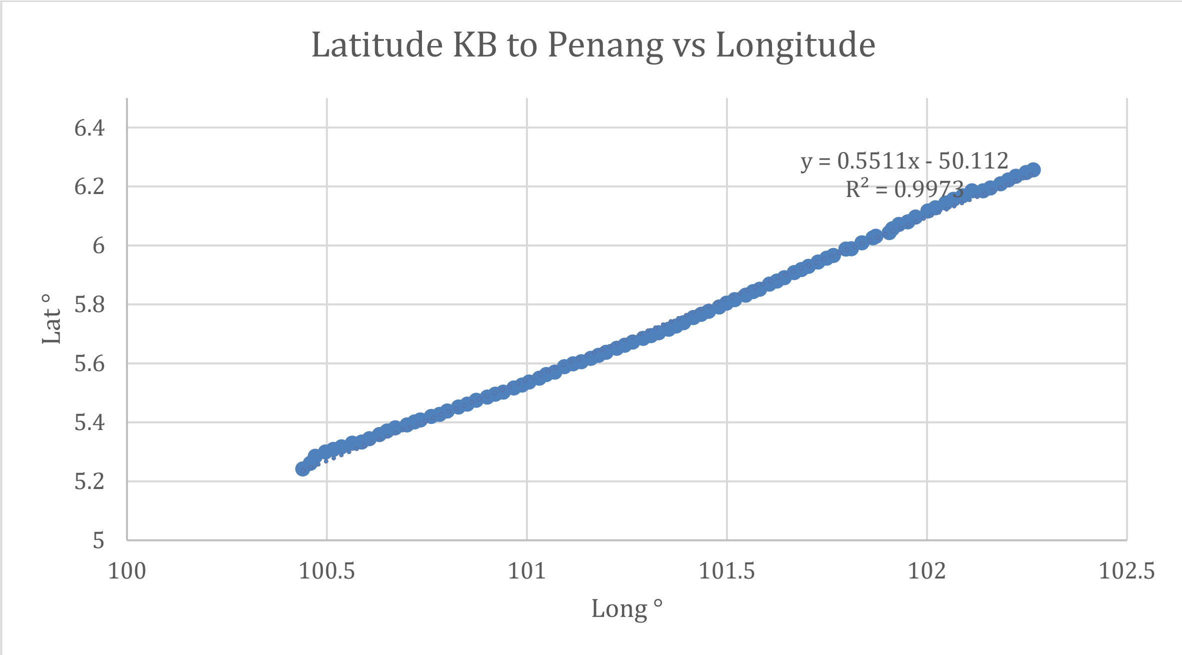

Figure 62: Trend direction on the segment Kota Bharu to Penang

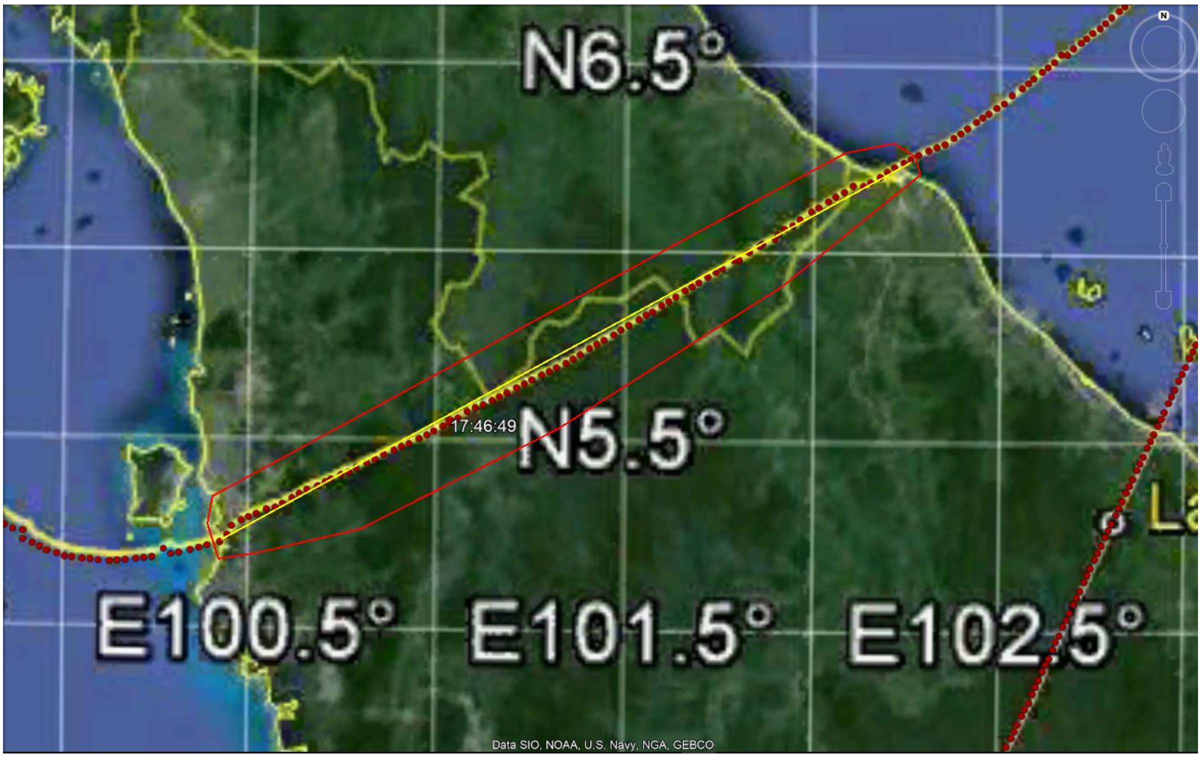

Figure 63: Visual comparison of the Geoscience track with the path at track 241°

6.4 Turning around Penang Island and heading to Pulau Perak

6.4.1 Introduction

The segment studied here is illustrated in Figure 64 (dark red dots). Several key aspects of the Geoscience track are worth exploring:

1. Pass well south of Penang Airport (VPG waypoint)
2. A possible slight left turn manoeuvre before passing Penang Island (green arrow 1)
3. A coasting which took place south of Penang (Green Arrow 2)
4. An obvious non-linear path from the turn to the last point before Pulau Perak

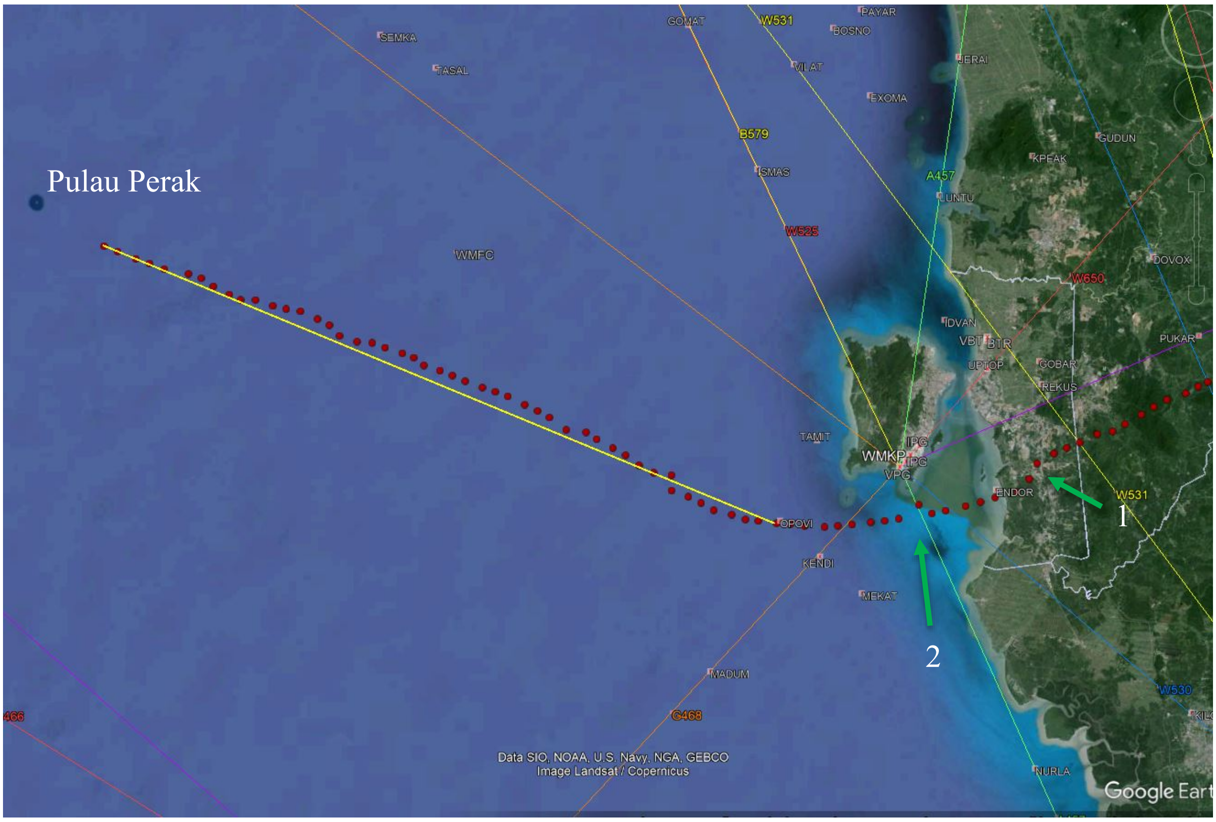

Figure 64: Geoscience track in the turn South of Penang and on the way to Pulau Perak

6.4.2 Passing well in the south of Penang Airport (VPG waypoint)

Near Penang Airport (VPG), the upper airspace structure does not include waypoints except VPG (cf Figure 65) which is on 8 routes of which 7 originate or terminate there. Coming from Kota Bharu, the only documented route is the B219 represented by the purple line in Figure 64.

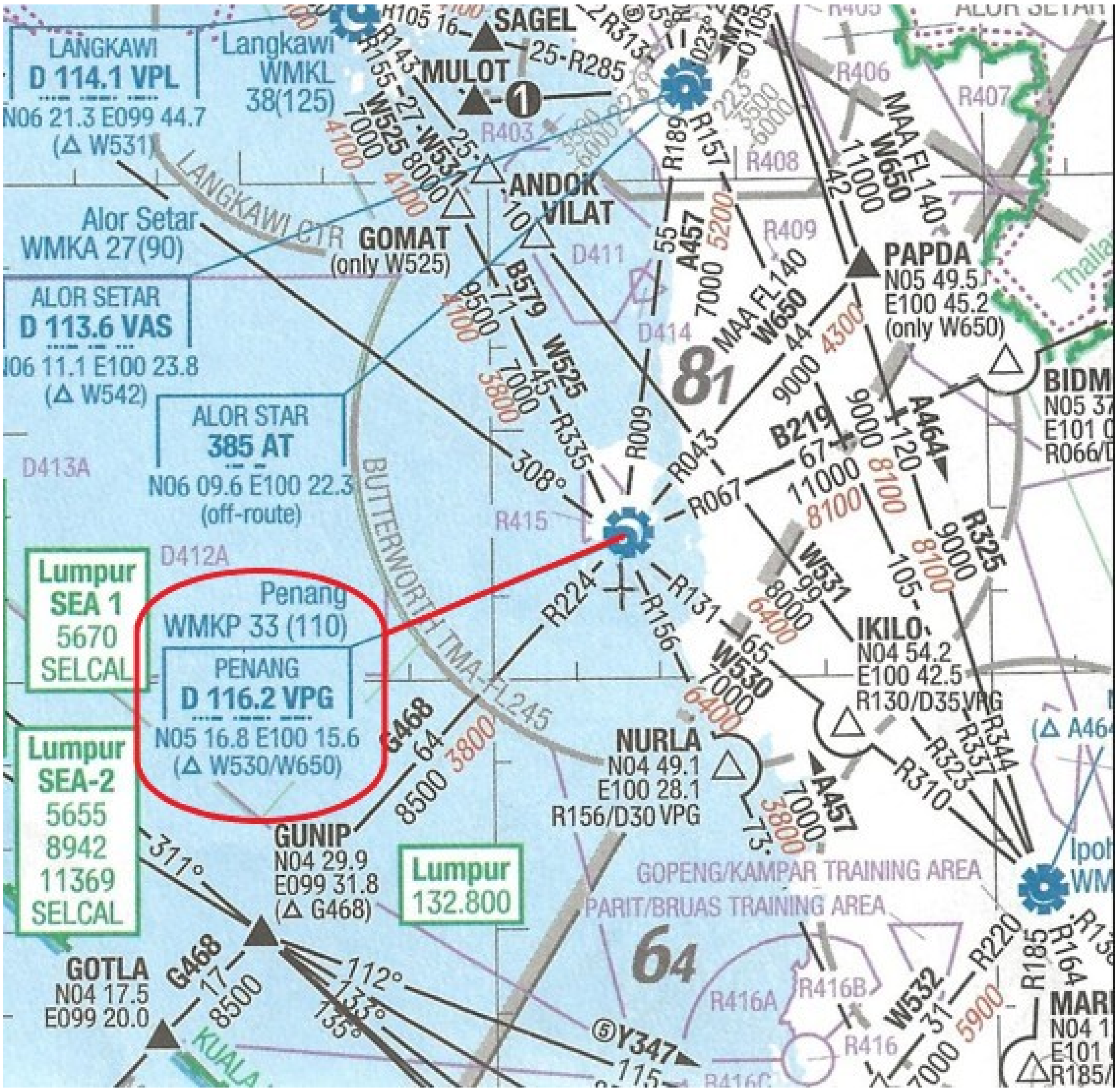

Figure 65: Unique IFR upper airspace waypoint in the vicinity - WMKP at Penang Airport
source: LIDO- route manual

The Geoscience track shows that not only does it not fly over WMKP by far at a distance of ~4.8 Nm but that it does not pass abeam to the north which should have been the trajectory of an aircraft in LNAV mode. Even in heading mode, the plane's trajectory would have been much smoother and closer to the WMKP.

Additionally, remember that ENDOR, KENDI and OPOVI waypoints are not IFR upper airspace waypoints. Figure 66 shows that these points are standard arrival waypoints when approaching Penang Airport. A pilot would never use lower airspace navigation/approach waypoints at high flight levels. Thus, they would not be used for navigation purposes at the current flight level.

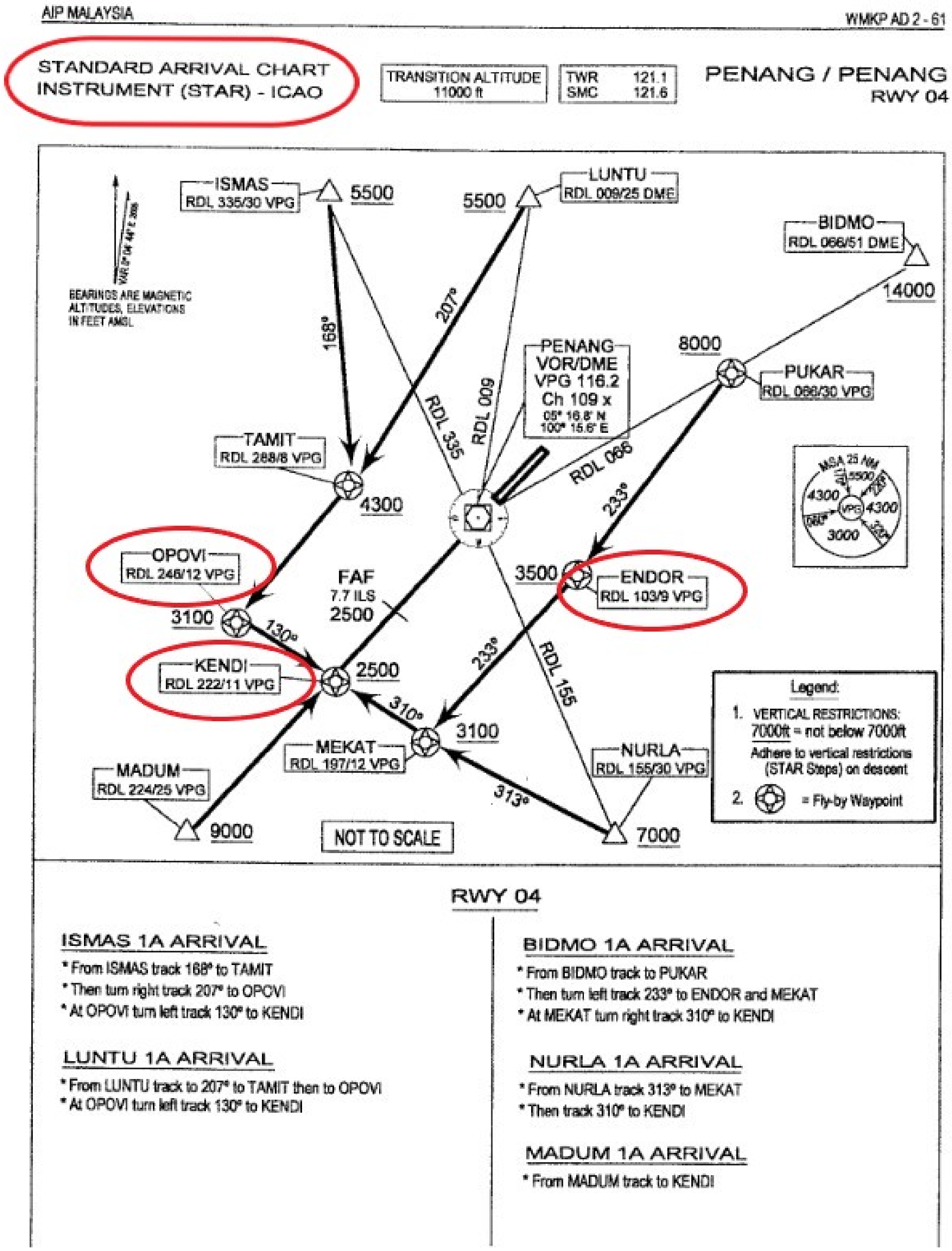

Figure 66: Arrival waypoints at Penang Airport
source Malaysian AIP

This supports the hypothesis according to which the turn was made manually in continuity with the previous segment.

6.4.3 Left turn manoeuvre before passing Penang Island

The green arrow 1 in Figure 64 points to a specific location where the Geoscience track raises questions. Two options are possible here.

The first one is to consider that the projection on the ground was correctly done by the RDP. Then, this peculiar S-shape that would not match the trajectory of an auto-piloted aircraft fits well with the manual mode. In order to turn properly to the right around Penang, the pilot could have needed to see the light of the Island through the windshield of the cockpit when banking. To achieve this a slight left turn put the aircraft a little further away allowing the person in command to see correctly the lights.

The second option – the preferred one – is to consider that the projection on the ground was poorly done by the radar data processor (RDP) because it was a place where the radar signals disappeared time to time.

6.4.4 Coasting that took place in the South of Penang

Section 4.7.4 above identified that a coasting took place from the location indicated by green arrow 2 in Figure 64. This comes from the coverage limit of one of the military PSR radars. Considering that the predicted points constitute a smooth and continuous path with the previous points but one and the following points, we can consider the point designated by the green arrow 2 as a kind of "outlier".

6.4.5 Non-linear path after the turn at Penang

Finally, as illustrated in Figure 67, the behaviour of the Geoscience track (dark red dots) compared to the linear segment (in yellow) on a true track at 291° shows that the LNAV function of the aircraft did not have control of the plane. It is not necessary to perform numerical trend analysis to see this in Figure 67.

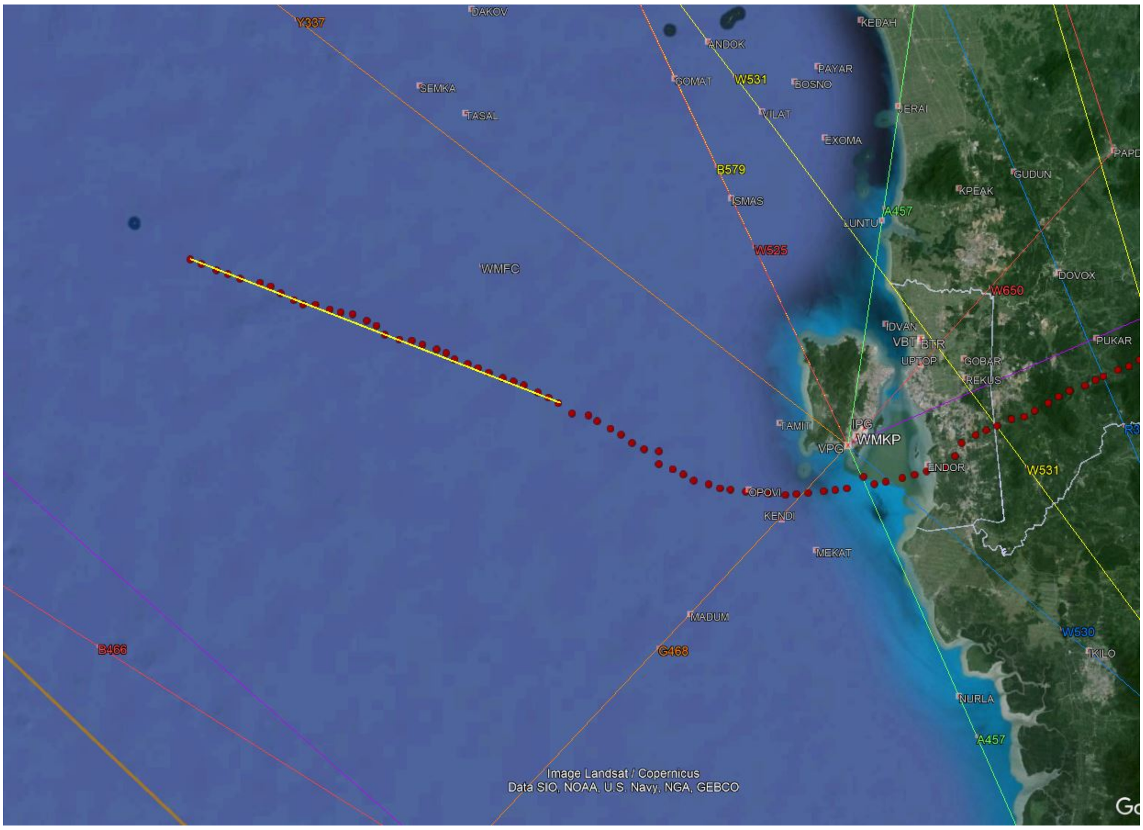

Figure 67: True heading at 291° after turning around Penang (yellow) compared with Geoscience points (red)

By extending the yellow trend line at the true track 291° towards the "future", the trajectory targets the VAMPI waypoint (see Figure 68) which was flown over by the plane according to the radar image presented at the Lido hotel. On this image (see Figure 69) one can see that the radar echoes are not aligned on a straight line confirming the behaviour of the last part of the Geoscience points, i.e. oscillating around this direction.

