Mull of Kintyre – Analysis of Available Data

Summary

This report has evaluated the available data associated with the Mull of Kintyre accident investigation, and certain conclusions have been reached as to the most probable flight path of the aircraft from the time of takeoff until the point of impact. These conclusions are supported by consistency in the data and that fact that alternative conclusions are either rejected by the data, or required that the aircraft had been piloted in a manner that is unusual or unlikely. These conclusions are summarized as follows:

- The aircraft was following its intended flight path up to the selection of the waypoint change
- At the waypoint change, the aircraft did not follow the directed flight path to the next waypoint, rather the aircraft made a small course change to the right, i.e., away from the directed flight path and more directly towards the Mull
- From the Aldergrove ATC fix until the aircraft was approaching the landmass, the flight was conducted at a true airspeed that tended towards the higher end of the normal cruise speed range
- The aircraft slowed as the landmass was approached to a true airspeed that is more consistent with the initiation of a cruise climb profile, however the increase in wind strength at the Mull compensated for the reduction in airspeed such that the aircraft groundspeed remained approximately constant
- Large variations in airspeed during the flight, for example those associated with a significant reduction in airspeed at the waypoint change, are generally precluded by the compensating actions that would have been necessary to achieve the high average speeds that have been noted
- The aircraft flight path established in the proximity of the Mull was at an insufficient climb rate to clear the terrain, in particular due to the fact that the unexplained course change to the right placed the aircraft flight path over the area of highest local terrain

Prepared by:
James Mitchell
Technical Fellow
The Boeing Company

1 Introduction

The purpose of this report is to analyze the data recorded as part of the crash investigation and to probe for its correctness. Correctness, in this sense, is defined by two factors. Firstly, consistency between the various pieces of data must be established. Secondly, the data must be tested for credibility, i.e. if assembling the data into a flight path description requires that the aircraft travel faster than its known speed limits, or climb at an excessive rate, then that solution must be discarded. A finding of both consistency and credibility between the pieces of data will assist in developing a clearer picture of the aircraft flight path, both in position and time, from takeoff up to the point of impact on the Mull.

2 Known Data

Known data is assembled from a number of sources, as listed below. These include the RACAL (Thales) report based upon their retrieval of data stored within the SuperTANS and responses to follow-on questions, data from the air traffic control communications with the aircraft, meteorological reports, and data taken by the AAIB during their investigation of the crash scene. (Note that the names RACAL and Thales will be used interchangeably within this analysis).

1. Initial Fix (Source: RACAL Report para. 2.2.2)
    a. Time: 16.07.09.9 UTC (GPS)
    b. Position: N5441.10, W00611.89
2. Forecast Winds (Source: Aldergrove Met Area Forecast)
    a. Surface Winds: 12 - 18kt @ 150 degrees
    b. Winds at 2000ft: 25kt @ 190 degrees
3. ATC Fix (Source: NATS Recorded Speech Transcript)
    a. 7 miles from Aldergrove VOR
    b. Bearing: on 027 radial from VOR
    c. Aldergrove VOR @ N5439.66, W00613.79
    d. Fix at 16:46:25 GMT (synchronized to UTC)
4. Point of Impact (Source: AAIB Report paras. 5.4 & 5.9)
    a. Position: N5518.67, W00547.65 (Hand Held GPS and Ordinance Survey)
    b. Altitude: 810ft amsl
    c. Aircraft Track (from tire tracks): 012 degrees True
5. Conditions at Impact (RACAL Report paras. 2.3, 2.4, 2.6, & 2.8)

(Note that these data specifically define conditions at equipment power down, and not necessarily conditions at impact. It is likely that the equipment remained powered for some limited time during the period that the aircraft broke up after impact. As will be shown later, this has some effect on the application of the data.)

a. Time: 16:59:10.4 GMT, 16:59:36.0 UTC (GPS)

b. Position

i. Position (GPS): N5518.61, W00547.80
ii. Position (Doppler): N5518.65, W00547.49

c. Altitude

i. Pressure Altitude: 1100ft ± 50ft
ii. Baro-Altitude: 665ft ± 50ft
iii. GPS Altitude: 750ft

d. Speed

i. TAS: 127.6kt
ii. GPS Groundspeed: 150kt
iii. TAS Groundspeed: 151kt
iv. Doppler Groundspeed: 156kt

e. Heading & Track

i. Magnetic Heading: 42.2 degrees
ii. True Heading: 34.4 degrees
iii. TAS Track: 026 degrees True
iv. GPS Track: 025 degrees True
v. Doppler Track: 023 degrees True

f. Wind: 30 knots from 170 degrees

i. WINDN = 29.77kt, WINDE = -5.26kt

g. Steering Commands

i. Distance to WP: 86.7nm
ii. Time to Go: 32min
iii. Steer Command: Left 14 degrees (2 left chevrons)
iv. Heading to Steer: 25 degrees Magnetic