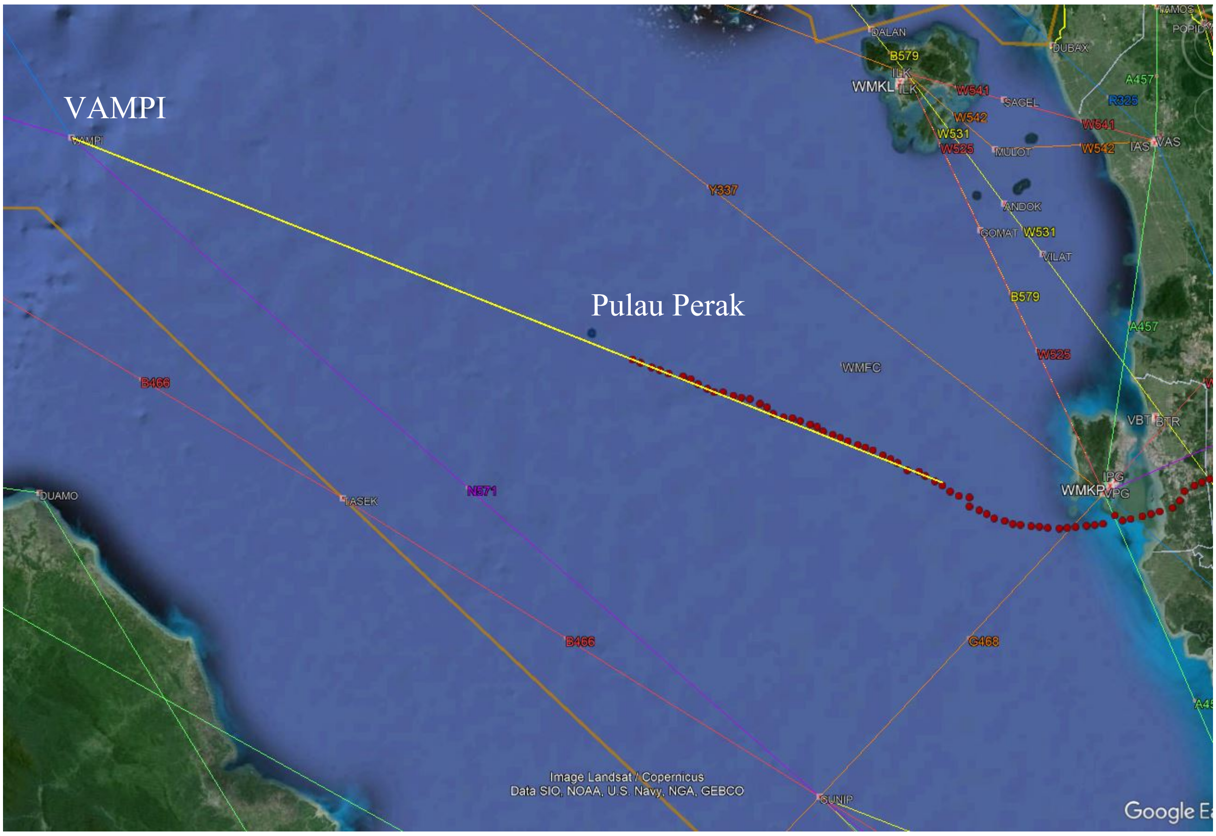

Figure 68: Projection of the true track at 291° after the last Geoscience point before Pulau perak

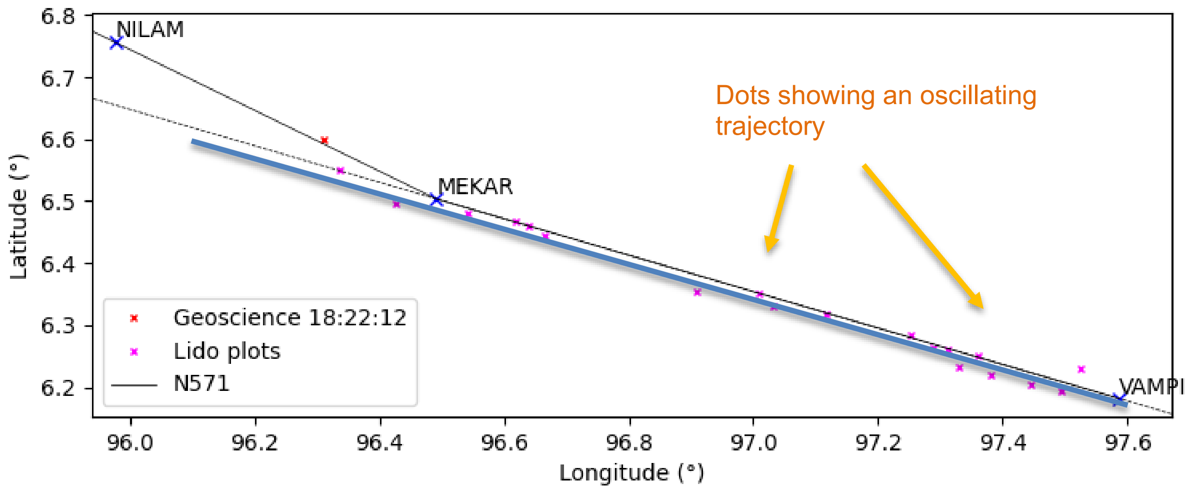

Figure 69: Digitised points (pink) of the image presented to the families at the Lido Hotel and the Geoscience LSTRP (red)

6.4.6 Conclusion

All the points analysed above agree to show that the aircraft was more likely flown manually during the turn at Penang than controlled by the LNAV function which would have been much more precise in continuity and linearity of the path.

6.5 Last Radar Point (LSTRP) location

6.5.1 Introduction

The different sources mentioned in 3 above as well as other examples such as the path presented at the Lido hotel place this last point in different places. In fact, it has been also given several names: Latest Updated Air Defense Radar Point, Latest Radar Point, Latest Primary Radar Data 18:22. In the Geoscience dataset, we notice that this last radar point (LSTRP) was placed exactly on Route N571. We think this is because at the time of its creation for its use to help the search and rescue, that is a few hours after the disappearance, the plane was thought to be in LNAV navigation mode on this route. Referring to the Malaysian Final Report [11], this point is characterized as "10Nm past MEKAR" and the Lido radar image shows that the last radar echo is clearly south of Route N571.

The track created between the last point of the previous segment (#3) and this LSTRP is in fact a straight line drawn between these two points and is certainly not the output of the radar tracker.

6.5.2 Inferred position

That being said, what information is available regarding the LSTRP (Last Radar Point)?

The only radar traces available come from the image presented to the families at the Lido hotel. These points have been digitised as shown in pink in Figure 70 while the last Geoscience radar point (LSTRP) in red is located exactly on Route N571.

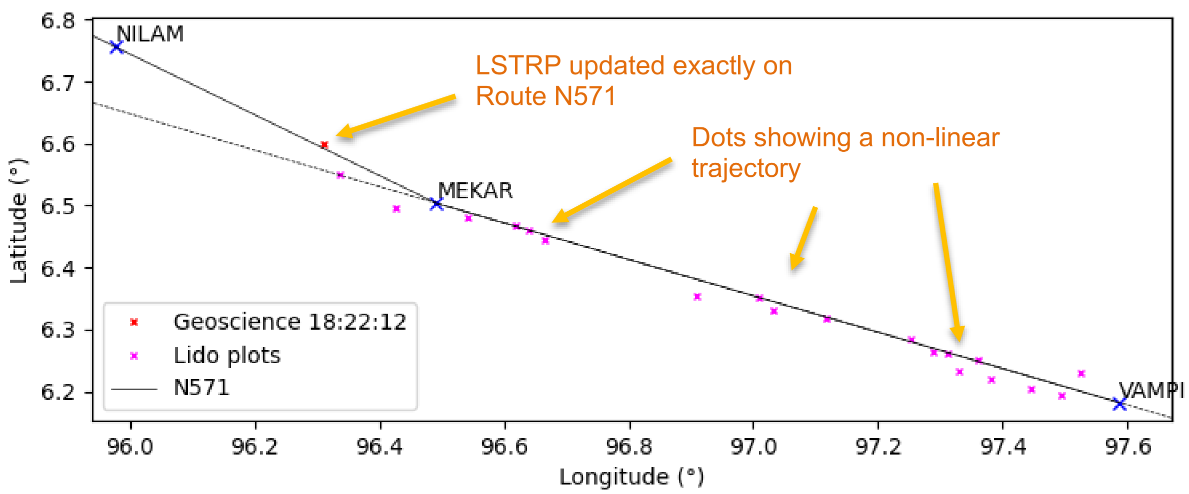

Figure 70: Radar blips digitised and placed in situation on the map (Source Lido Image)

In addition, the final Malaysian report [11] provides two key pieces of information: the blip reappearing at 18h15 and the official LSTRP at 18:22 UTC. Placing these points in accordance with the report, with the Lido points and the given LSTRP point in the Geoscience dataset, their relative positions appear clearly inconsistent as shown in Figure 71 and in an enlarged image in Figure 72.

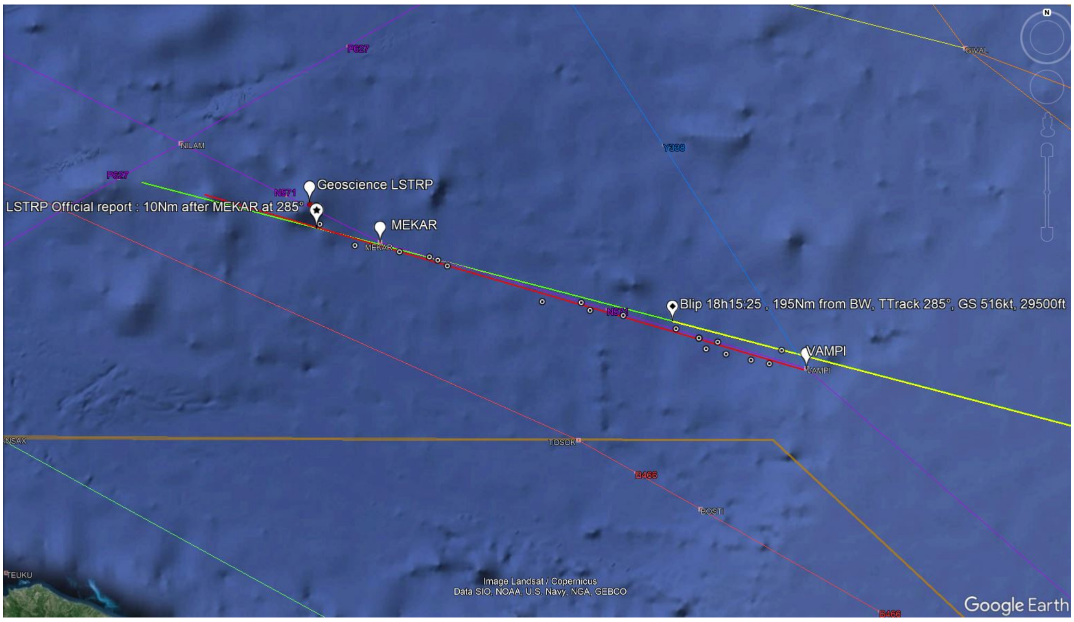

Figure 71: Positions of the so-called Last radar point and route followed by MH370 (source Official Malaysian Report)

In Figure 72, the position of the LSTRP provided by the Lido blips is visible thanks to the small dot very close in the northeast of the Malaysian final report's point LSTRP.

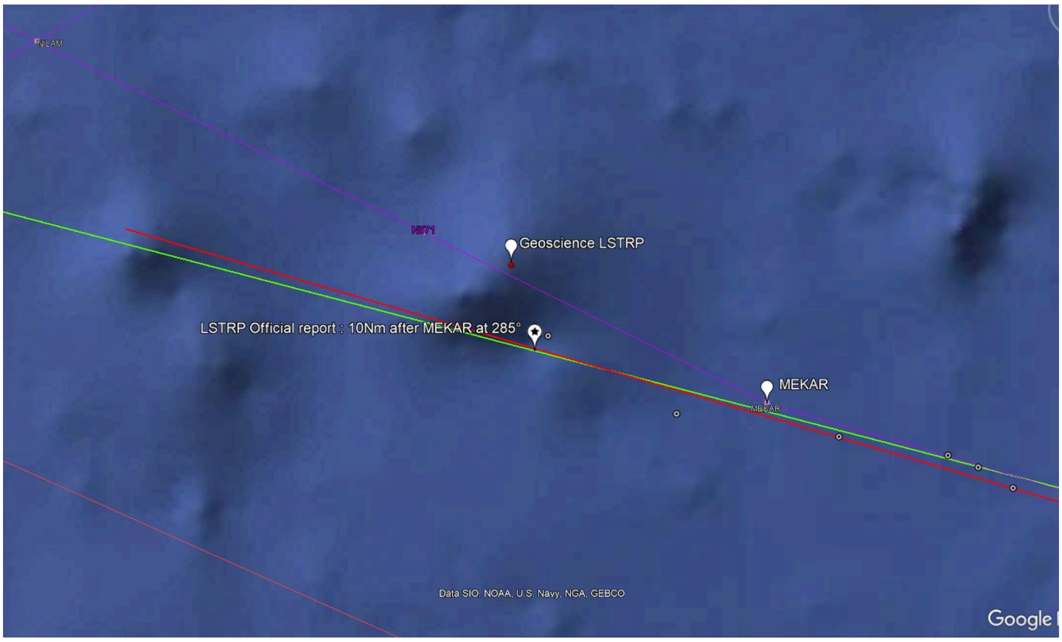

Figure 72: Positions of the Official LSTRP and the Geoscience dataset LSTRP

6.5.3 Conclusion

The information differs between the numerical value of Geoscience and the indication of the final report. There are at least two other discrepancies with the photo of the Lido Hotel and also with the photo published on April 29, 2014 for example.

Based on the available information, it is most probable that the Geoscience LSTRP was placed on route N571 specifically in absence of more precise info at that time. In fact, the most logical conclusion is to consider that the LSTRP is located 10 Nm after MEKAR as indicated in the Malaysian report but in the direction provided by the trend line of the Lido image i.e. [6.540°N; 96.328°E].

7 Vertical profile from IGARI until the Last Radar Point (LSTRP)

7.1 How Military Radar Data Plot worked

In our analysis of radar coverage in correlation with the reference map from the 2014 ATSB report [4] and with Geoscience digital data, the military Radar Data Plot system data fusion does not indicate which radar source was used and when it was used.

Throughout the remainder of this report, please keep in mind the necessary distinction between received echoes and points in the dataset produced by the radar data processor. These are sample locations at relatively regular intervals along a reconstructed track. They do not represent specific echoes precisely.

When the data does not show local linear behaviour of the track - which occurs when the points are blurred and scattered - it reveals a high level of position uncertainty that has occurred at the edge of radar coverage. Conversely, a good continuous geometric behaviour of the track encompassing points forming an uninterrupted line is compatible with a smooth flight trajectory and occurs where a good radar coverage has allowed the correlation of data coming generally from 2 radars simultaneously.

In fact, the radar data processor (RDP) only appears to have created a point if two independent sources provided data for the same location. This hypothesis comes from the absence of a track after 18:01:49 UTC while Western Hill was the only radar capable of receiving echoes from planes between Pulau Perak until the last radar point at 18:22:12 UTC.

Important note: The reference map of the ATSB 2014 report and the Geoscience data come from the consolidation of data from 2 separate radars simultaneously. If only one radar received the echo at a given time, no point is displayed. But unfortunately, when two radars are supposed to have correctly received the echoes, it is also not guaranteed that their outputs were taken into account simultaneously.

This last point raises a specific question: why is no continuous track displayed during the U-turn after IGARI (Gap-1) and also between 17:28:12 and 17:29:28 UTC (Gap-2) ? The two gaps are well within the radar coverage of Bukit Puteri (see white arrows in Figure 73). The detailed analysis below will present our hypothesis about what data source was used by the Radar Data Plot algorithm at a particular location. The reason for this non-systematic use of available data is unknown to the authors at the time of writing this article. This appears to be a specific Sentry C2 system configuration parameter.

Important note: *For the determination of radar coverage limits, we used the horizon angles provided by [15], which uses data from the Shuttle Radar Topography Model (SRTM) as a terrain elevation model. The coverage limit curves at the different flight levels are calculated with an azimuthal resolution increased by us to 1/8°. The refraction level is a setup parameter that will be considered as indicated in section 5.1.3.*

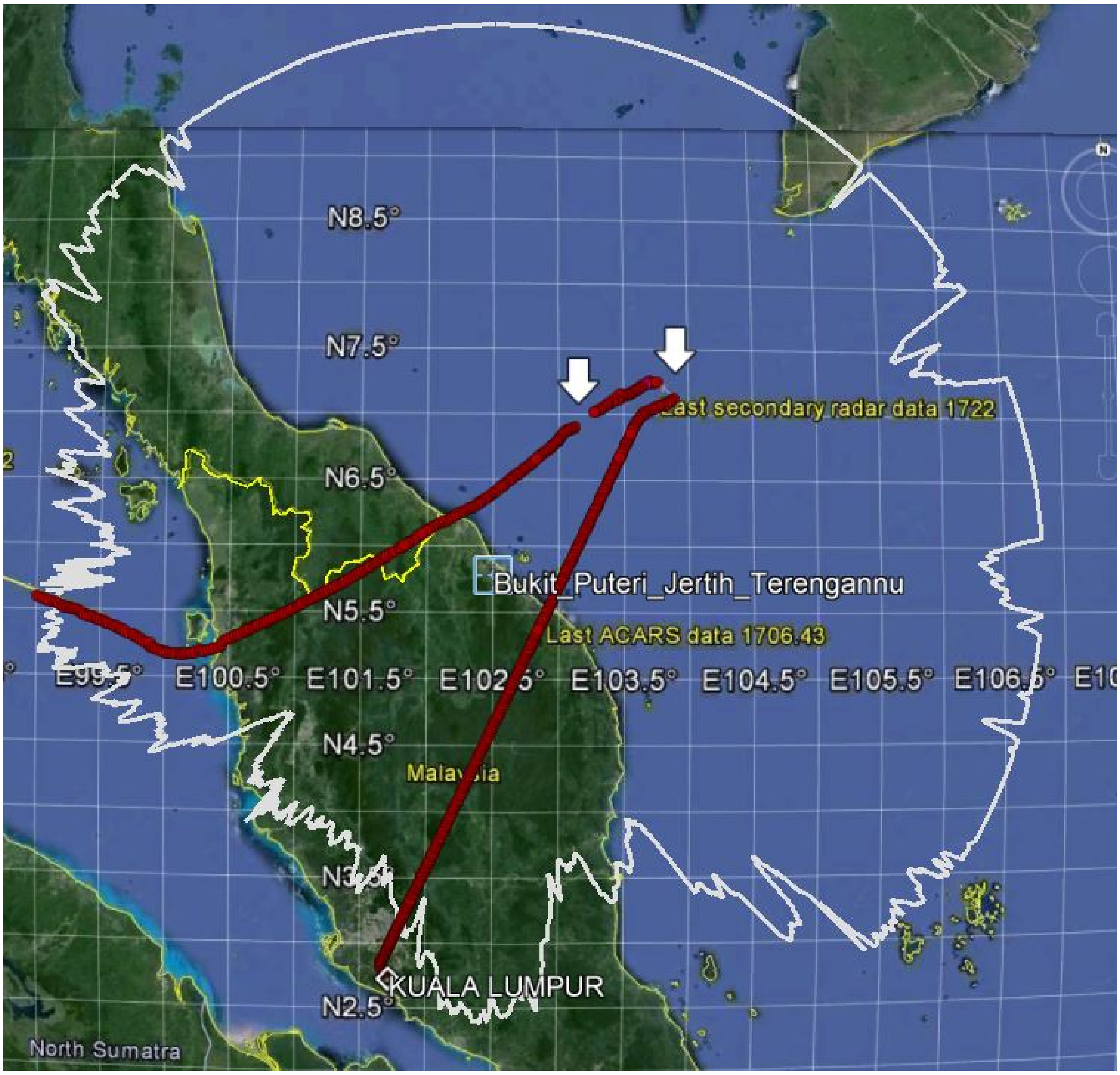

Figure 73: Bukit Puteri radar covered the areas of the two "gaps" in the track

7.1.1 Conclusion

Considering the observations made above, the range of the different radars and the need for the RDP to have two different data sources to correlate the echoes, it is assumed that the Geoscience data will help extract information about the altitude or the vertical profile of the aircraft at certain locations along the track.

Paradoxically, the absence of points in certain parts of the Geoscience track provides valuable information on altitude i.e. no information means information!

However, the precision of the analysis will be such that only high-level indications can be drawn.

7.2 Abeam IGARI and before the U-Turn

7.2.1 Introduction

Thanks to both SSR/ADS-B data, during the passage abeam of IGARI, it is well established that the aircraft was at FL350 with a ground speed of 471kt. This was exactly in the middle of the standard LNAV turn towards BITOD, the next waypoint located on Route M765. At this precise moment, the SSR/ADS-B data became no longer available but the military PSR radars continued to produce 8 points most probably coming from received echoes for a short period only (see Figure 67).

The last 5 of these points were coasted (in green in Figure 74) as identified in section 4.7.1 above. Is this because two of the radars did not receive returns of sufficient quality, i.e. the plane was out of range for them, or because of a selective choice of sources by the RDP?

It is assumed that at the last echo received and therefore at the last non-coasted point, the aircraft was level at approximately FL350. Climbing is not an option because the echoes would have been still properly received and led to the creation of more "normal" points. Conversely, a steep descent is also not a preferred option given the echoes received a minute later at a further distance implying a climb.

Thus, let's have a closer look at the Geoscience data in relation with the radars' coverage.

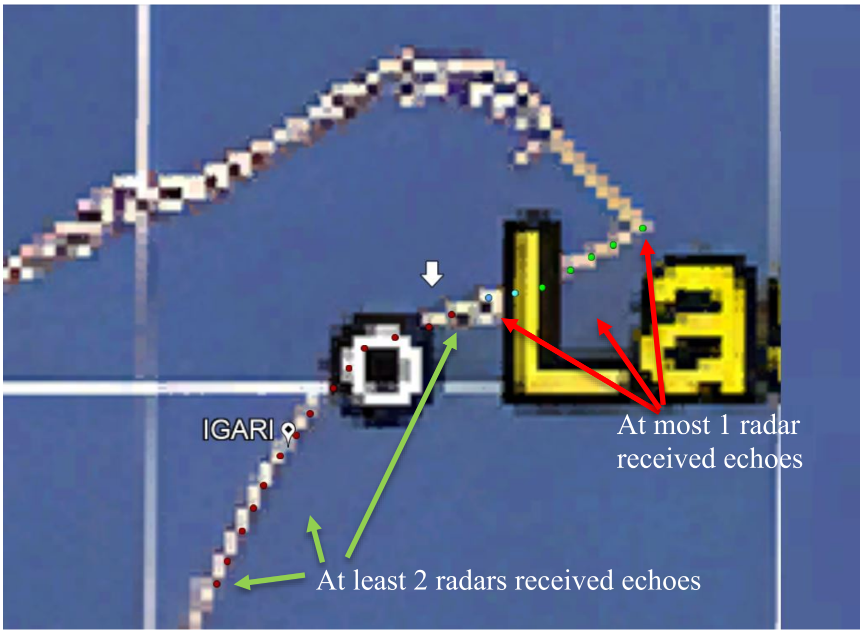

Figure 74: Geoscience points after IGARI until the end of coasting (green dots)

Following the findings in Section 5.1 above, Bukit Puteri, Bukit Ibam and Western Hill are the 3 radars that could have received echoes from the aircraft.

7.2.2 Bukit Puteri radar

Figure 75 shows the radar coverage range of Bukit Puteri at FL230 with 5% refraction in light grey and the range at FL380 with 20% refraction in pink. The Bukit Puteri radar should have detected any aircraft flying between FL230 and FL380. Its data therefore constituted a potential input to the military RDP.

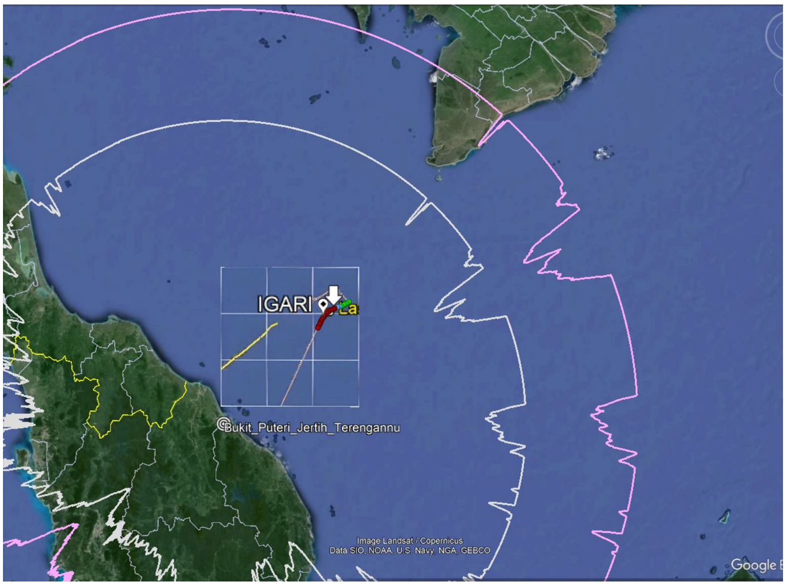

Figure 75: Bukit Puteri radar coverage (FL230 at 5% and to FL380 at 20% refraction)

7.2.3 Bukit Ibam radar

Figure 69 shows the coverage range of Bukit Ibam radar at FL230 with 5% refraction in blue and the range at FL380 with 20% refraction in light blue. The fact that IGARI falls between the two extreme coverage areas requires more detailed analysis to identify what the exact capability of the radar was.

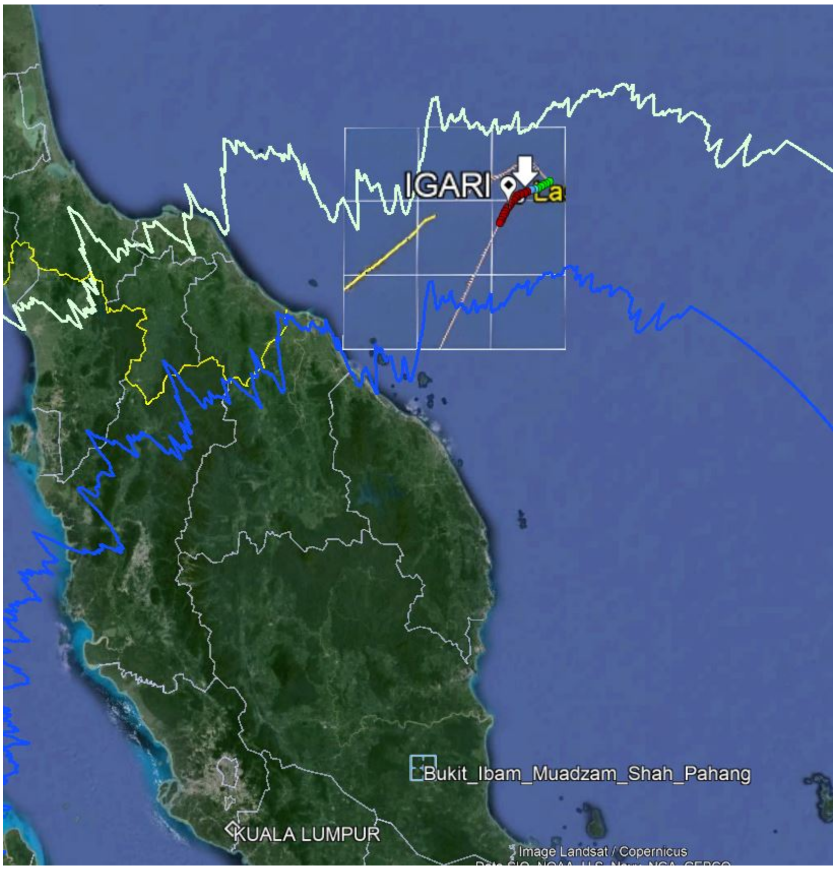

Figure 76: Bukit Ibam radar coverage (FL230 at 5% and to FL380 at 20% refraction)

At the start of this segment, the aircraft is known to be somewhere near FL350. In Figure 77, the red points were created from echoes received from planes flying at this level. The different curves show the coverage limit of Bukit Ibam at FL350 for three different refraction levels. Basically, all potential echoes should have been captured by this radar in the area south of the green curves for a refraction greater than ~7%.

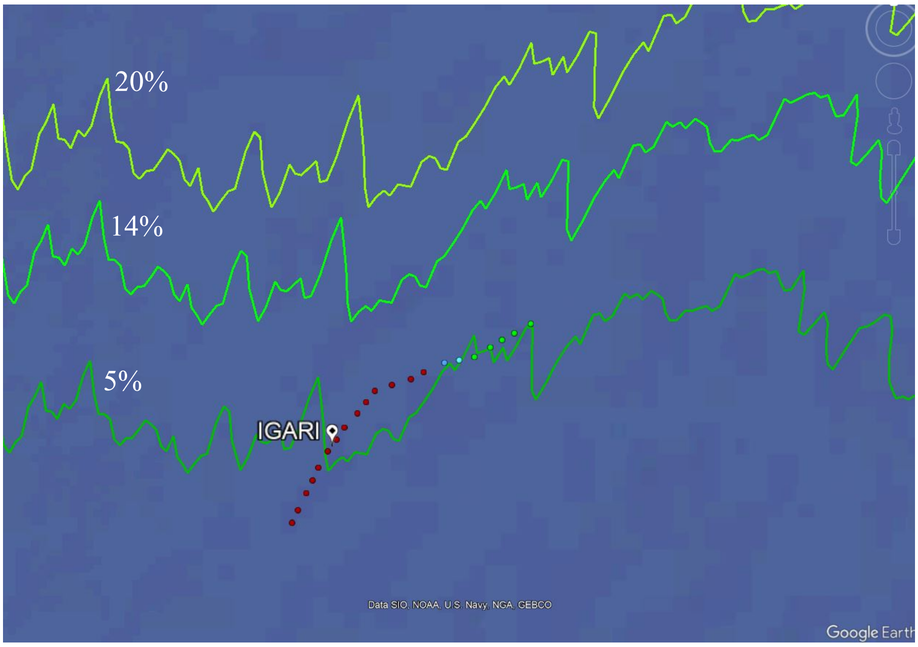

Figure 77: Bukit Ibam coverage range at FL350 for 5%-14%-20% refraction

The loss of echoes at FL350 means that, according to Figure 77, this would have happened if the refraction was near or below 6% due to the relative position of the boundary between the red points and the coasted points. This level of refraction is unrealistic, as demonstrated in section 5.1.3.

Thus, echoes should have been received and provided their share of information to the RDP.

7.2.4 Western Hill radar

Similarly, consider the third radar capability at approximately FL350. Figure 78 represents the evolution of the Western Hill coverage limit for refraction levels 5%, 14% and 20%.

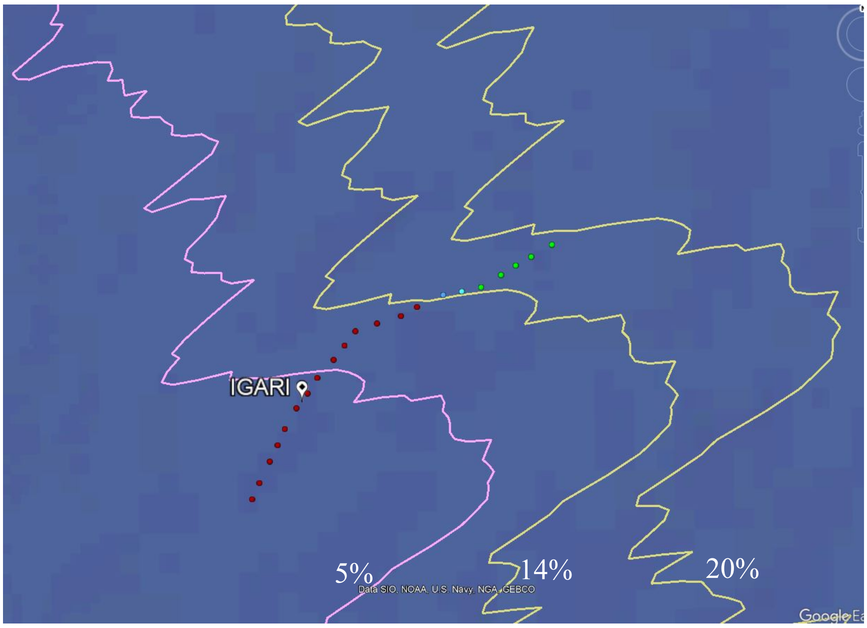

Figure 78: Western Hill coverage range at FL350 for 5%-14%-20% refraction

A more precise examination of the refractions at 14% (Figure 79) and 17% (Figure 80) shows that it is also necessary to take into account the resumption of echo reception at the end of the turn. The exit from radar coverage at this location must be analysed with a view to re-entry a few nautical miles further.

Figure 79 compares the impact of flight level between FL340 and FL355. The yellow line represents the outer limit at 14% refraction of the Western Hill radar range at FL350, while the red line is FL340 and the pink line is FL355.

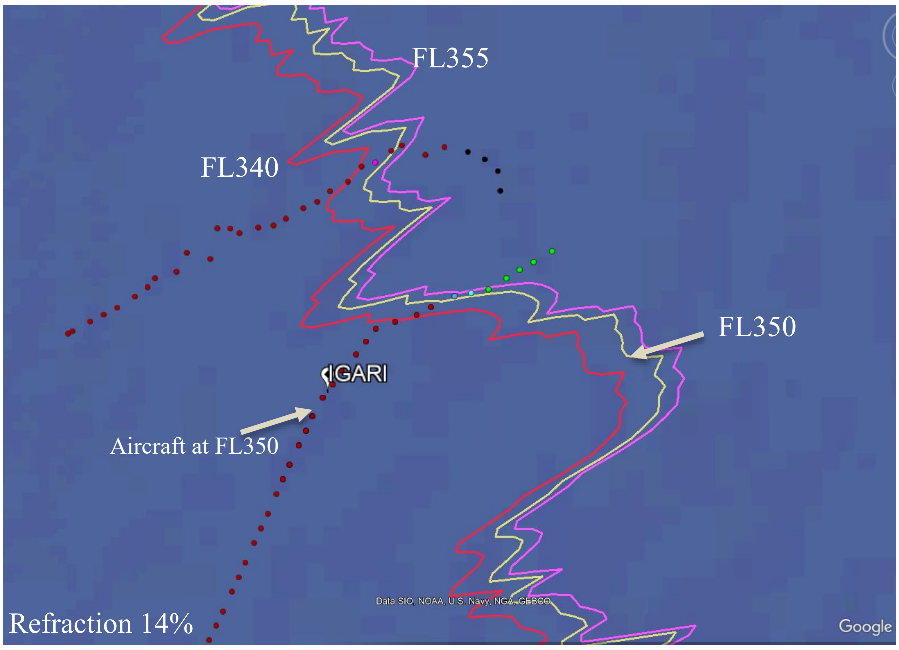

Figure 79: Western Hill coverage range at FL340 (red), FL350 (Grey) and FL355 (Pink) at 14% refraction

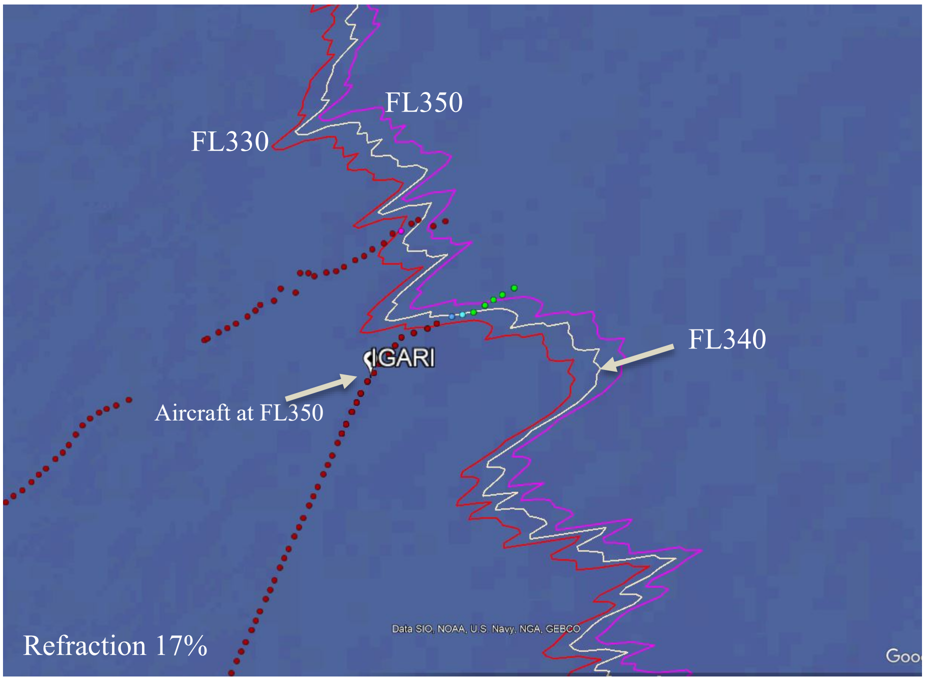

Figure 80: Western Hill coverage range at FL330 (red), FL340 (Grey) and FL350 (Pink) at 17% refraction

Assuming FL350 at IGARI, it can be seen from Figure 80 that the shape of the coverage limits at about 17% refraction provides the most probable explanation as to why echoes were lost in this area

Mapping the shape of Western Hill's radar coverage with the disappearance and reappearance of red points indicates that Western Hill was the driving factor in producing the track, keeping in mind that the red points are objects resampled in function of received echoes.

The aircraft appears to have left the radar coverage of FL340 along its boundary and re-entered at a flight level above FL350. Considering the first two red dots in the second dataset after Gap-1, they appear to be at ~FL355. The fact that a coasting took place combined with the fact that no echo was received along the actual trajectory – now known today - shows that the aircraft remained below the detection level of Western Hill for a minute.

As seen in section 6.2 above, the aircraft was almost certainly manually controlled and the turn had started when the echoes were lost. So, a valid question is whether the plane had climbed slightly, a natural consequence of a pilot pulling back on the stick to compensate for the lower lift during the U-turn?

But before this, this would mean that a slight descent during the manual turn to the right would have occurred before disappearing from the radar due to lower lift. This is a normal tendency during manual turning. This would then have been compensated for on the next sharp U-turn to the left, resulting in a slight increase in altitude later.

It is worth considering here that the aircraft became less reflective when it initiated a turn to the right. Its trajectory became almost aligned with the radials of the Western Hill radar head. It provided smaller reflective surfaces for echoes. Thus, the radar cross-section of the aircraft decreased considerably because the aircraft was “seen more from the rear” and possibly because of the warm engines exhaust. The level of the signal returned to the radar decreased accordingly, which had an impact on its detection due to the lower quality of the echoes. The effect would be similar as descending.

So, the loss of echoes could be either way or a combination of both. In the latter case, this means that the aircraft was lost at flight level around ~FL345 approximately or even ~FL350.

Concerning coasting, the last 5 points from the predictive algorithm are represented in green.

They are perfectly aligned with Route M765 as shown in Figure 81. Their R-Square linearity coefficient is 0.9994, which is very close to 1. In addition, it is 100% known that the aircraft did **not** follow this route. Thus, the coasting algorithm probably used additional available information. The most likely information was probably the filed flight plan since SSR messages were no longer received.

The blue dot and light blue dot are coloured differently from the previous dots because they could somehow have been the start of the coasting as they are perfectly aligned with the first coastal green dot (R^2 = 0.9977).