6. Waypoints (Source: RACAL Report para. 2.11)

a. Initial Fix: N5441.10, W00611.89, Var = W8.0

b. Waypoint A: N5518.50, W00548.00, Var = W7.5 (Lighthouse???)

c. Waypoint B: N5643.00, W00514.00, Var = W7.5 (Corran)

7. Other Data

a. Waypoint Change Selected: N5517.73, W00548.43 (Source: RACAL Report para. 2.12.4)

i. Leg Change Alert: 30 seconds (1 minute?) before waypoint

b. Last Altitude Update (Source: RACAL Report para. 2.8.9.2 and subsequent clarifications)

i. Latitude used for derivation: N5518.65

ii. Time from Power Down: 30<n<31 counts (1 count = 0.6 sec)
iii. Derived Baro-Altitude: 468ft ± 50ft
iv. Derived Pressure Altitude: 900ft ± 50ft

c. Last Steering Command Update (Source: RACAL Report para. 2.12.1)

i. Position: N5518.58, W00547.82
ii. Distance to WP: 86.83nm
iii. Bearing to WP: 12.4 degrees
iv. Heading to Steer: 17.5 degrees
v. Track Angle Error: -13.6 degrees
vi. DC Steer Command: Left 14.1 degrees
vii. AC Steer Command: Left 12.6 degrees
viii. Heading Rate: 0.07 degrees per second

d. RAF Macrihanish Information (Source: Sectional Charts NN2903 & NN3001)

i. TACAN/VOR: N5525.86, W00539.06
ii. TACAN Frequency: Channel 107

3 General Mission Profile Assessment

3.1 Overall Flight Path Assessment

The overall horizontal navigation picture is shown in Figure 1. This identifies the basic planned route parameters from the initial navigation fix to Waypoints A and B. The following Table lists the latitude and longitude of the major points of interest.

Location	Position	
	Latitude	Longitude
Aldergrove VOR	N5439.66	W00613.79
ATC Fix (derived)	N5445.90	W00608.28
Initial Navigation Fix (V813)	N5441.10	W00611.89
Waypoint A	N5518.50	W00548.00
Waypoint B	N5643.00	W00514.00
Waypoint Change	N5517.73	W00548.43
Last Steering Command	N5518.58	W00547.82
Point of Impact (OS)	N5518.67	W00547.65
Point of Impact (Doppler – A/C)	N5518.65	W00547.49
Point of Impact (GPS - A/C)	N5518.61	W00547.80

Conversions: 1 arc minute of latitude = 6080 feet = 1 nautical mile
1 arc minute of longitude = 6080*cos(lat) feet = 1*cos(lat) nautical mile

It should be noted that the initial fix location was entered prior to takeoff, and is therefore assumed to be the location of the aircraft parking spot when electrical power was first applied. Also, these notes and analyses, in general, are conducted in an aircraft frame of reference, i.e. with respect to aircraft measured position. It is accepted that there is a small error between the aircraft GPS positions and the true positions. However, for the purposes of developing an overall aircraft flight path with respect to position and velocity, only relative information is necessary and these differences have no immediate effect. Where these differences are important is in developing an estimate of the aircraft vertical flight path with respect to the final point of impact, and this will be addressed at the proper time.

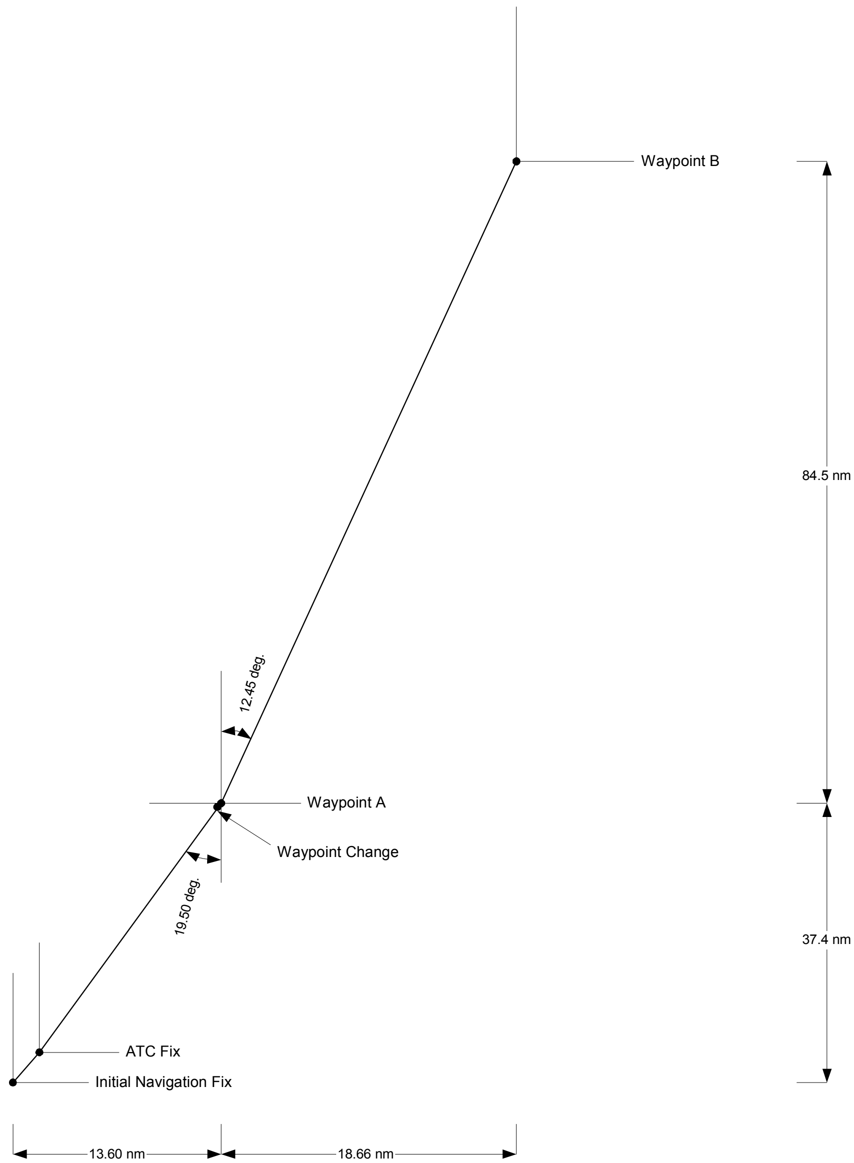

Figure 1. Overall Flight Plan Geometry

Using the ATC fix as a point of reference, the following bearings are calculated:

- Bearing from ATC Fix to Waypoint A: 19.50 degrees True

- Bearing from ATC Fix to Waypoint Change: 19.55 degrees True

The close agreement of the these two data points effectively confirms that, given the accuracy of the ATC fix, at the time the waypoint change was selected the aircraft was closely following the selected route from the initial fix to Waypoint A.

The bearing from Waypoint A to Waypoint B is 12.45 degrees True. At the selection of Waypoint B, made approximately 0.81nm short of the actual waypoint, the flight crew would have received a left turn steering command of approximately 7 degrees to make their next route leg.