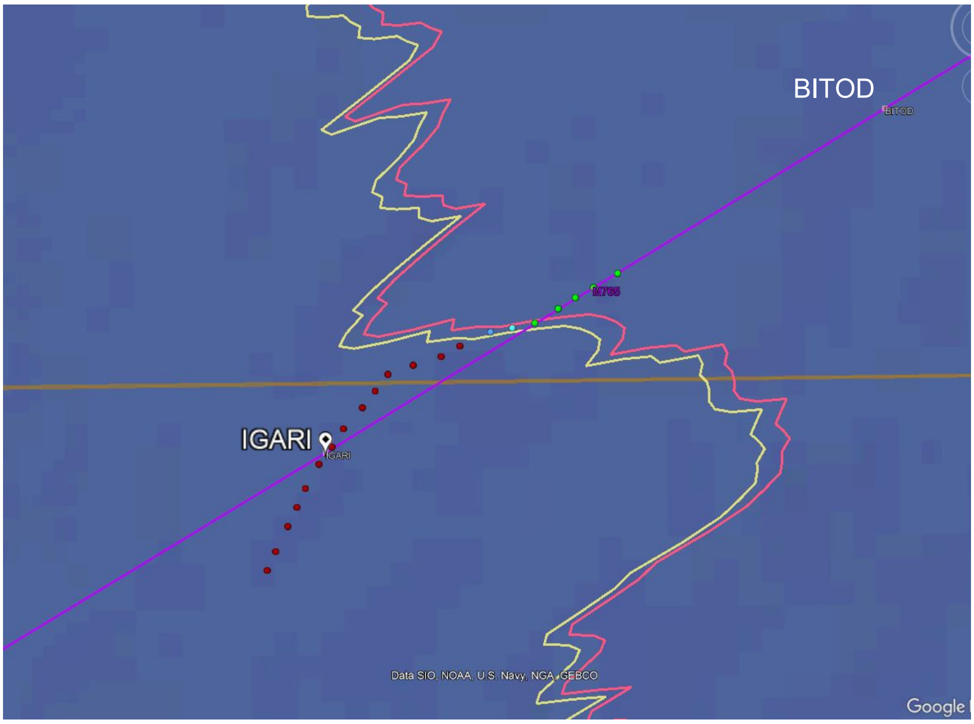

Figure 81: Coasted points after IGARI are on Route M765 towards BITOD (blue and green dots)

For verification of the refraction parameter, the coverage capacity of the Western Hill radar for a refraction level equal to 26% could be evaluated. Figure 82 illustrates that at the start of the coasting the aircraft would have been at FL300 (red limit). This would mean a descent of 5000 feet in one minute from IGARI. This also shows that the aircraft would have climbed back up to FL330/FL340 (yellow/white limits) in one minute to reappear in line of sight, which is +3000fpm. In that day's weather conditions, with that mass and with the Trent engines, this is aeronautically unrealistic. Similar reasoning was done with Bukit Ibam coverage, which led to the same conclusion.

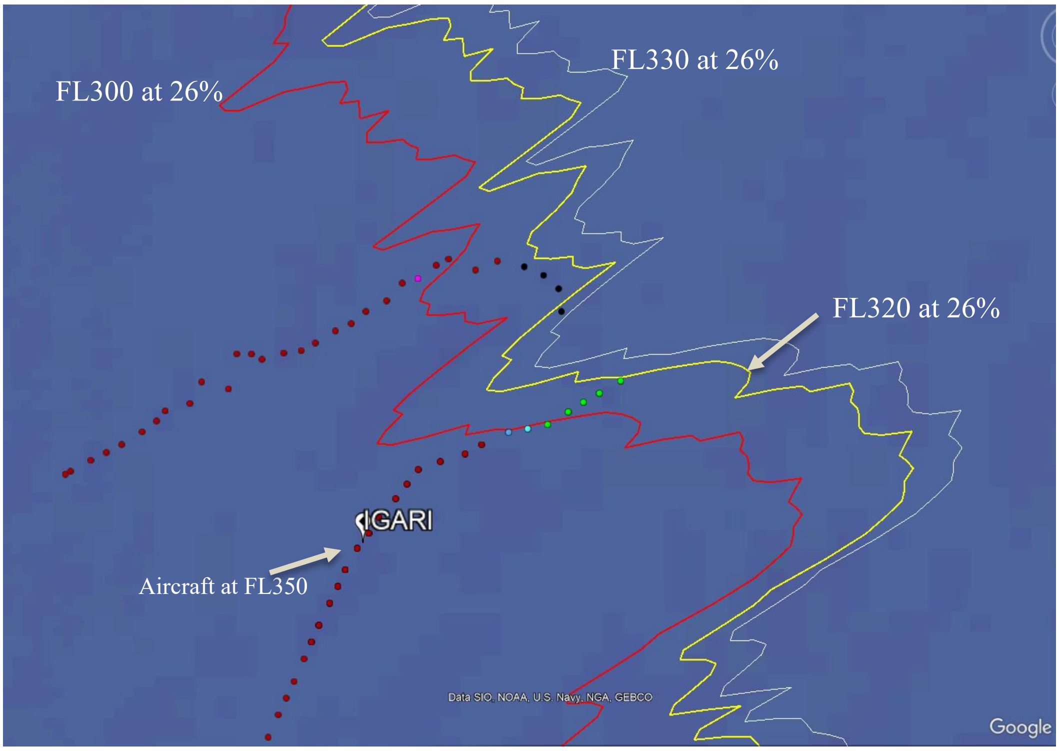

Figure 82: Western Hill radar coverage for FL300 (red), FL320 (yellow) and FL330 (White) at refraction level 26%

7.2.5 Conclusion

After IGARI when exiting from the radar coverage, two radars should have also received echoes from the aircraft, namely Bukit Puteri and Bukit Ibam. Despite this, coasting occurred, indicating that the "weighting" of the Western Hill data was essential in the track reconstruction process in that location and at that time. We make the assumption here that Bukit Puteri data was not used in the data fusion process.

At this location, it can be concluded that the aircraft either remained level at ~FL350 or descended slightly to ~FL345, probably due to the slight right turn manoeuvre. Then, a slight climb followed when turning around sharply to the left. This resulted probably from natural compensation by the pilot for the loss of lift during turns and in night-time conditions.

7.3 During the U-Turn (Gap-1)

7.3.1 From the Entry point to the U-Turn

As shown in section 7.2 above, the segment under consideration here is closely linked to the turn initiated after IGARI and constitutes the natural continuation of it.

From the above analysis, it is clear that the aircraft was "lost" by the tracker but was still visible to the radars in Bukit Puteri and Bukit Ibam but not to Western Hill.

7.3.2 Coherent reception of echoes

Recalling the results of section 4.6.2.1 above, Figure 83 illustrates evidence of resumption of echoes acquisition (white arrow). The difference in texture and colour between this blurred cloud and the coasting junction line is visually obvious. These dots form a kind of cloud.

The conclusion of Section 4.6.2.1 above, this probably comes from the use of two slightly offset images during the merging process leading to these double lines, which should actually overlap.

Figure 83: Re-acquisition of radar echoes (Arrow) during the U-Turn after IGARI

Thus, the Geoscience dataset is presented in Figure 84 with additional identified points (in black). Either the black points were missing in the data provided to Geoscience, or the latter chose to ignore them and draw an artificially wider U-turn as a "nicer turning track" display.

In our study, these points will only serve as an indication as they are not officially provided.

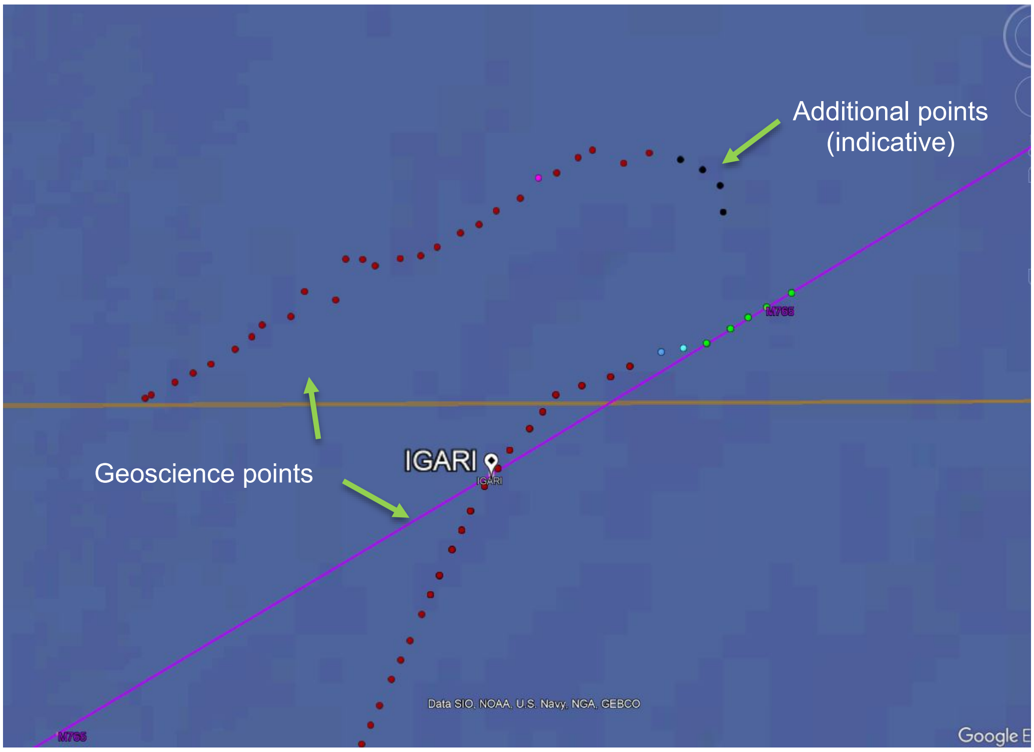

Figure 84: Geoscience points in the U-Turn (red) with additional indicative points (black) identified in Section 4.6.2

The emphasis now is on determining approximately, if possible, at what flight level the aircraft was during the U-Turn and the exit from it.

The same method will be applied here again using the shape of the radar coverage limit for different flight levels while also taking into account possible refraction levels.

7.3.3 Bukit Puteri radar

Figure 75 presented in section 7.2.2 above showed that the radar coverage range of Bukit Puteri at FL230 with 5% refraction and at FL380 with 20% refraction is such that any aircraft would have been detected when he was flying between these levels. Subsequently, at this location, radar data from Bukit Puteri was likely available to the RDP, but there is doubt about its use due to the absence of points.

7.3.4 Bukit Ibam radar

Figure 85 shows a zoom of the radar coverage range of Bukit Ibam at the U-turn location. The resumption of echo reception after localization of the gap took place at ~FL350. The plane had stayed level or had recovered from its previous slight descent.

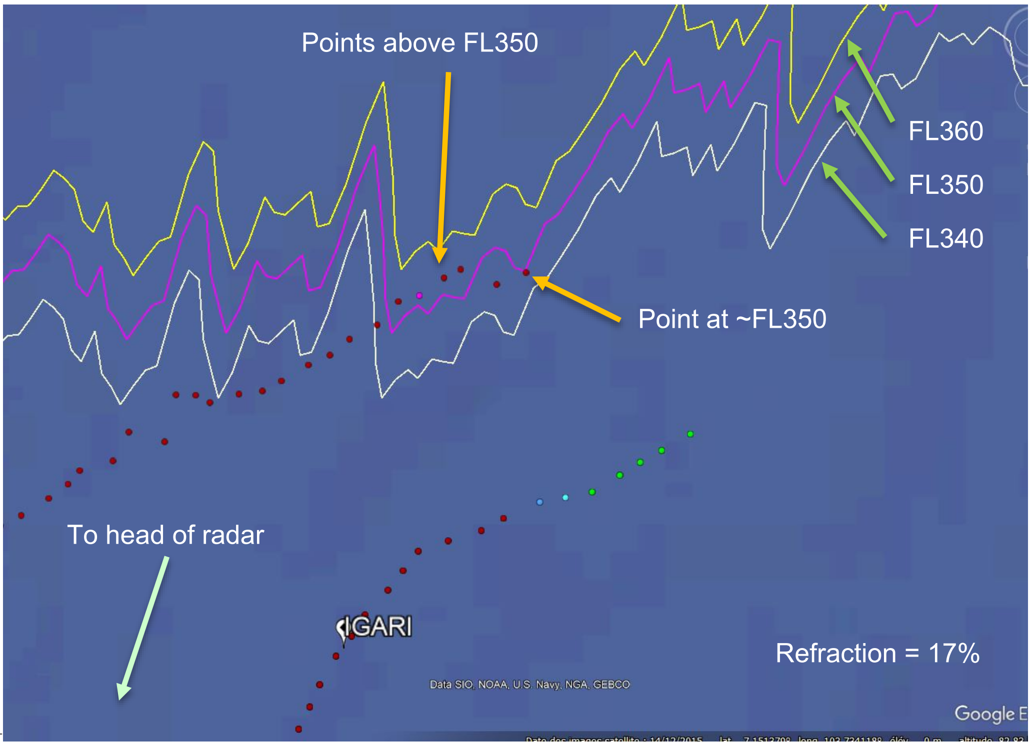

Figure 85: Bukit Ibam radar coverage at FL340, FL350 and FL360 for a refraction of 17%

It might be worthwhile to recall that when the plane began the U-turn, its trajectory became almost radial from the head of the Bukit Ibam radar. Thus, the aircraft's radar cross section decreased significantly as the aircraft was "seen" from behind during the U-turn. Thus, the level of the signal returned to the radar has also decreased. This could have impacted detection due to a reduction in the quality of echoes when turning.

7.3.5 Western Hill radar

Similarly, consider the third radar capability at the U-turn location. Figure 86 shows the coverage limit of Western Hill at FL330 and FL360 for a refraction level estimated at 17% refraction.

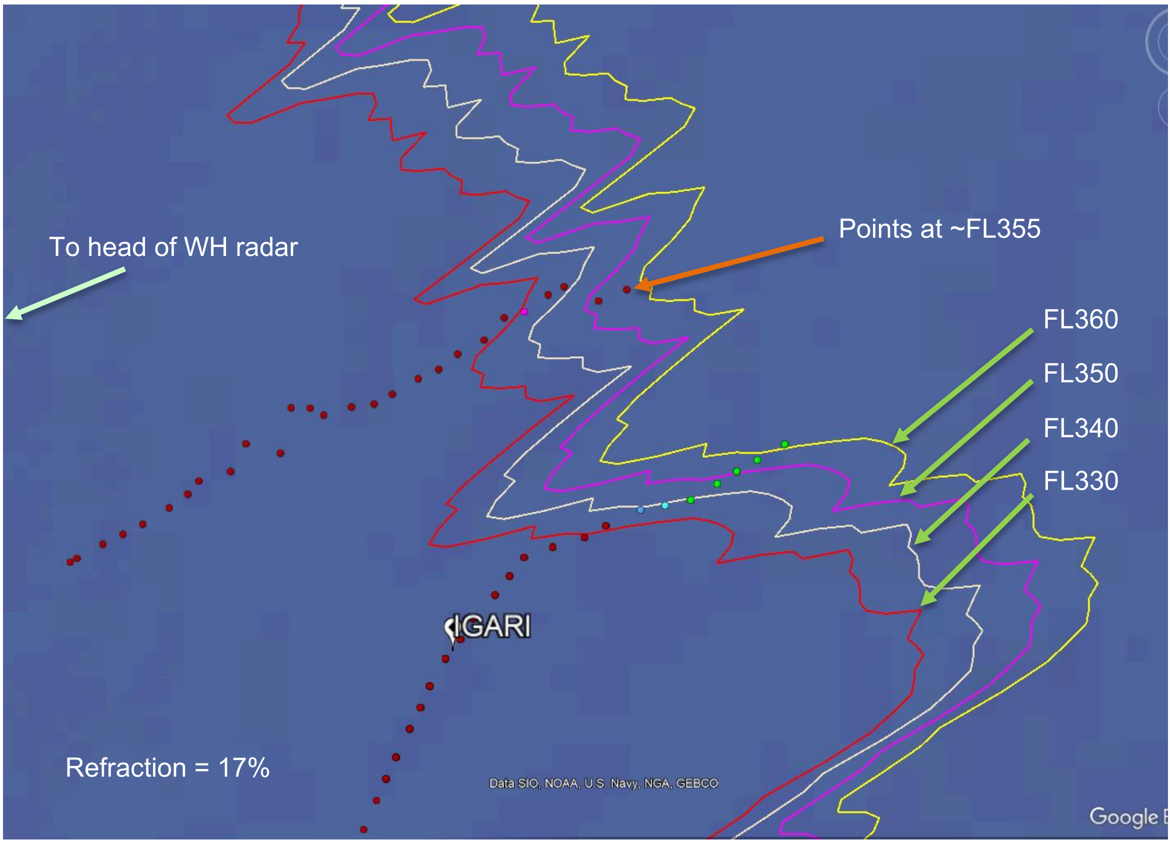

Figure 86: Western Hill Coverage limits for FL330 to FL360 with 17% refraction

The flight level at which echo reception resumed appears to be ~FL355 between the purple (FL350) and yellow (FL360) curves. This result is consistent with the level found for the Bukit Ibam radar which is ~FL350 or slightly above.

It is worth considering here that as the aircraft began the U-turn to the left, its trajectory became almost orthogonal to the Western Hill radar head with the aircraft banking to the left providing more reflective surfaces for the echoes. Thus, the radar cross section of the aircraft increased significantly as the aircraft was viewed "more from above." The level of the signal returned to the radar increased accordingly. This could have had an impact on detection by increasing the quality of the echoes, which could explain the creation of the indicative black dots in Figure 84.

Subsequently, Figure 87 provides an additional convincing element. It shows the visually "identified" black spots in relation to the radar range of Western Hill. The location of these 4 points corresponds very well to the shape of the range limit at that location. The very particular concave shape corresponds perfectly to the gap missing points.

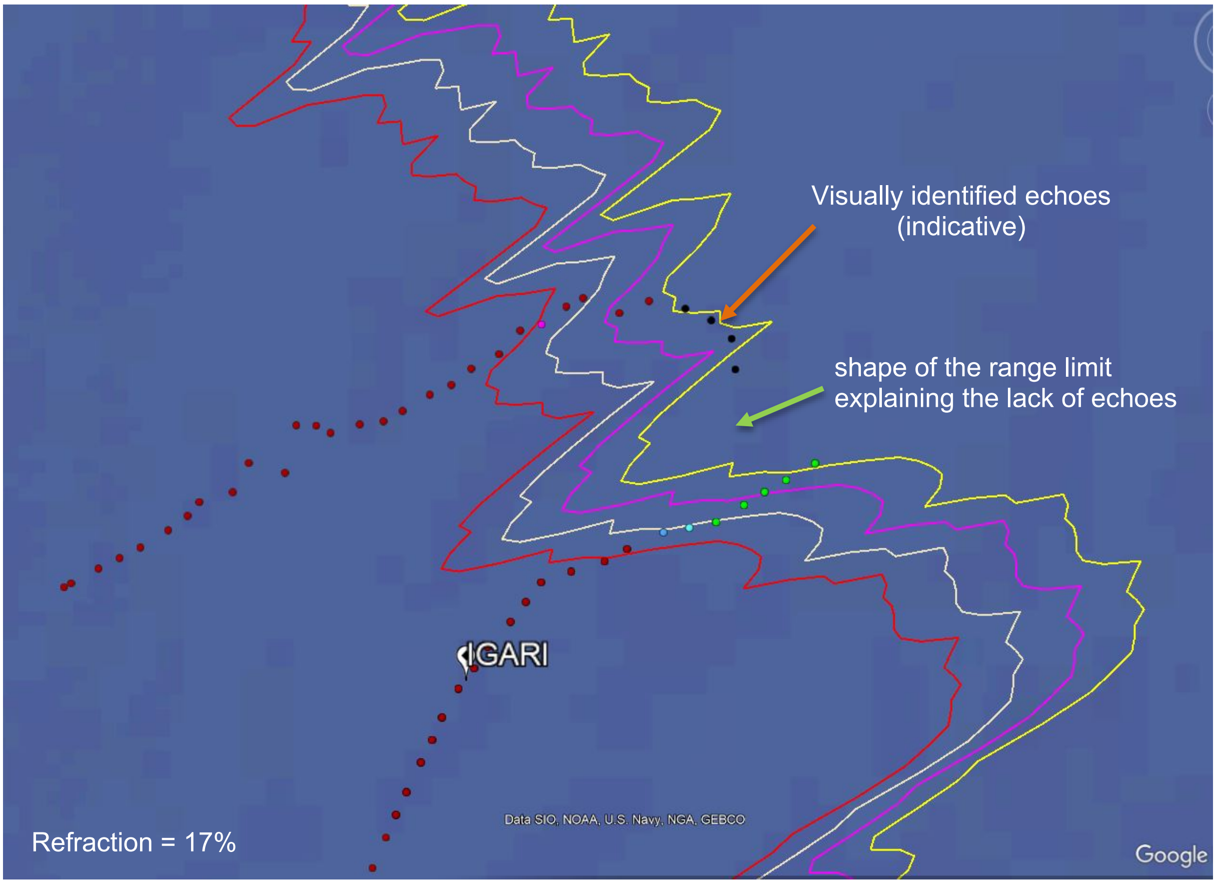

Figure 87: Indicative black blips Western Hill Coverage limits for FL330-360 with 17% refraction

7.3.6 Conclusion

Simultaneously displaying the coverage of the two radars in the same image, as shown in Figure 88, allows us to see that the aircraft was most likely at ~FL350 before the end of the U-turn and between FL350 and FL360 at the exit of the U-turn, i.e. ~FL355. This means that during the U-turn left, the aircraft climbed between 1,000 to maximum 1,500 feet in about 1:30 minute.