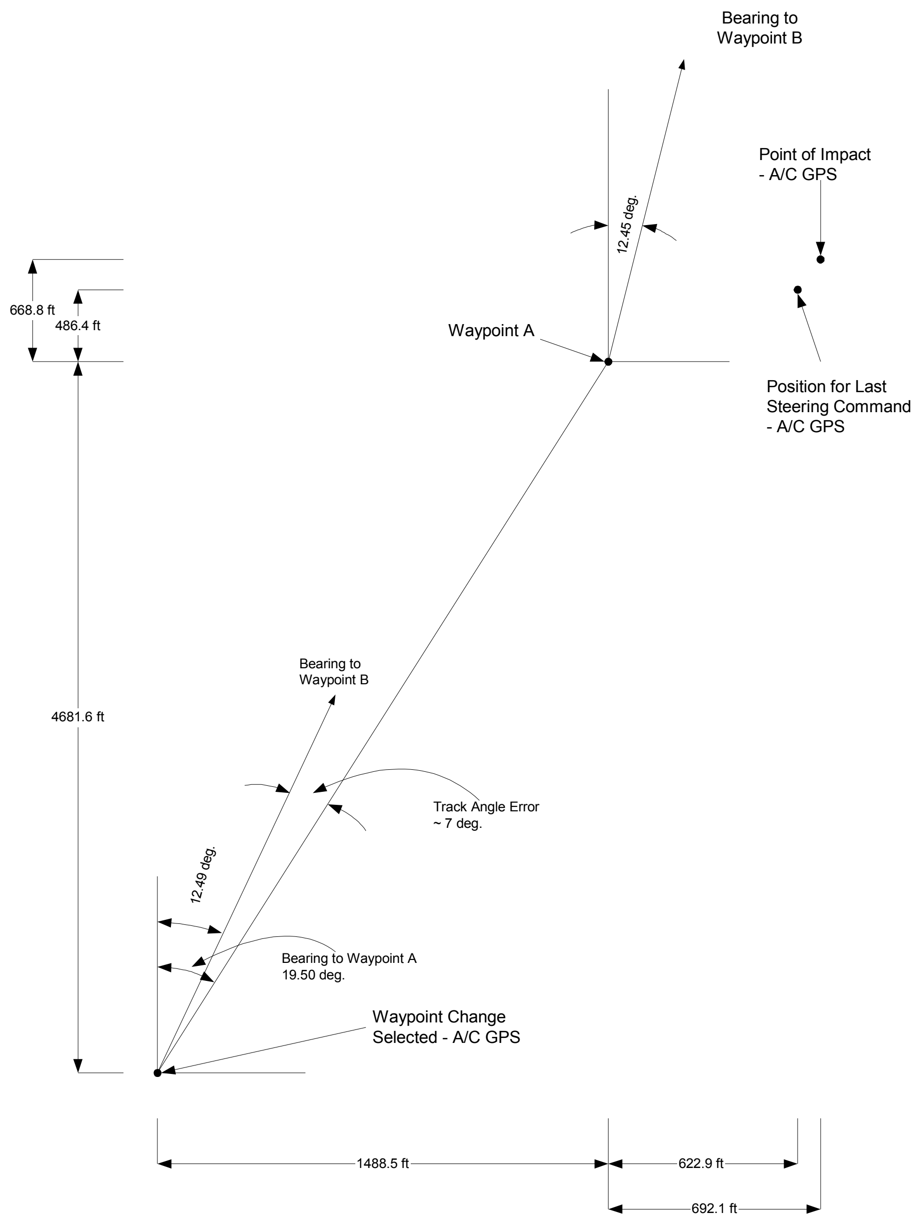

Figure 2. Flight Path Geometry Relative to Waypoint A

Figure 2 shows the relative geometry of the aircraft situation relative to Waypoint A. This sketch is approximately to scale, and it is clear from the position at impact that the aircraft had not made the turn to follow the directed course to Waypoint B. In fact, the aircraft was now not only right of the new course, it was also right of its original course from the ATC fix to Waypoint A.

The bearing from Waypoint Change to Last Steering Command is 22.22 degrees True, which indicates that the route of the aircraft is ~3 degrees right of the initial route and ~10 degrees right of the directed route from Waypoint A to Waypoint B

The bearing from Last Steering Command to Point of Impact is 20.77 degrees True, which indicates that, at the last moment, a left turn was initiated by the aircraft

This data would seem to indicate that the flight crew had made a conscious decision, for some reason, not to follow the directed route to Waypoint B. Some further discussion of the possible reasons behind this unexpected change of course is provided in Section 4.3.