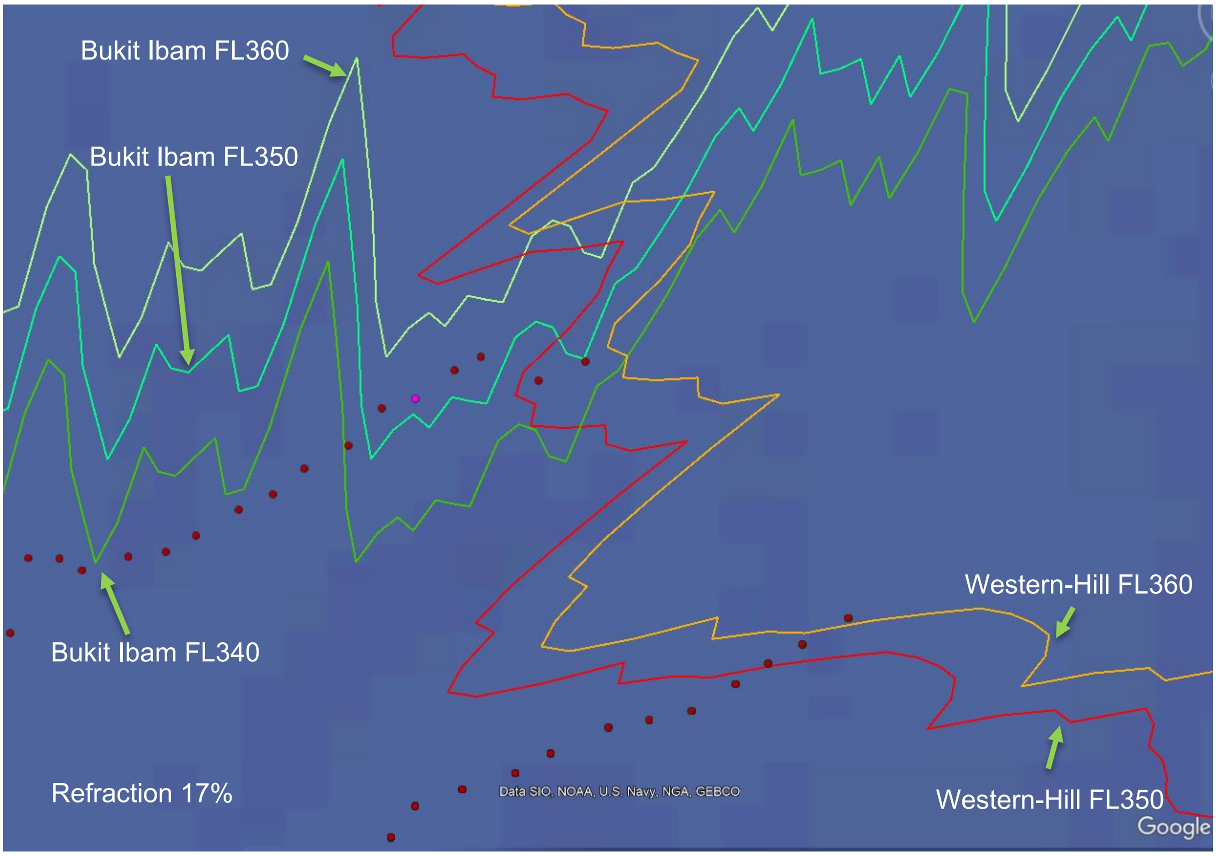

Figure 88: Fusion of Bukit Ibam and Western-Hill radars coverage between FL340 and FL360

The corresponding climb rate is between ~700 and ~1000fpm, which is considered operationally acceptable for the aircraft during a turn and under the manual control of an experienced pilot. During such a tight IFR turn at night, pulling-up on the stick is a safe manoeuvre. Recalling section 6.2.1 above, this is consistent with the aircraft limitation that it could not fly much higher than the FL370 maximum given its current mass, weather conditions and the limited thrust capability of the aircraft Trent engines at this altitude.

A conservative conclusion would be to consider that the aircraft was in the vicinity of ~FL355 at the official exit point and possibly ~FL360 as it could have climbed a little longer, but not much further as explained below.

7.4 From Exit point until Gap-2 in radar coverage

7.4.1 Analysis

The focus now shifts to analysing the next segment between the Exit point of the U-turn and the start of Gap-2 in radar coverage. First, the particular area highlighted by the red circle in Figure 89 will be detailed. Secondly, the coasting highlighted in yellow will be discussed.

Before entering the area highlighted by the red circle, the track displays an almost straight segment starting at the Exit Point (pink dot in the figure) and flown in approximately 1min 20s. The received echoes led to the creation of a coherent and well-correlated geometric trajectory in an almost straight line showing a well-established flight path at 238°. This geometry reveals that the plane was indeed in the FL360 line of sight of the radars. Remember that the plane was estimated at ~FL355 upon exit from the U-turn.

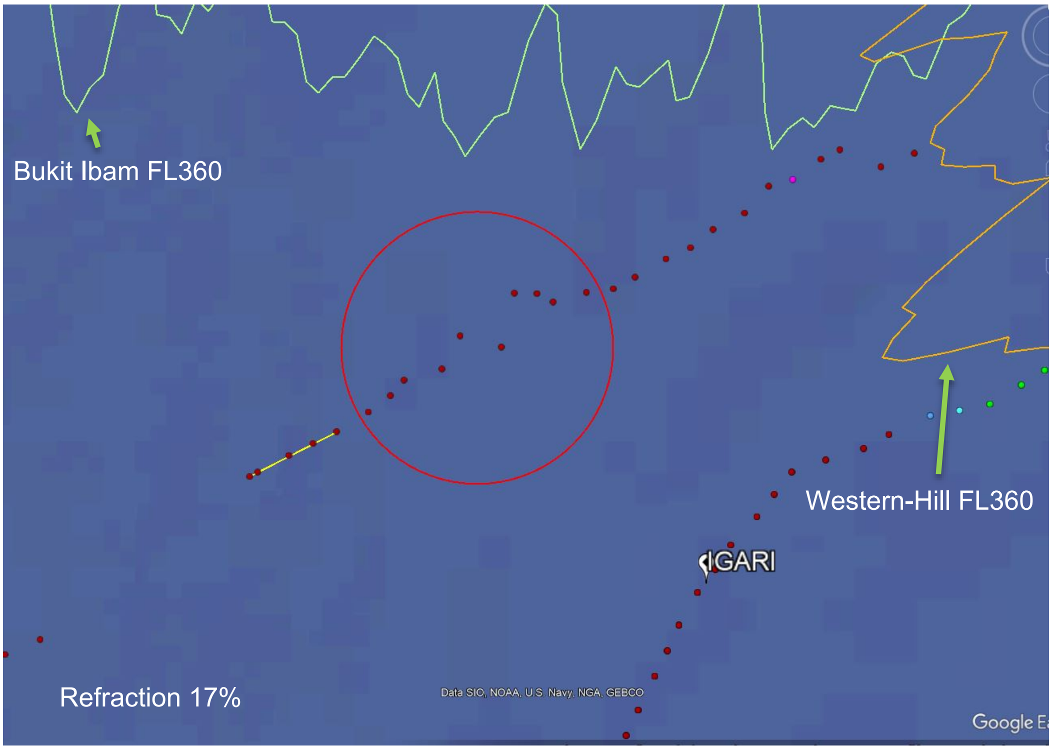

Figure 89: The path from the official Exit the U-Turn until Gap-2 in the radar coverage

Inside the red circle, the dots are scattered without any clear trajectory that would indicate a normal flight path of an aircraft.

Such a spreading of points is not compatible with a potential turn. The question is why does the trajectory show erratic behaviour after such a clear linear trajectory? If the aircraft had remained at ~FL355, no such behaviour should have been visible because the aircraft would have remained in the radars line of sight. The scattered dots do not display a continuous, smooth trajectory, although the pilot could have initiated a very slight S-shaped correction. In all cases, they reflect a drop in quality of the echoes received. The most likely reason is that the aircraft had reached the limit of radar coverage at that location. This indicates that it was most likely descending.

Figure 90 shows that at the beginning of the spread of scattered points there is a strong correlation with the Bukit Ibam coverage limit for a flight level around ~FL330. Low quality echoes were received up to the last 5 points before the gap. These 5 points show a remarkable linear R-squared value of 0.9997, indicating a coasting that began between ~FL320 and ~FL310. Remarkably, it presents better linearity than the coasting detected after IGARI confirming that it is indeed coasting. This is the reason why there is a gap in the RDP track.

This is fully consistent with the analysis of section 4.7.2 above.

But why only one data source was used by the RDP remains a valid question, as Bukit Puteri data does not seem to have been used.

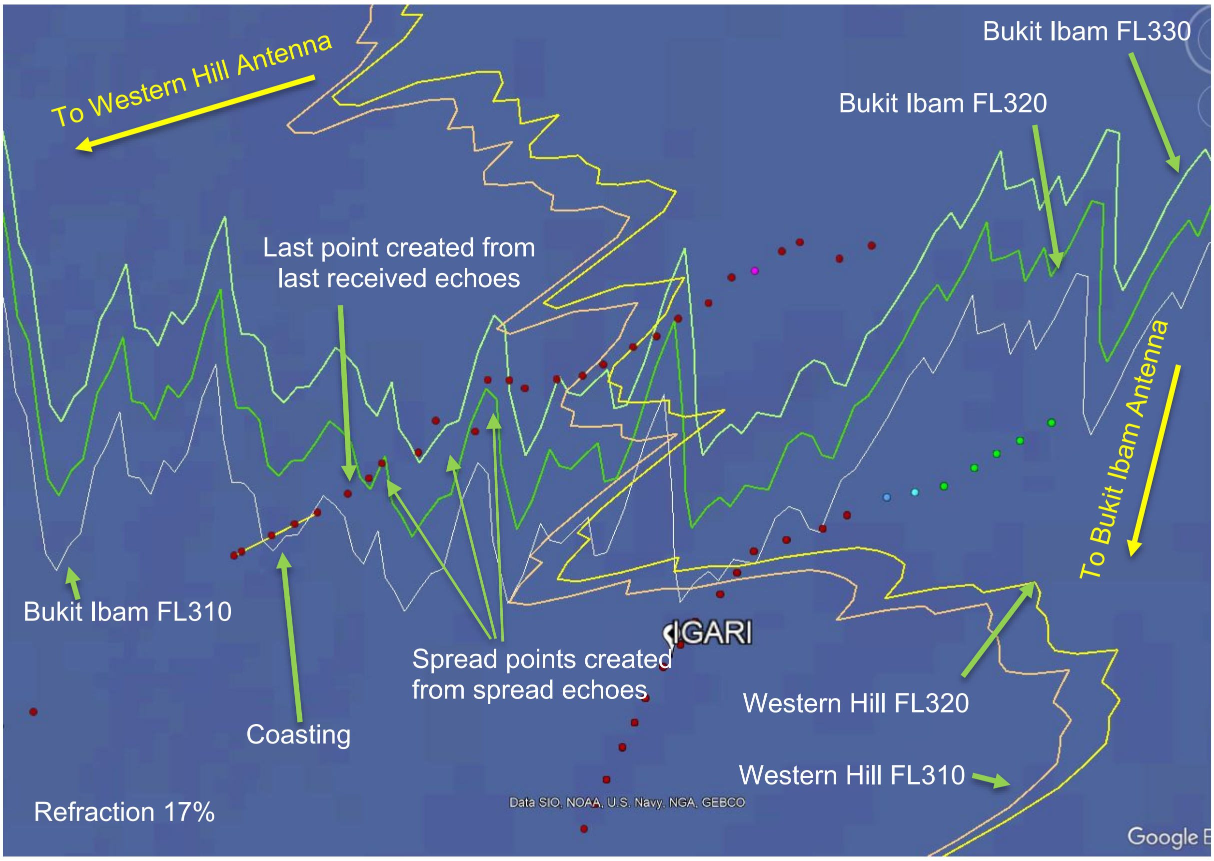

Figure 90: Dispersed points close to Bukit Ibam FL320 and Western Hill FL310 coverage limit

7.4.2 Missing data in Geoscience dataset: Gap-2

This section addresses Gap-2 in the track identified the Geoscience dataset as shown in Figure 73 above.

The presence of this gap in the data is both intriguing and very useful. The plane's flight level was such that it should have been visible to the radars at Bukit Puteri and Western Hill. But of the two, we have to assume that only Western Hill data was used.

Thus, the emphasis will be placed on the capabilities of the Bukit Ibam radar. Figure 91 presents an additional key element about the flight level in Gap-2 and provides an explanation of this gap itself. At the end of the gap, echoes were received at the edge of Bukit Ibam coverage at ~FL280/290 (green and thin white lines respectively).

The drop in quality correlated with the resumption of echo reception shows that the aircraft “crossed” the gap at a maximum flight level close to ~FL280. The red line in Figure 91 shows that ~FL280 (or a little below) is the level where no echo could have been received correctly while at ~FL290 some echoes could still have been correctly received.

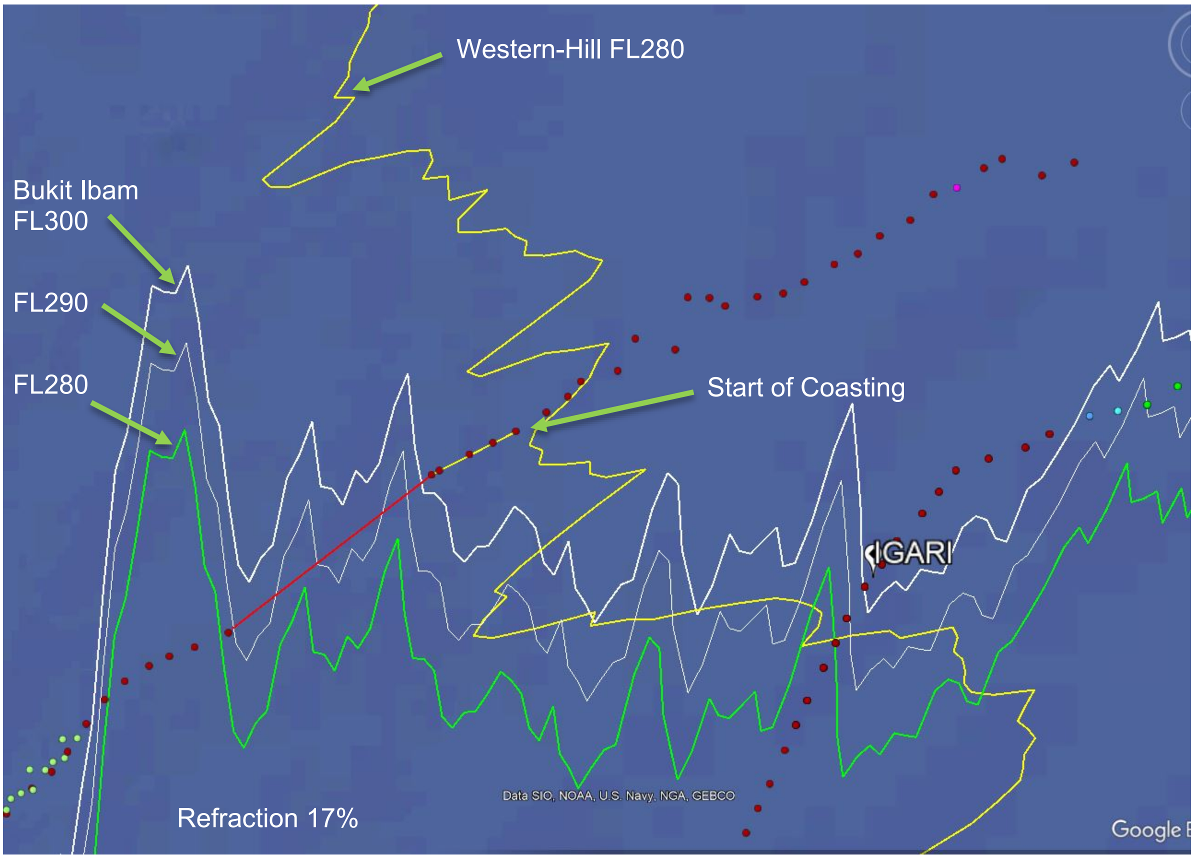

Figure 91: Coasting in relation with Western Hill coverage at FL280 and Bukit Ibam at FL280-FL300

7.4.3 Conclusion

At the U-Turn Exit point, the aircraft appears to have reached ~FL355 (with a possible maximum at ~FL360). Then, after a clearly visible near-linear trajectory that lasted a little over a minute, the aircraft began a descent at a speed of ~ -2700fpm. It disappeared below ~FL310, creating a two-minute gap with a coasting just before its boundary. When the aircraft reappeared at the exit boundary of Gap-2, Bukit Ibam's radar coverage range indicates that it was close to ~FL290 and climbing.

7.5 At the Exit limit of Gap-2 and after

7.5.1 Analysis

It should be noted that the end of detection by the Bukit Ibam radar coincides with the start of coverage by the Kota Bharu civil approach radar represented by the green dots in Figure 92. This explains why the military Chief of Staff declared they were working with DCA to track the aircraft in Kota Bharu vicinity.

Figure 92 shows that the point created by Bukit Ibam before just before the first point created by the civilian radar tracker is estimated between ~FL300 and ~FL310. Therefore the point is at approximately ~FL305. Remember that the first point created by the Kota Bharu civilian approach radar is the result of the prior reception of a certain number of echoes of sufficient quality.

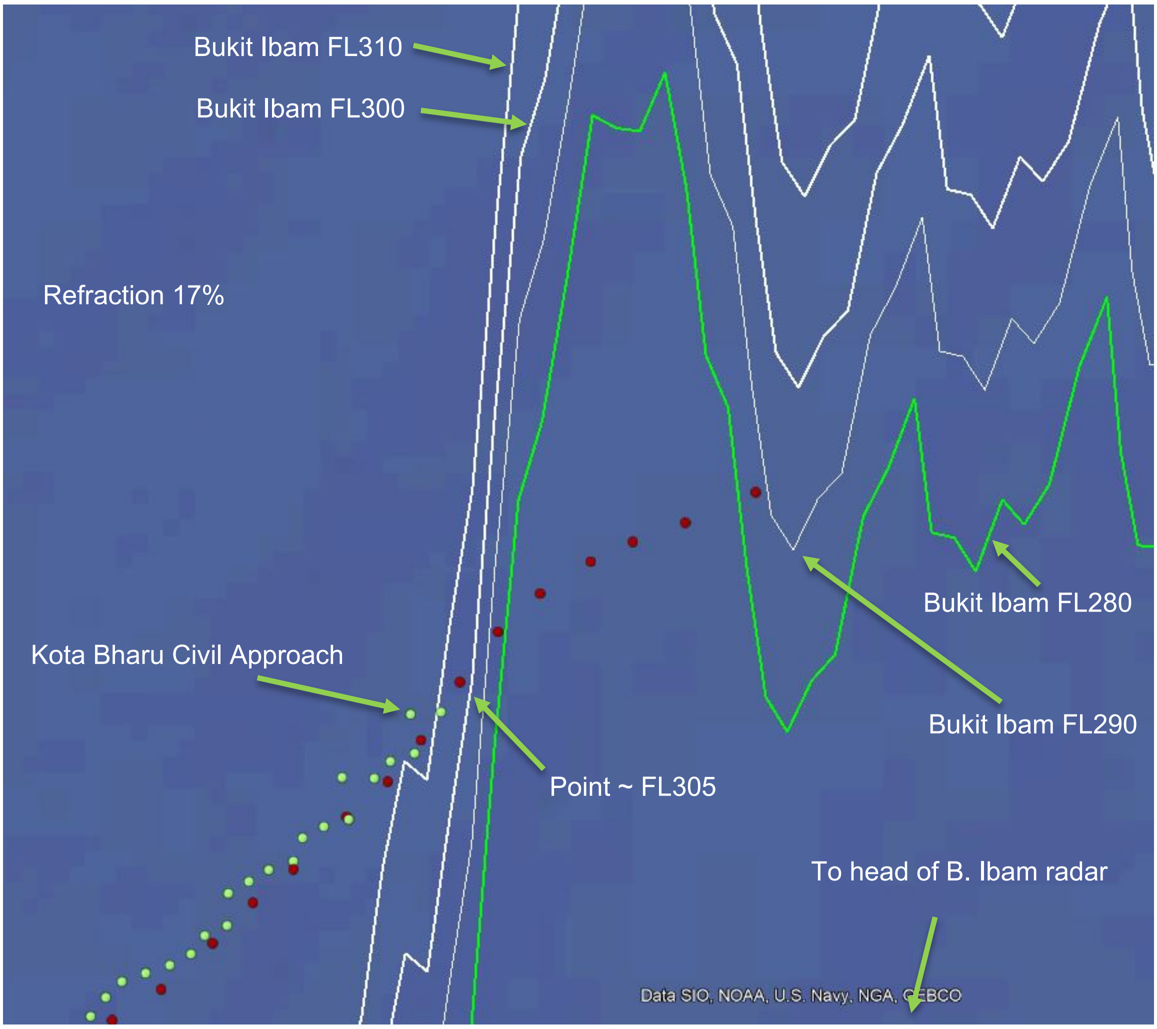

Figure 92: Exit of Gap-2 between FL300 and FL310 just before receiving Kota Bharu echoes

Consequently, it appears that the aircraft must have climbed back from ~FL290 to approximately ~FL305 when it was back in Bukit Ibam's line of sight after leaving Gap-2, i.e. inside the loop of the green curve in Figure 92 (in the south of it). This represents a climb rate of approximately ~+1,500 feet per minute, which is within the capabilities of the aircraft.

7.5.2 Conclusion:

Thus, we can conclude from the resumption of echo reception after Gap-2 that the aircraft had reached at least level ~FL305 and was climbing at this location.
If the aircraft had been at ~FL290 or above within the gap, it would have been detected and no "gap" in the data would have existed. Thus ~FL280 or slightly below is the most likely level flown within Gap-2.