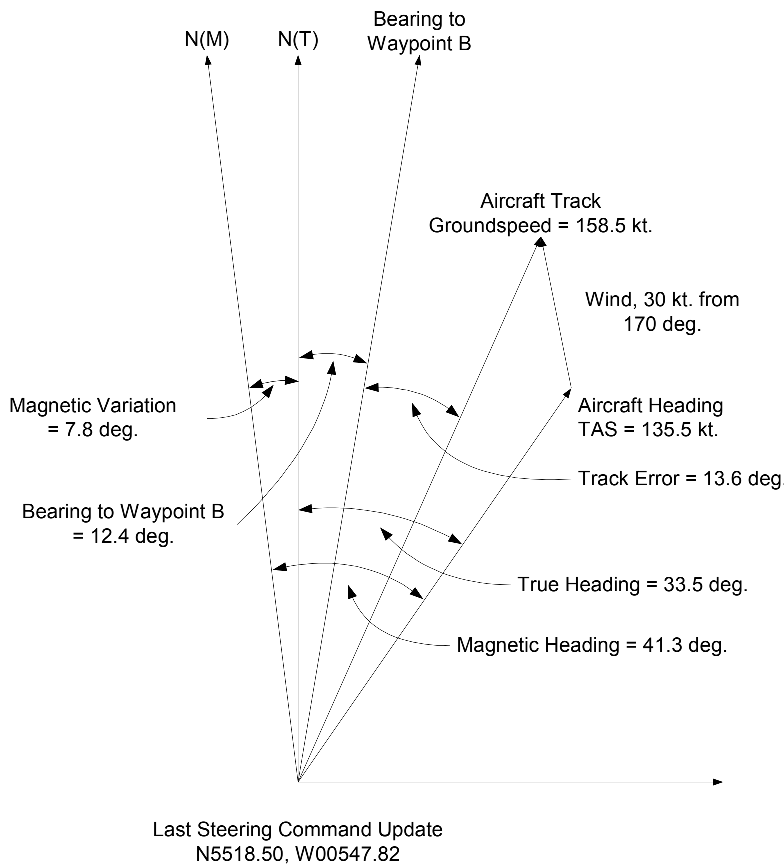

Figure 3. Flight Path Geometry at Last Steering Command Calculation

Figure 3 shows the aircraft flight path definition that can be calculated from the SuperTANS data logged at the last time the steering command calculations were updated. The steering command calculations are updated every second, which implies that this data was recorded less than a second before impact. Based on the differences in latitude and longitude between the steering command calculations and the point of impact (aircraft power down), and using the last known aircraft ground speed, it is estimated that these last calculations were made ~0.75 seconds prior to impact. The data appears to make a consistent set, i.e. no inconsistencies were noted between the SuperTANS recorded data and hand calculations. It should be noted that at the time these calculations were made, the aircraft appears to have been close to a "wings level" flight condition. This observation is based on the last recorded value for aircraft turn rate, which was indicating +0.07 degrees per second, i.e. a very gradual turn to the right. This does not address the aircraft rate of climb or descent at the time, since this data is not recorded as part of the steering command calculations.

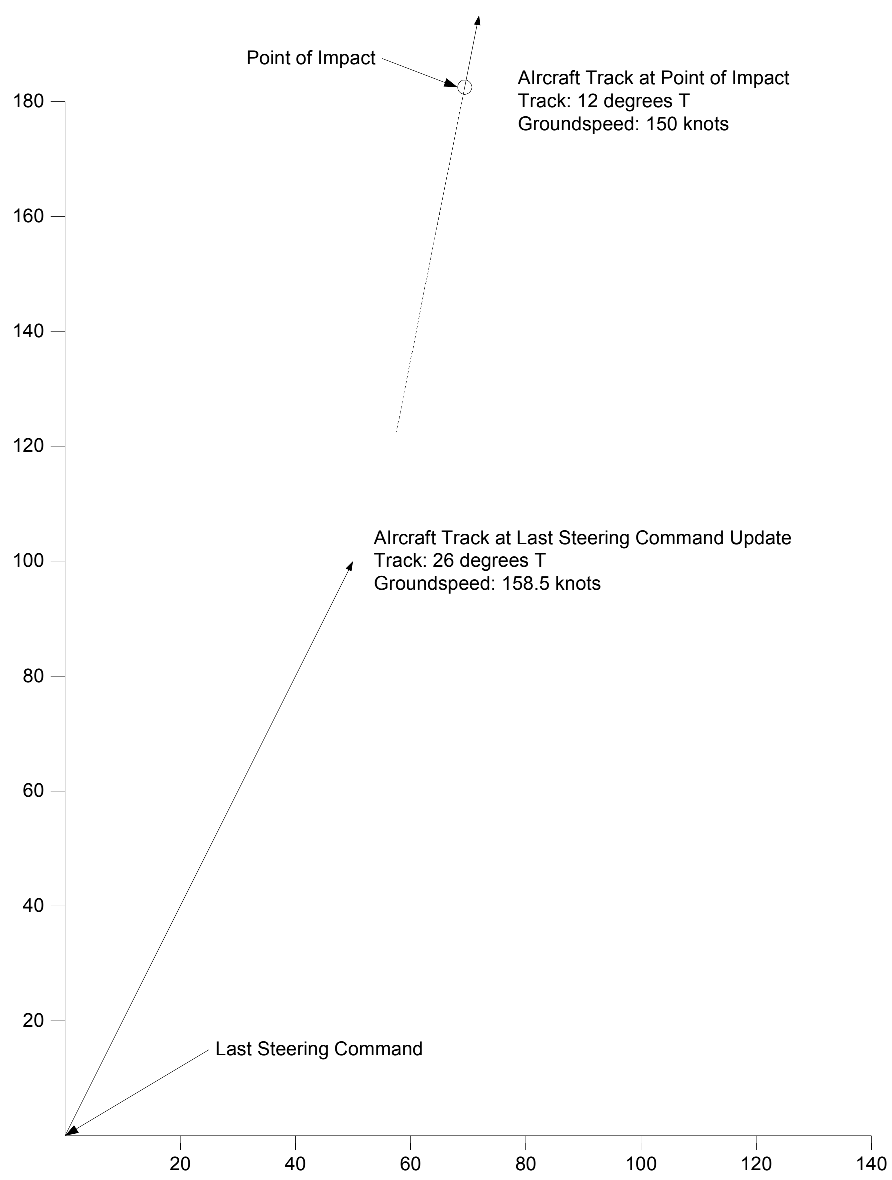

Figure 4. Point of Impact Geometry Relative to Last Steering Command

Figure 4 shows the aircraft flight path from the time the last steering command calculations were recorded until the point of impact, using the wheel track direction as the “preferred” source of information for the aircraft track at point of impact. The only data that is undeniably valid for the actual point of impact is the aircraft track based upon wheel track directions, which was documented by the AAIB. As noted in section 2.4, the recorded SuperTANS data related to the point of impact must be considered to be potentially misleading at some level. Since this data strictly refers to the conditions at equipment power down, and since it is not known how long power was available to specific pieces of equipment following impact, it must be considered to have been possibly compromised to a lesser or greater extent by the process of the aircraft breakup. For example, detachment of the pitot-static tubing during the aircraft breakup can corrupt the last recorded airspeed measurements. However, other data can be assumed to be still valid, i.e., because of the limited time span, the wind speed and direction can be assumed to be unchanged from the values used for the last steering command calculations.

3.2 Aircraft Velocity Assessment

The only fully homogenous set of values of aircraft velocity that can be determined are the measured values that were documented as part of the steering calculations. As discussed above, the value of the measured aircraft velocities “at impact” are subject to question, as they truly represent values at power down and thus could be corrupted by the effects of the aircraft breaking apart. As will be discussed later, they also do not correlate well with other physical evidence when taken purely at face value. The other means of developing the aircraft velocity profile is to use measurements of time and distance. Two sets of measurements are available to determine a usable aircraft average groundspeed; the time and aircraft position associated with the last aircraft ATC fix; and the time and position associated with the point of impact, or more precisely the time of equipment power down. The time and position at power down are measured accurately, as shown in section 2.5.a and 2.5.b. The time for the ATC fix is also stated accurately, as shown in section 2.3.d. However, the position for the ATC fix is not stated with the same accuracy, therefore it must be evaluated over a range of possible values to develop a clearer picture. The range of values analyzed is listed below:

1. Range: nominal = 7nm; range 6.75nm to 7.25nm
2. Bearing: nominal = 027 degrees; range 026.5 degrees to 027.5 degrees

Reducing this array of data results in a maximum distance from the ATC fix to the point of impact of 34.97nm and a minimum distance of 34.46nm. Dividing these values by the time taken, which is 13 minutes 11 seconds, the maximum average groundspeed becomes 159.1kt, the minimum average groundspeed becomes 156.8kt, with a mean average groundspeed of 158kt.

However, groundspeed itself is not the only parameter that must be analyzed, as the aircraft heading did not remain constant over the mission, and the wind speed and direction also should not be assumed to be constant. For wind speed two possible values are available to this analysis. The first is the calculated wind speed and direction that resulted from the aircraft steering calculations. The last recorded values from these calculations place wind speed at 30kts, and wind direction from 170 degrees True.

However, these values should be considered to be only applicable for the last minutes of the flight, and not constant over the duration. Note that these values are also consistent with the weather forecast for the immediate area of the accident, which estimated winds at 20kt at 170 degrees, gusting to 30kt.

The second is the weather forecast from Aldergrove at the start of the mission, as documented in the accident report. This placed the forecast wind speed for the local area, including the local coastal waters out to 40km (~22nm), at 12-18kts and wind direction at 150 degrees True at the surface, and 25kt and 190 degrees at an altitude of 2000ft. Based upon the last altitude update from the SuperTANS as well as the flightplan, the aircraft was likely flying at a low altitude of between 400-500ft. Consequently, the surface winds are considered to be more applicable to a calculation of average airspeed.