Section 6.3 above demonstrated that the aircraft was manually flown in this area. Although it is difficult to find a clear explanation for the descent followed by a small climb, a possible interpretation could be that the captain simulated an emergency descent following the start of a (voluntary) real depressurization and wanted to mislead passengers and cabin crew while putting them in such a situation.

7.6 Kota Bharu

7.6.1 Introduction

In Kota Bharu inbound and outbound segments, the match of the Geoscience dataset with the Kota Bharu PSR dataset is very good with respect to the track (see Figure 93).

At the time of writing this report, only a high-level quick analysis has been carried out to correlate geoscience data with civil approach radar digital data. Further analysis is underway. But the military Chief of Staff's declaration at the press conference [3] de facto correlates the correspondence of the two sets of data.

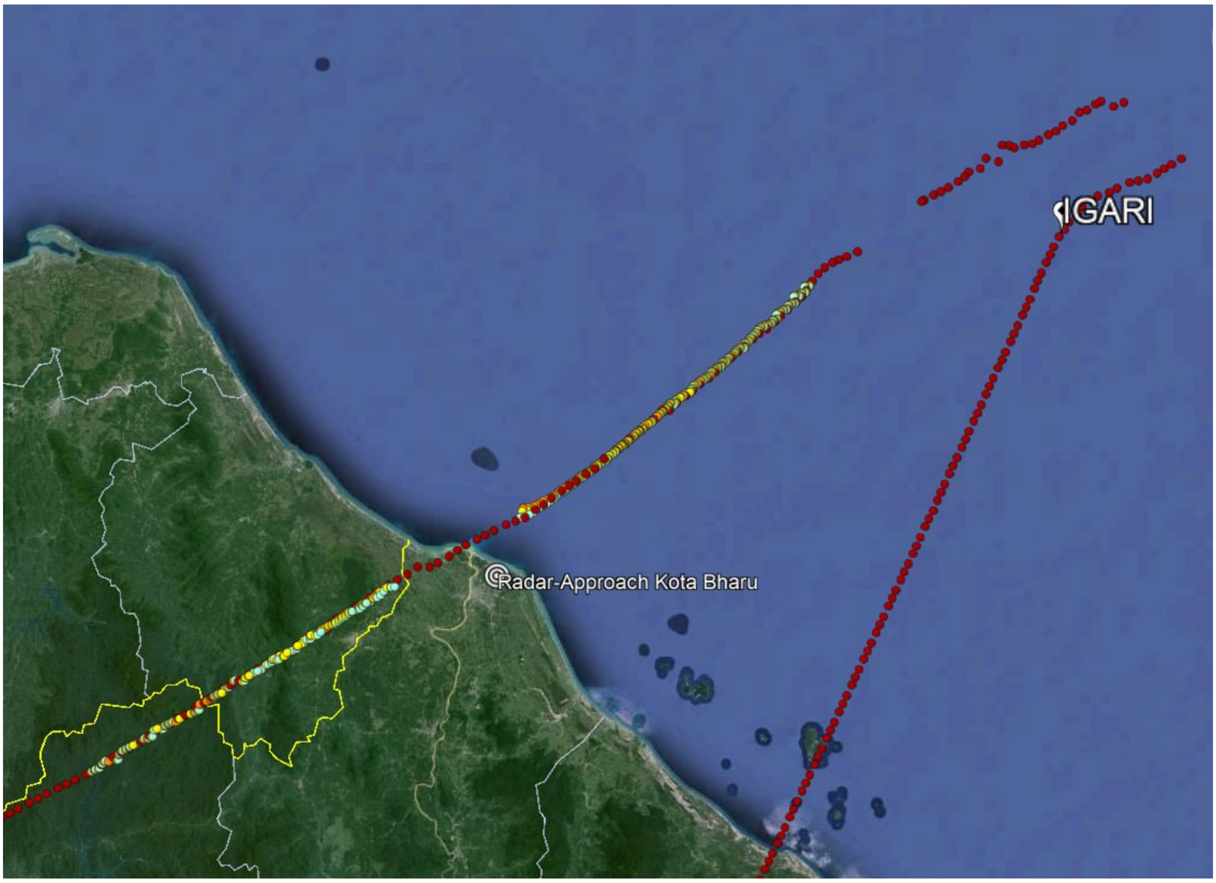

Figure 93: Geoscience data (red) and Kota Bharu PSR data (FL0 white, FL250 Orange, FL300 yellow and FL380 blue)

However, the Geoscience dataset includes three times fewer points than the civilian dataset and those provided do not overlap. Sometimes it's even one in four only. This is clearly illustrated in Figure 94 for altitude 0ft.

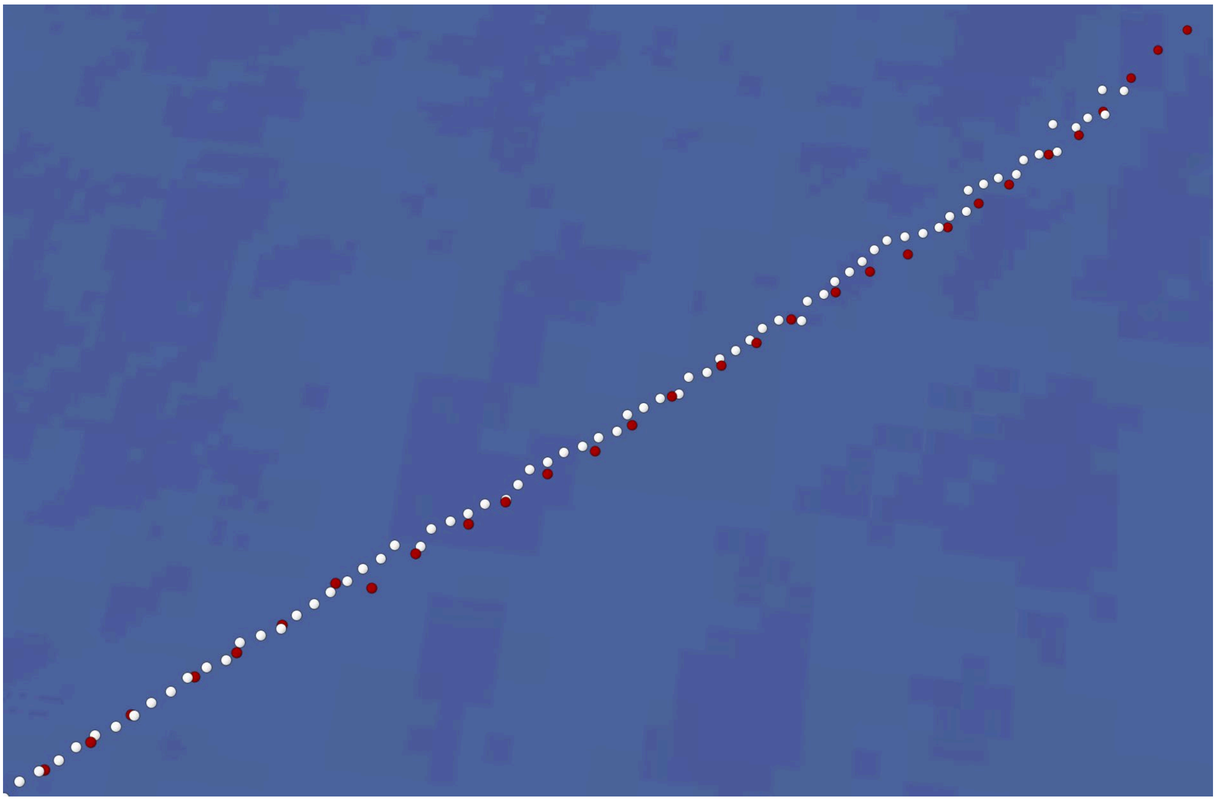

Figure 94: Close-up of Geoscience data (red) and Kota Bharu PSR data (FL0 white)

Any point-to-point comparison is therefore inappropriate. At this stage, all comparisons with civilian radars must be made at track level.

7.6.2 Analysis

No information could be obtained on altitude because the aircraft was flying radially towards the radar head. Therefore, for all locations, any altitude would result in a ground projection exactly on the Geoscience ground track no matter what. Thus, no a priori discrimination could be carried out since the Gaussian distribution of the distance of the points to a 10-degree polynomial ground path – optimised for Geoscience data – is of the same order of magnitude whatever the altitude. But this result was actually expected.

When flying over the cone of silence of Kota Bharu, data is still available in the Geoscience dataset.

7.6.3 Conclusion

When detected by the first echoes received at Kota Bharu, the aircraft was at least at ~FL305. No further information is available at this time.

The next available information was provided when the aircraft was located south of Penang Island.

7.7 Approaching Penang Island

Near Penang Island a very detailed analysis has not yet been carried out. It's in progress. This is a difficult area since the military radar network is denser. However, a closer look yields some interesting results. Before proceeding further, it should be noted that Geoscience data is available in the gap zone between the coverage of the two civilian PSR approach radars where Butterworth radar data is missing. In fact, Geoscience data is available in the different segments where Butterworth data is missing.

7.7.1 Analysis

In the inbound and outbound segments south of Penang Island, the match of the Geoscience dataset with the Butterworth PSR dataset is not good with respect to the track. Figure 89 shows that the Butterworth dataset includes discontinuous segments that are not superimposed on the Geoscience data, regardless of the altitude between FL230 and FL380.

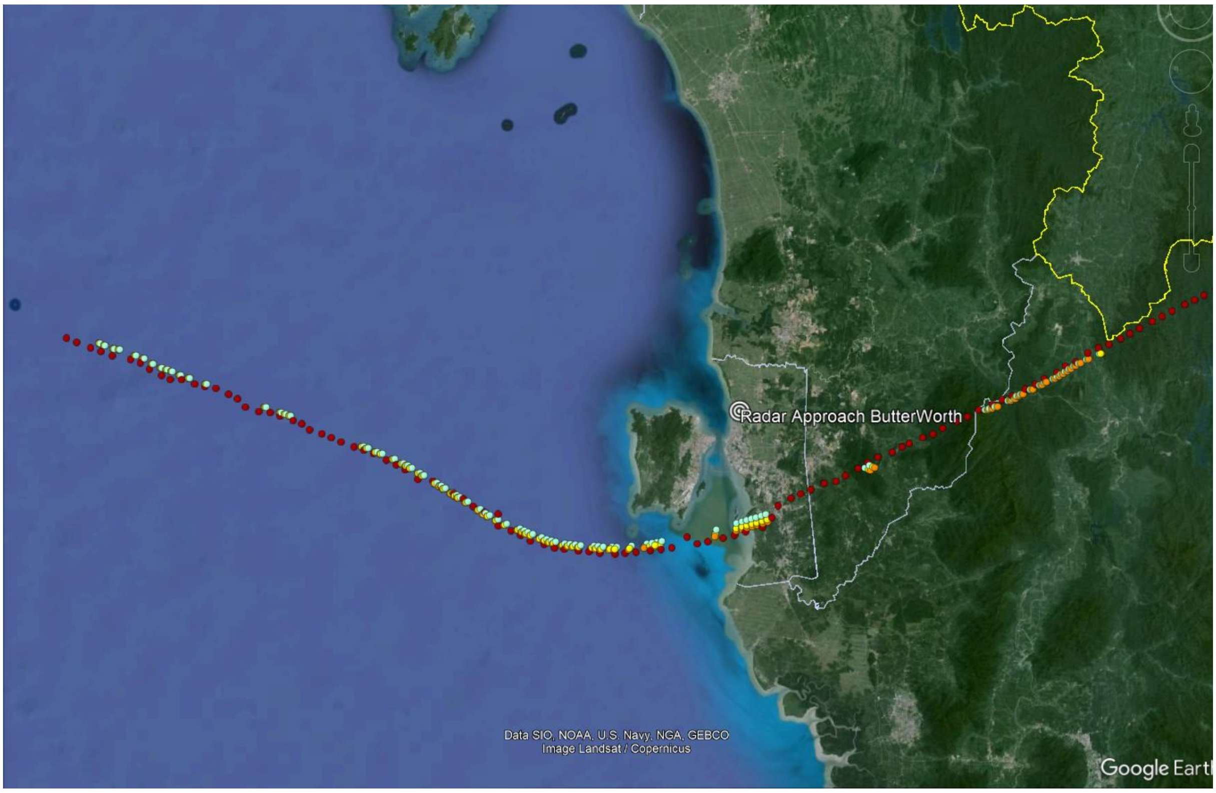

Figure 95: Geoscience data (red) and Butterworth PSR data (FL250 Orange, FL300 yellow and FL380 blue)

Figure 96 illustrates the inconsistency between the two sets of data, i.e. the ground projection of the trajectories at these altitudes.

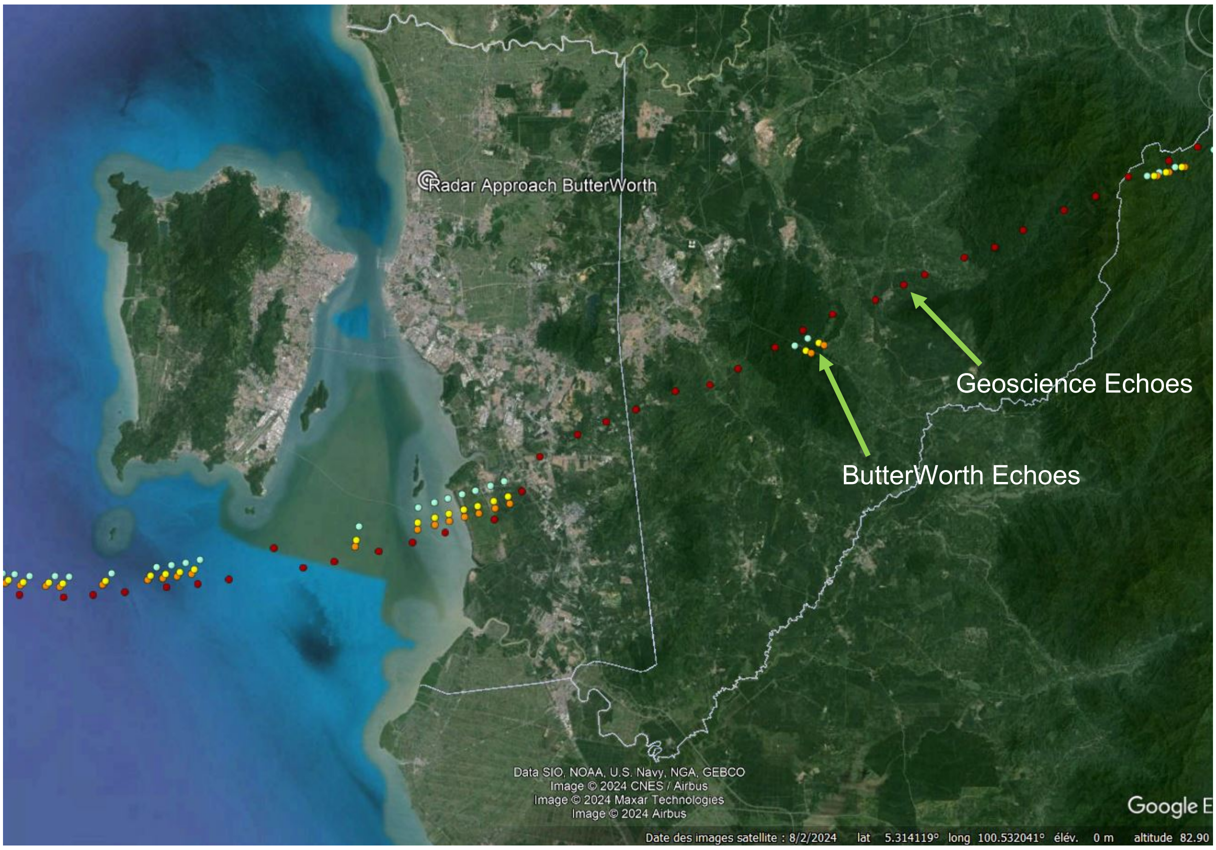

Figure 96: Geoscience data (red) and Butterworth PSR data (FL250 Orange, FL300 yellow and FL380 blue) - Close-up

But if we consider the trajectory calculated at a height of 0 feet with the echoes received by the Butterworth radar, the image is much more interesting. In Figure 97 we can see that at Butterworth longitude the RDP appears to start using Butterworth data (remember this is also a military radar). The match is very good during the turn and not so good towards the end of the capture near Pulau Perak.

At this location (green arrow and a little further), several data sources were available to the RDP, which shows a use of these sources in an alternating manner.

Figure 97: Geoscience data (red) and Butterworth PSR data (0ft white)

As mentioned above, this calls for further investigation that will be documented in a separate report.

7.7.2 Conclusion

The plane was followed by the military to the south of Penang. There is not enough "extraordinary" pieces of evidence to extract altitude information until a few nautical miles before the coastline of mainland Malaysia.

The most likely assumption is that the aircraft – manually controlled – flew at a quasi-constant flight level.

7.8 The turn in the south of Penang Island

This section discusses the segment of the track during the turnaround Penang Island, including the detection of the co-pilot's cell phone by the Celcom terrestrial network.

7.8.1 Analysis

Recalling section 4.7 above, coasting was detected in this area and is indicated by arrow 4 in Figure 29. A zoom is provided in Figure 98 where 4 segments were potentially detected as coasting segments. The sample correlation coefficients (R^2) are extremely close to 1 displaying almost perfect linearity that a manually piloted aircraft cannot achieve, thus confirming coasting at these locations.

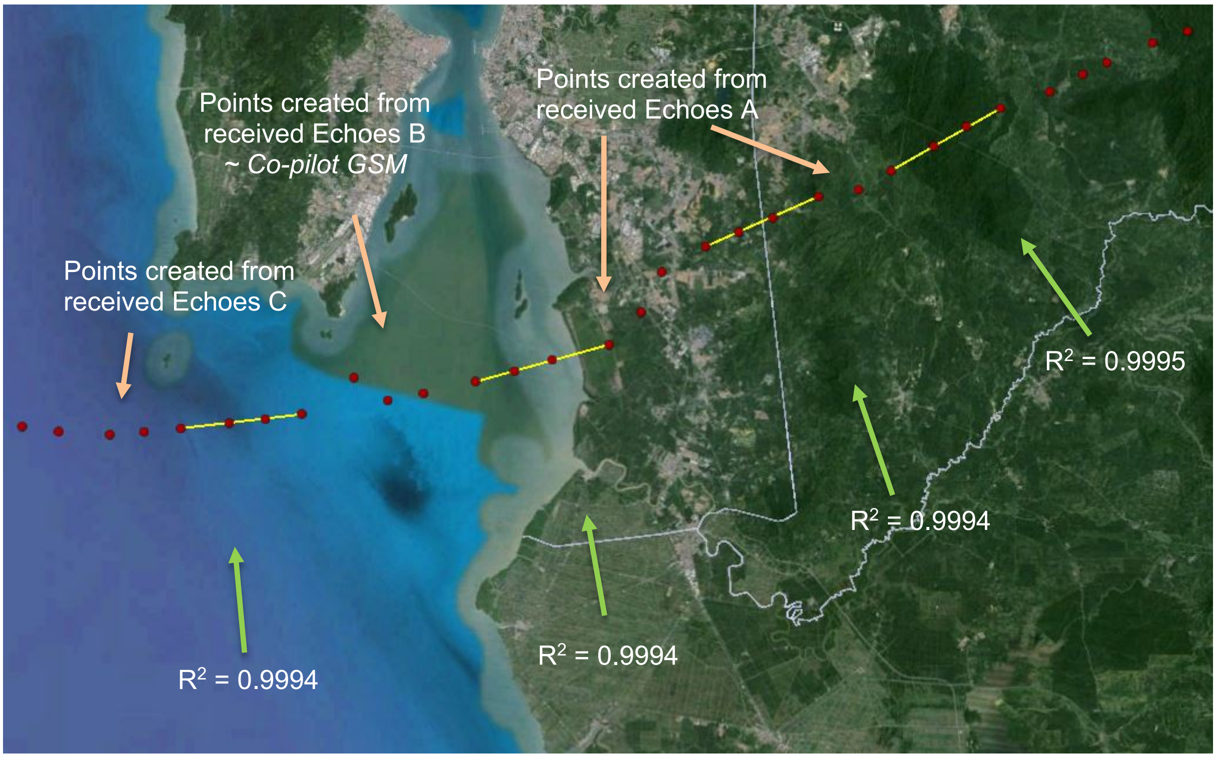

Figure 98: Identified segments coasted by the tracker in the south of Penang (yellow straight-line segments)

Outside these coasted segments, echoes have been actually received and points created noted A, B and C in Figure 98.

The discontinuity of the data provided by Butterworth had an obvious influence on the reconstruction of the track. It appears that intermittent use of Butterworth data has taken place, coupled with echoes actually received by Bukit Ibam. This would explain the “chaotic” situation and the succession of coasted segments. The A echoes received were well within Bukit Ibam coverage for FL250 and above. The echoes received C are well correlated with the Butterworth coverage.

Figure 99 deals specifically with points created after having previously received echoes, which appears to be the last echoes received by Bukit Ibam. The three points between the coasted segments coincide very well with the end of coverage of the Bukit Ibam range between FL300 and FL325.