From the overall aircraft flight path shown in Figure 1, it can be seen that the majority of the mission, from the ATC fix up until the accident, was conducted at a constant aircraft track of 20 degrees, i.e. the bearing from the initial fix to waypoint A. Using this track, and the surface wind speed (15kt average) and direction, the groundspeed values calculated above result in average true airspeed values of 147.6kt (minimum), 150.0kt (maximum), and 148.8kt (mean). It should be noted that this range of airspeeds is somewhat higher than the generally accepted operating parameters for the aircraft, where a cruise airspeed of approximately 135kts is normally used as being optimum for both aircraft range and pilot comfort.

This range of airspeeds is consistently higher than the measured true airspeed value derived from the last steering command calculations, i.e. 135.5kt, which leads to a conclusion that the aircraft was probably flying at a relatively high airspeed until the Mull coastline was approached, at which point the aircraft slowed. Interestingly, this reduction in airspeed is countered by the increase in wind strength at the Mull, such that the net aircraft ground speed remains effectively unchanged.

3.3 Point of Impact Assessment

At first sight, there appear to be some inconsistencies in the data recorded as being “at impact”. In particular, the recorded aircraft track differs from the evidence of the wheel tracks on the ground. Similarly, the recorded groundspeed differs from the groundspeed that can be derived from the “to go” display data. Some of this, as noted above, could be due to the effects of the aircraft breaking up, since the data nominally corresponds to equipment power down, not point of impact. Other potential sources of apparent data inconsistency would be the different rates of data sampling, the effects of applied data filtering, and the latencies associated with certain display calculations, which, as would be expected, are tailored towards the lower dynamics associated with navigation maneuvers. These effects could be potentially significant, as the aircraft maneuvering associated with the last seconds of flight immediately prior to impact, and the effects of the impact itself, would have caused large dynamic variations in many of these parameters.

A particular example of the data sampling and latency effects is shown in the recorded value of GPS position at power down. The RACAL report, in paragraph 2.4.1, documents the GPS position at power down as N5518.61, W00547.80. However, the same report, in paragraph 2.9.3, shows that there was a subsequent GPS position recorded, which had not yet been processed by the SuperTANS. This position shows the aircraft at N5518.64, W00547.78, which is approximately 190 feet from the originally recorded position, at a bearing of 21 degrees. The same paragraph states that the GPS receiver updates its position once per second, and transmits that data five times per second to the SuperTANS. The SuperTANS continuously reads this input data, but only processes it once per second. Consequently, it can be surmised that the difference between the two positions is separated by 1 second, where the second value is actually closer to the "real" position at power down, and the first value is closer to the "real" position at impact. In fact, based upon this data sampling sequence, the second recorded value could describe the aircraft position as much as 1 second prior to power down, and the first recorded value, which although listed as the aircraft position at power down, could actually be as much as two seconds prior to power down.

To initiate the analysis, Figure 5(a) was constructed solely from a "triangle of velocities" as one method of determining the aircraft flight conditions at the point of impact. This shows what the aircraft track and heading would have been if the airspeed and groundspeed parameters recorded as being "at impact" were assumed to be both correct and consistent. Using the same wind speed vector as for the steering commands, the aircraft track is calculated at 28 degrees True. This has to be incorrect for two reasons: firstly it places the track of the aircraft to the right of the known bearing from the last steering command calculation to the point of impact; and secondly it does not agree with the physical evidence of the tire tracks.