This also corresponds very well to the maximum flight level at which the Celcom terrestrial network antenna could detect the co-pilot's mobile phone circa ~FL300/FL310.

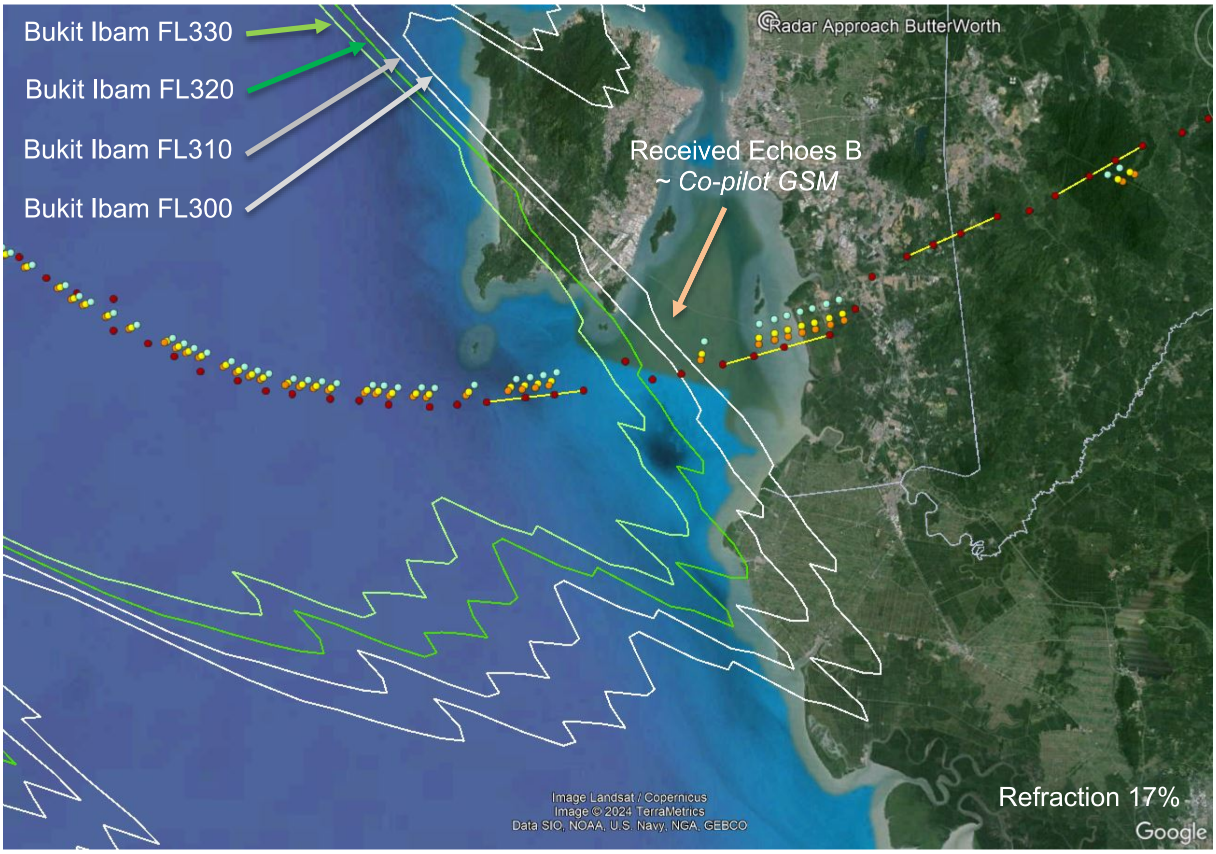

Figure 99: Bukit Ibam range coverage limit in the gap with no echo from Butterworth

7.8.2 Conclusion

During the turn south of Penang, there are two elements showing a correlated indication that the possible flight level of the aircraft was between ~FL300 and ~FL325.

If in general the understanding is relatively clear, a more detailed analysis could provide more clarity. It will be documented in a second, more elaborate report.

7.9 From South Penang Island to near Pulau Perak Island

7.9.1 Introduction

This section covers the segment from South Penang Island to the vicinity of Pulau Perak Island.

7.9.2 Analysis

Figure 100 illustrates this segment, which is continuous and filled with points until its end. It is interesting to note that the gaps missing Butterworth points are filled with points from reliable sources because they were not coasted except for the 5 coasted points underlined with the yellow line (sample correlation coefficient R^2 = 0, 9995). Coasting begins before the end of the Butterworth dataset. And the plane was out of range of Bukit Ibam.

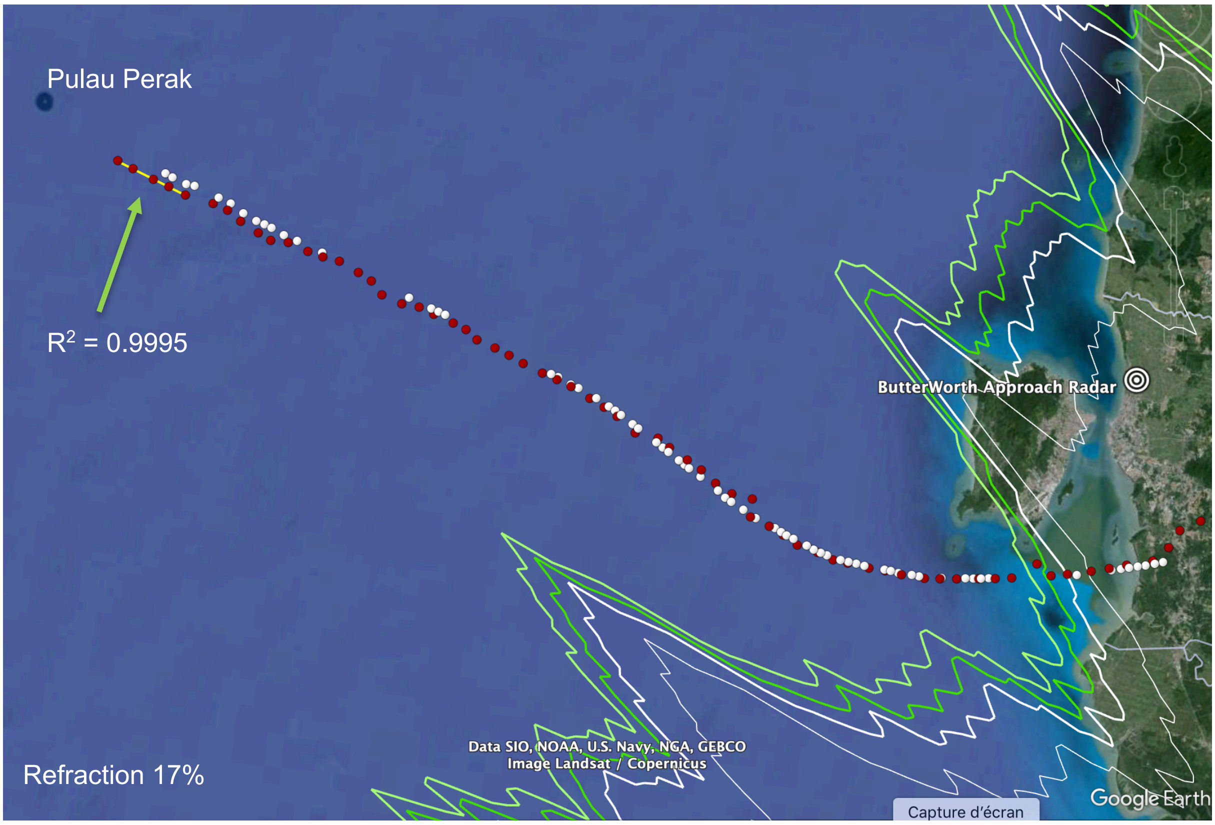

Figure 100: From Penang Island to Pulau Perak (Geoscience and Butterworth)

The aircraft left the south of Penang but was still tracked by Butterworth and Western Hill as points are present until reaching the vicinity of Pulau Perak Island. In this area, it could be possible that Bukit Puteri data was used.

As there is no more point (except the very last LSTRP point at 18:22:12 UTC), and as the Butterworth and Bukit Puteri coverage limits are located in this region, it is appropriate to analyse the possible impact of this radar.

Figure 101 provides a close-up of the Butterworth track points and Bukit Puteri maximum range for FL320 to FL330 in this area. The echoes captured by Butterworth appear to be the last to contribute to the Geoscience track. In addition, the last point created from the echoes received before the last 5 points coasted is located at approximately on the maximum range curve of ~FL330 Bukit Puteri.

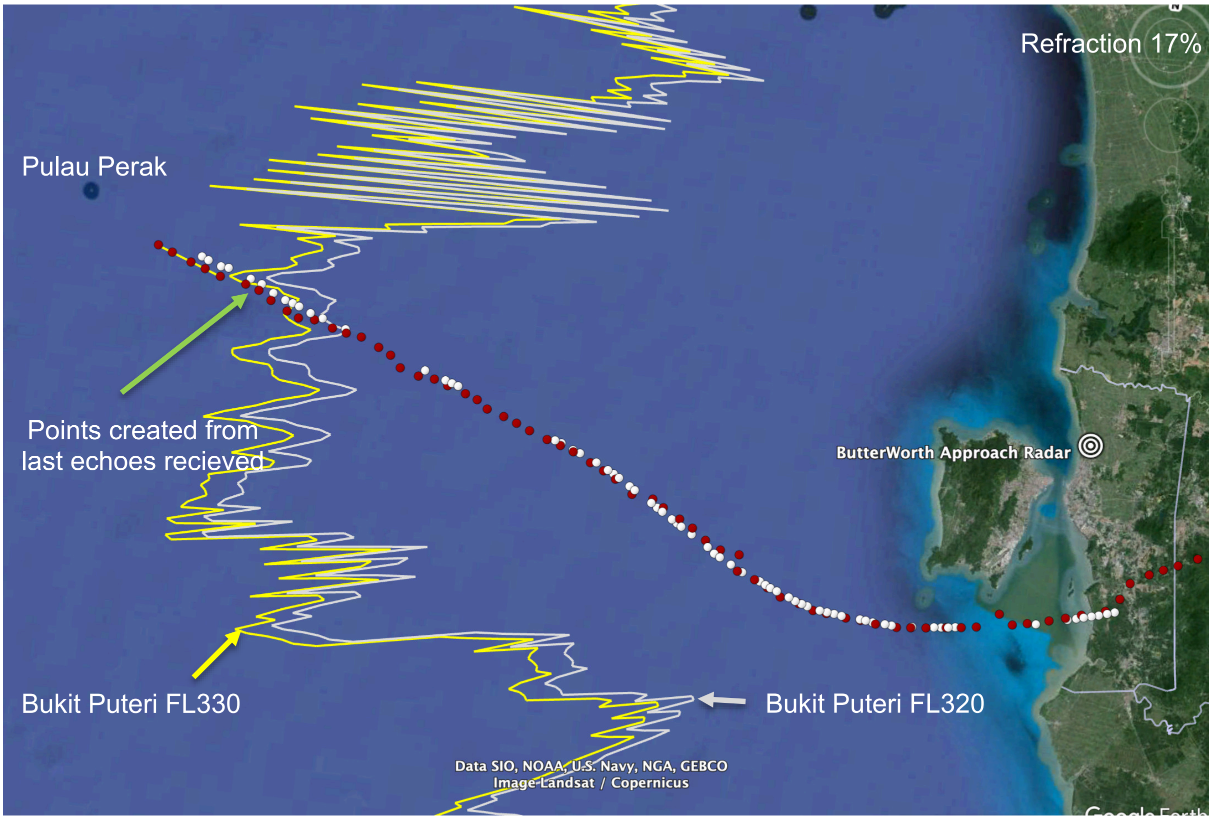

Figure 101: Butterworth track (white dots) and Bukit Puteri radar coverage limit (FL320 & FL330)

7.9.3 Surrounding traffic

At this point, let's consider the surrounding traffic that MH370 had to be aware of. The most restrictive is the Emirates EK343 which left Kuala Lumpur with the transponder code 2140 which communicated with the Butterworth SSR radar. MH370 already had this traffic in full visibility before the turn south of Penang thanks to EK343 position lights and strobes lights. When MH370 was turning at Penang, EK343 was at FL326 as shown in Figure 102 constructed from the records of PlaneFinder application. MH370 was obviously aware that traffic on this route was climbing. Therefore, to stay safe, there was no reason to climb even more that at night it is difficult to estimate the relative position of other traffic.

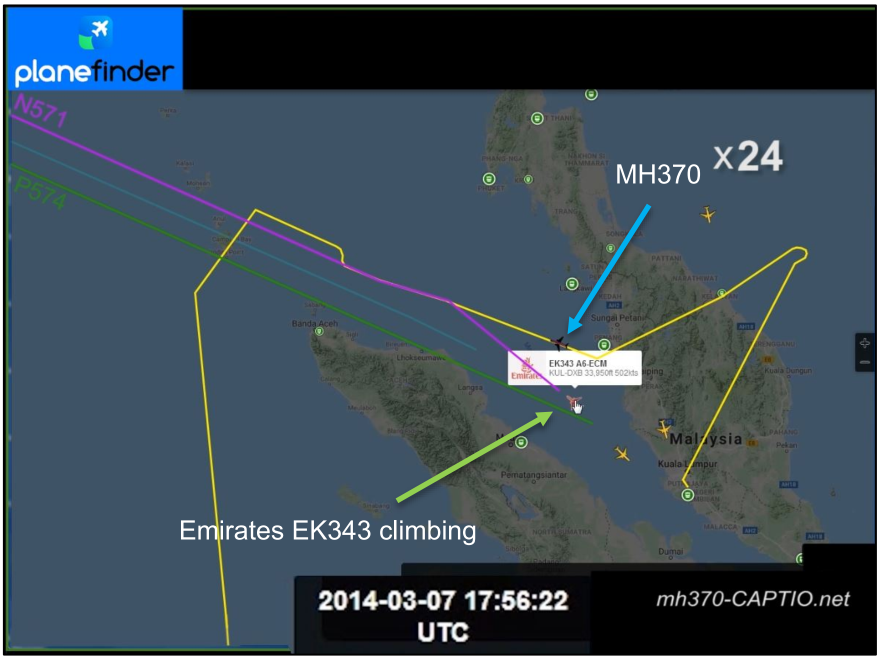

Figure 102: Relative position MH370 and Emirates EK343(FL326) at 17h53:28

Thus, it appears that at 17h53 both MH370 and Emirates were at similar levels i.e. ~FL325 for EK343 and ~FL300/~FL320 for MH370.

At 18:15:48, when the last ADS-B message was received from Emirates EK343, the situation is illustrated in Figure 103. The MH370 was leading the EK343 by ~31 Nm at a very similar speed ~510 kt. EK343 was established on Route N571 at FL340. To avoid detection, MH370's relative best situation would have been below the following traffic, so the EK343 pilot would not be able to see and detect it. Flying overhead would have potentially exposed MH370 to detection for at least four reasons: First, the EK343 pilot could have seen it because the sky was relatively clear in that area. Second, the wake vortices could have crossed the trajectory of EK343 because their natural move is downward creating potential turbulences. Third, the exhaust gases - and maybe possible contrails - could have been detected visually by the EK343 pilot. Fourth, the presence of traffic without any information on their TCAS while ATC is looking for a missing aircraft would have triggered the EK343 crew’s attention.

So, climbing and crossing EK343 flight level was definitely not the best option for MH370.

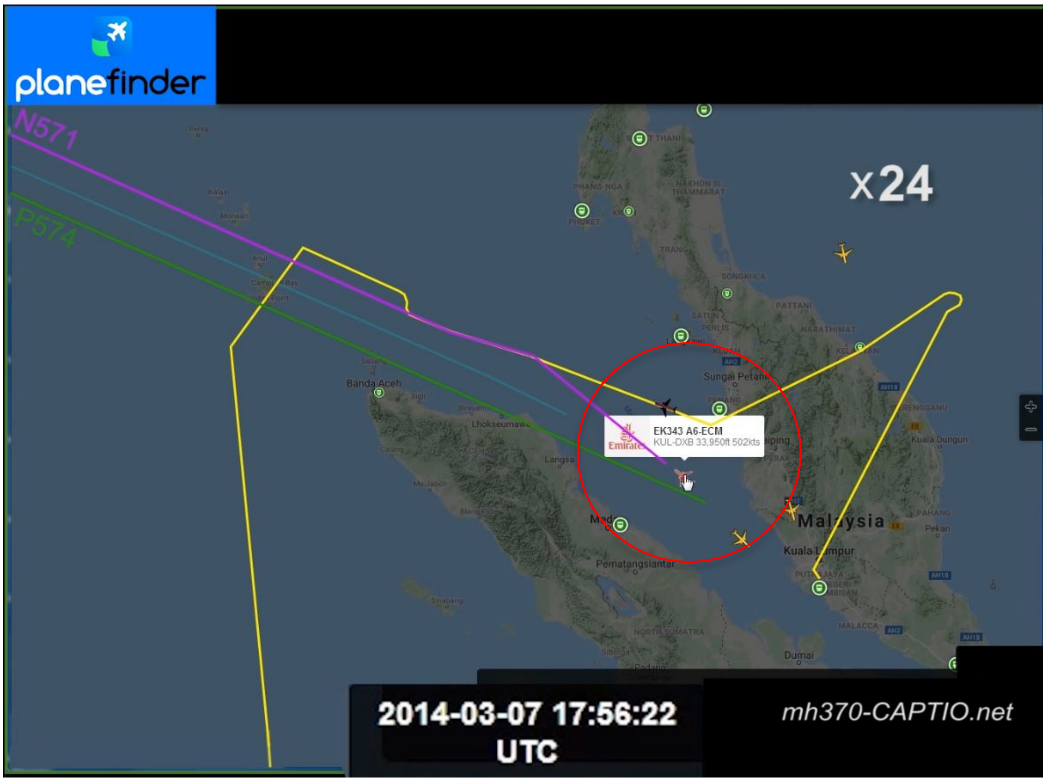

Figure 103: Relative situation of MH370 and Emirates EK343 (FL340) at 17h56.

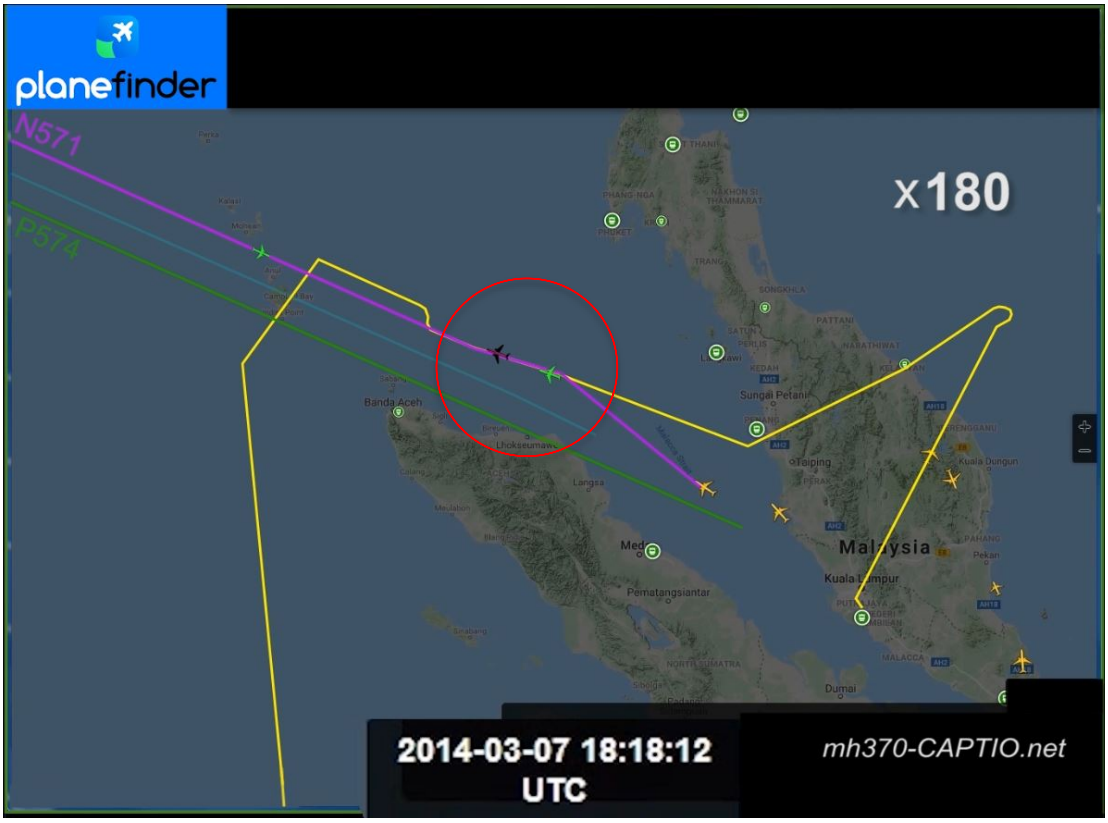

Figure 104: Relative situation of MH370 and Emirates EK343 (FL340) at 18h18 and Indigo 6E53 (FL330)

7.9.4 Conclusions

MH370 manually turned in the south of Penang at a level no higher than ~FL310 because the co-pilot's mobile phone was detected by a terrestrial network antenna. It was lost near the island of Pulau Perak. Due to surrounding traffic, the Emirates E343, MH370 had no advantage in climbing and likely stayed at ~FL300 or ~FL320 because of RVSM rules to fly even FL number when flying westbound. This is consistent with the flight level detected at LSTRP at 18:22:12 which is at ~FL300 as analysed below.

Thus, there are three lines of evidence converging to support the conclusion that the aircraft was at ~FL300 or possibly ~FL320 in the south of Penang and probably near the same level FL300 or at ~FL320 when the signal was lost by Butterworth and Bukit Puteri.

7.10 The last radar point (LSTRP)

7.10.1 Introduction

The Geoscience dataset includes a particular point, which is isolated, and not in continuity with the previous points forming the track to Pulau perak.

In the original JSON data file, this point is called "Last updated air defense radar point" in the attribute field "Name": "Path to connect the ***last updated air defense radar point*** to the data in the air defense radar". The designated data called "Air Defense Radar Data" is the track to Pulau Perak.

The point "Last Updated Air Defense Radar Point" is also referred to as LSTRP in this report and as shown in Figure 105.

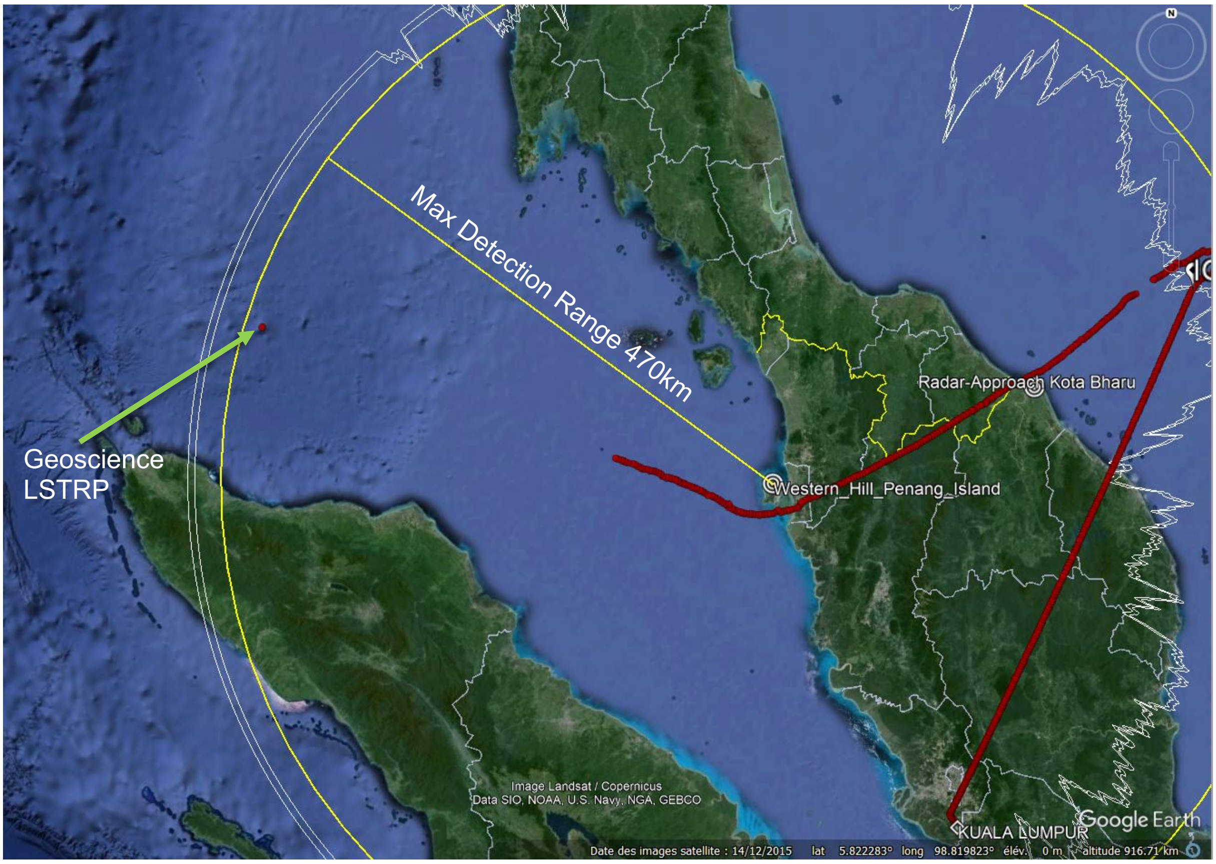

Figure 105: Last Radar Point (LSTRP) and the Western Hill detection capability

7.10.2 Analysis

According to [16] and [17], the effective range of the Western Hill radar is 500 km. This is a radar from the previous company AMS (then SELEX and now Leonardo), model RAT31-DL. Its detection range is actually 470km. The detection range is linked to the radar-specific parameter “reception time” which constrains the time window during which the radar “listens” to the echoes thus determining the maximum range.

Figure 105 clearly shows that the LSTRP is 8Nm within the yellow circle whose radius is the maximum detection range. The white circles represent the effective (theoretical) ranges at FL290 and FL300 around the FL295 reported in the official Malaysian final report of 2018. Thus, this presents a consistent picture as the maximum range of Western Hill is concerned with the detection of LSTRP which appears close to its “reception time” limit.

But the exact location of the LSTRP requires further examination.

Figure 106 shows very clearly where the LSTRP was actually detected, as indicated by the arrow " Lido’s LSTRP". But, the Geoscience LSTRP is precisely located on the N571 route while the linear trend clearly shows that the aircraft was not precisely on the route confirming that it was not under the LNAV function of the Auto-Pilot. If it were, it would have been exactly on the route due to the aircraft's high-precision navigation capability. The green line in Figure 106 shows that it flew south of Route N571. Recall that the plane was manually flown to Pulau Perak. This would therefore logically have been a continuation of the recent past.

At this point, a key analysis of the phrase “Last Updated Air Defense Radar Point” makes sense. The plane was probably not detected on Route N571. But in the early hours of the investigation to determine the potential trajectory of the plane, it was probably believed that the aircraft was under LNAV navigation, which was the obvious first option to follow. The word “Updated” reflects the process followed by the military: the point was relocated exactly on the N571 route, which is a standard LNAV route.

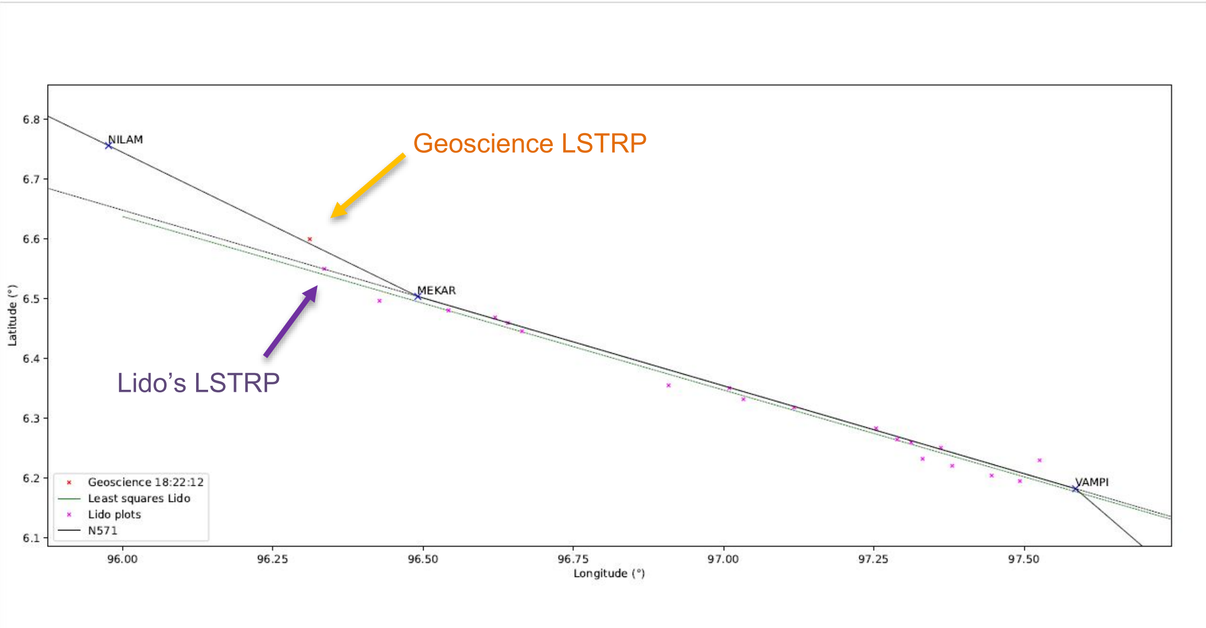

Figure 106: LSTRP situation with respect to Route N571 and Lido's Image points with their trend line

7.11 High-level considerations on speed

7.11.1 Analysis

Using the approximate time labels assigned to the Geoscience points, an interesting comparison was made from a specific point chosen after the U-Turn until the west coast of Malaysia before reaching Penang. For the sake of comparison with Kota-Bharu and Butterworth PSR data, the great circle distance was used as a first approximation. Each data source was compared with a hypothetical flight with a constant speed from the U-turn to the south of Penang. In Figure 107 we see on the two curves that the plane was timely behind (up to 55s) then catched up in the second part. This corresponds to the fact that the plane flew slower than the average speed at some distance before Kota Bharu, then accelerated to be faster than the average speed.

We see also that the civilian Kota Bharu data show relatively stable values, which slightly vary over time as we compare them with a constant speed, but do not jump. On the other hand, Geoscience data tends to "jump" compared to this average speed. This corresponds to the strong unrealistic variations that we see in the speeds: the position accelerates and slows down very quickly compared to the average speed, whereas in the Kota Bharu dataset this is not the case. On the other hand, we see the difference in scrolling between Kota Bharu data and Geoscience's.

This will be analysed in a subsequent analysis, which will be documented in another report.

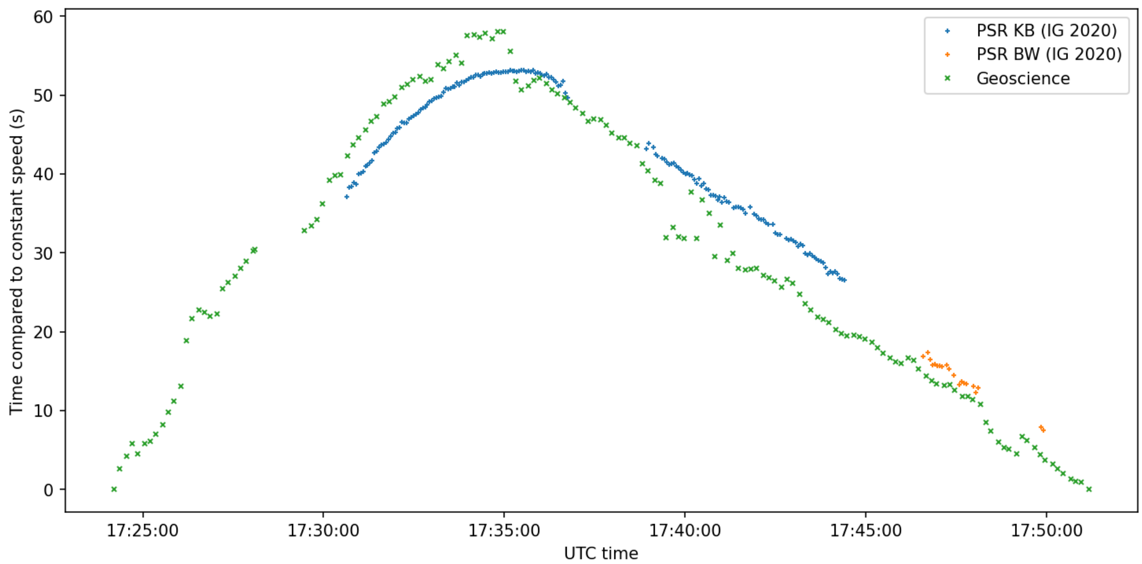

Figure 107: Time comparison of Geoscience, Kota Bharu and Butterworth with a hypothetical flight of constant speed over the great circle distance

7.12 Conclusions

Despite the reservations made above on the level of refraction, on the accuracy of the model and on the relativity of the information resulting from a morphological analysis (as opposed to absolute values), a sort of indicative vertical profile could still be outlined from the above analysis. Table 11 summarizes the results with the derived approximate values and Figure 108 (resp. Figure 109) schematizes the corresponding profile(s).

Question marks are placed where no relative information is available. Interestingly, when available, the estimated altitudes first provided by the April 2015 Malaysian Factual Information Report [15] are displayed in the last column. They correlate very well with our findings.

Table 12: Indicative and approximate vertical profile between IGARI and the Radar Coverage Exit (LSTRP) at 18:22 UTC

Time	**Event**	**Flight Level (+/-10)**	**Attitude**	**comment**
17:20:34	Abeam IGARI	FL350	Level	
			Level or Slightly descending	Slight descent, manually controlled
~17:21:53	Actual Start U-Turn	~FL345/~FL350		
17:22:30	Official Entry U-Turn	?	?	
			Climbing	Slight climb
17:24:40	Official Exit U-Turn	~FL355 (max 360)		
~17:25:42		~FL355		
			Descending	~-2700fpm
~17:27:21	Entry in Gap-2	~FL310	Descending	
	No data		Descending	~-2700fpm
?		~FL280	Stopped descent	
~17:29:28	Exit from Gap-2	~FL290	Climbing	~+1500fpm max
			Climbing	~+1500fpm max
~17:30:28		~FL305	Climbing	
	?	Estimated at ~FL300 or ~FL320 RVSM Semi-circular rule	Estimated: Level	Officially reported in [15]: ~FL330
~17:37:28	Abeam Kota Bharu	? (estimated ~FL300/FL320)	? Level?	
		? (estimated ~FL300/FL320)		
(17:39:59)	?	?		Officially reported in [15]: ~FL310
17:52:27	GSM Co-Pilot (Turn at Penang)	In antenna capability + semi-circular RVSM rule ~FL300	level	Antenna Maximum ~FL310
			Level?	
~18:00:58	Last actual point before Pulau Perak	Max ~FL325 semi-circular rule: ~FL300 or ~FL320	Level, close to documented airways	
	? EK343 traffic at FL340	? RVSM rule → ~FL300 or ~FL320	Level?	Stay below traffic
18:22:12	LSTRP	? FL295	Slightly descending at the end	Officially reported in [11]: ~FL295

Bearing in mind the presence of Emirates Traffic EK343 getting closer at FL340 on the left side above and the proximity of Route N571, one would think that the aircraft flew at an even flight level as requested by the RVSM semi-circular regulation, i.e. ~FL300 or ~FL320 approximately with some tiny ups and downs as it was manually controlled. But these vertical excursions had to be very limited as they were very dangerous considering potential opposite traffic.

When no information is available, the vertical profile was considered as smooth as possible and respecting the RVSM semi-circular rule thus levelled.

Basically, the above analysis leads to two types of profiles suiting best the radar information and the aeronautical constraints. One finishing at the constant flight level of ~FL300 (Figure 108) and the other at constant ~FL320 followed by constant ~FL300 in the Strait of Malacca (Figure 109).

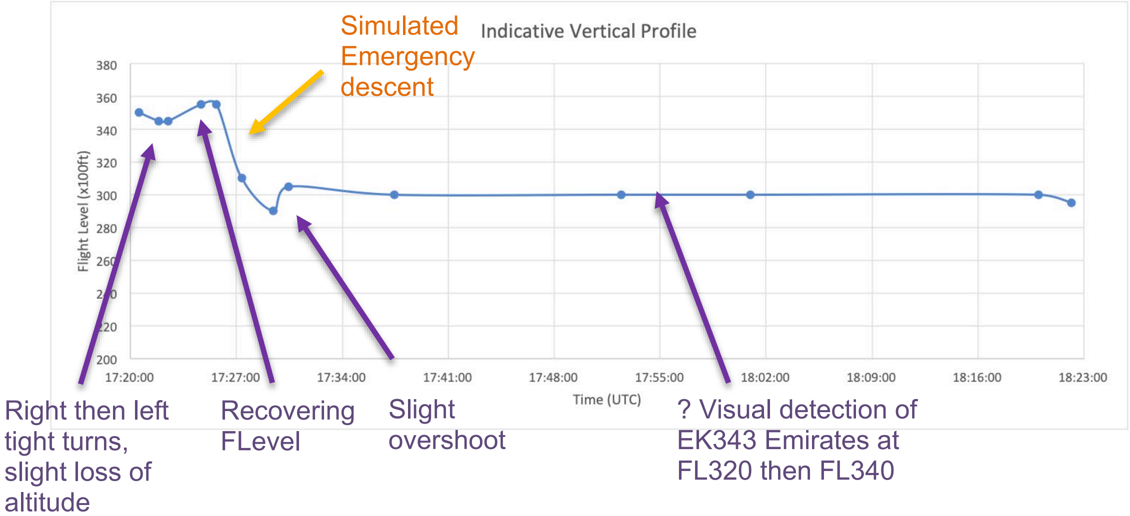

Figure 108: Indicative approximate vertical profile 1 (FL300) between IGARI and the Exit of radar coverage at 18h22 UTC

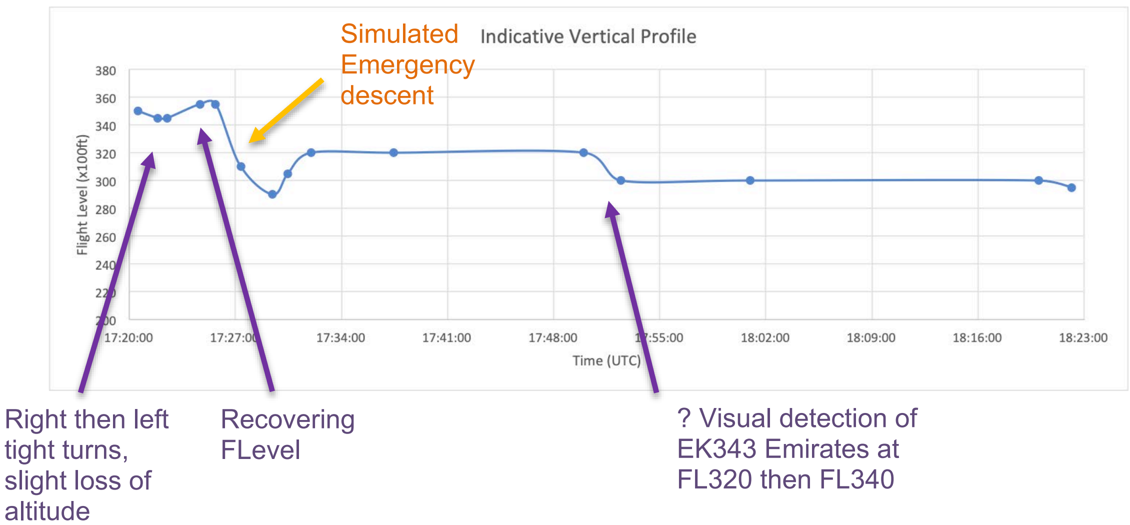

Figure 109: Indicative approximate vertical profile 2 (FL320/300) between IGARI and the Exit of radar coverage at 18h22 UTC

8 Overall conclusions

It has been shown that the data used by Geoscience Australia on their website to display the trajectory of MH370 between Kuala Lumpur and the last point inside military radar coverage matched the reference map published in Figure 2 of the 2014 ATSB report [4]. It is also coherent with the tracks published by the DSTG and by Boeing.

The Geoscience dataset was checked and it is concluded that it is almost certainly the data provided by the Malaysian authorities to the Australian Transport Safety Board (ATSB).

The key information provided by this dataset is the numerical values of the geodetic coordinates of the points sampled along the track reconstructed by the military radar processor. The time intervals between points approximately follow the 9/9/12 second pattern. But the precision of the provisional time labels does not allow instantaneous values of the plane's ground speed to be evaluated.

No altitude information is provided after crossing IGARI. Before this waypoint, the altitude value is provided in full consistency with the known ADS-B data. After IGARI, the track is the projection on the ground of the actual flight trajectory.

A detailed analysis of the provided Geoscience track points was carried out in two steps. First, the lateral geometry of the actual trajectory was taken into account to verify the flight navigation performance. Second, a high-level geometric analysis using the radar coverage morphology was able to infer information about the relative vertical movements of the aircraft. An enhanced height of terrain model has been enhanced with an azimuthal angular accuracy up to 1/8°.

The analysis confirmed important aspects of the MH370 trajectory between IGARI and the exit from the radar coverage at 18:22 UTC:

- The aircraft was manually piloted as the lateral navigation characteristics of its trajectory do not match the LNAV capability of the auto-pilot.
- The average speed of the aircraft is confirmed at ~510kt.
- An indicative approximate vertical profile could be determined showing that the aircraft descended after the U-Turn and slightly climbed back at either ~FL300 or ~FL320 and ended at ~FL295 at 18:22 UTC.
- This means a quasi-levelled flight path after Kota Bharu if respecting RVSM rules.
- The exact level of refraction is unknown, our modelling with 17% refraction provides the only coherent full picture of the radar coverage and fits with the aeronautical constraints.
- The level of precision of this high-level vertical analysis is estimated at +/- 2000ft

This is in full coherence with the reconstructed trajectory described in our report in [1] where FL300 was identified as the most likely level.

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