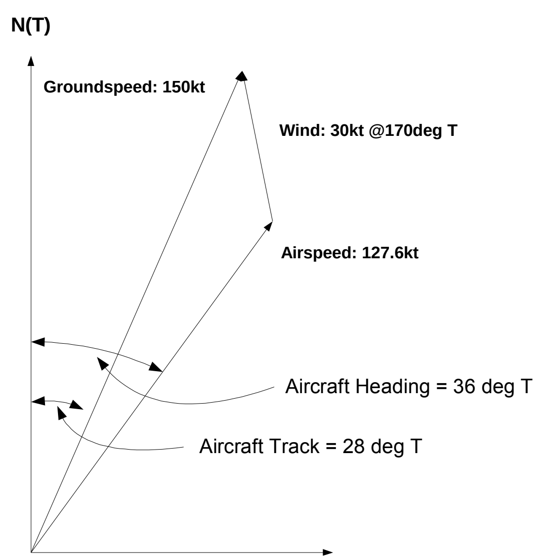

Figure 5(a). Flight Path Geometry at Impact Using Recorded Velocity Data

If, however, some different assumptions are made, a picture that is more consistent with the other available data becomes apparent. This is shown in Figure 5(b), where the assumption is that the aircraft airspeed remained relatively constant over the period from the last steering command being calculated and the point of impact. Given that the time difference between these two events is only ~0.75 seconds, and that the apparent change in airspeed would have required a deceleration over this period of ~0.6g's, this assumption seems valid. Using this airspeed, the evidence of the tire tracks, and the wind speed, an aircraft groundspeed just prior to impact of 162.8kt is arrived at, with an aircraft heading of 17 degrees T or 24.8 degrees M.

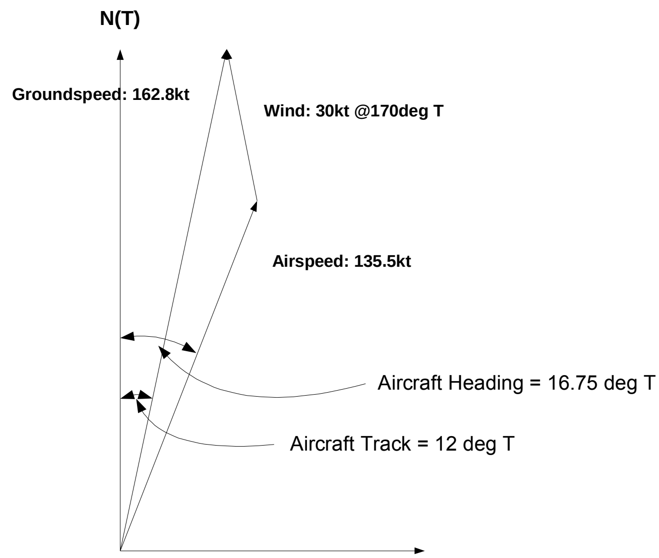

Figure 5(b). Flight Path Geometry at Impact Using Tire Tracks and Constant Airspeed

This calculated groundspeed value is consistent with the value of groundspeed derived from the last displayed values of distance to go and time to go values that were recovered from the steering display. These values were 86.7nm and 32min, respectively, which results in a groundspeed of 162.6kt, i.e. very similar to the calculated value of 162.8kt, particularly when the potential errors inherent in the resolution of the displayed data are factored in.

The effects of the data sampling, latency, and filtering described above could also explain the apparent inconsistencies between Figure 5(a) and 5(b), particularly if the filtering, etc, applied to the groundspeed measurements was different than that applied to the airspeed.

Finally, if a last second maneuver were attempted in order to avoid impact, the rapid application of aft cyclic would cause a zoom climb in which the horizontal momentum would be converted into a climb rate, and, depending upon its severity, would also result in a rapid loss of both ground and airspeed. If this explanation is applied to the difference between the recorded groundspeed of 150kt and the "calculated" groundspeed of 162.8kt, a derived instantaneous flight path angle of +23 degrees is the result. Alternatively, if the same comparison is made between the recorded and "assumed" values of airspeed are used, a derived instantaneous flight path angle of +20 degrees is reached. Both of these values correlate well with the findings of the AAIB for the probable aircraft flight path at impact. Note that a flight path angle of ~23 degrees at this airspeed requires a rate of climb of ~107 ft per second, or ~6500 ft per minute, which is clearly a non-sustainable value for the aircraft.

Note that the aircraft heading, ~25 degrees magnetic, also corresponds to the last displayed heading to steer value. However, this is most likely to be a coincidence, and not an indication that the pilot had turned to the correct heading for reaching waypoint B. This is due to the magnitude of the heading change from the last steering command value and the extremely short length of time in which it occurred, i.e. equivalent to ~19 degrees per second turn rate. The heading change is considered to be more likely due to some last moment emergency maneuvering prior to impact.

The only concern with this data, in fact, is with the indicated aircraft track and heading change over this last instant of flight. While this change appears irrefutable from the evidence, it does require that the aircraft be at a bank angle of ~35 degrees left wing down to be indicative of a normal coordinated turning maneuver, i.e. using aircraft roll and pitch controls. This angle of bank is not consistent with the reported evidence from the crash site, which indicates a bank angle of ~7 to 10 degrees left wing down. It is also not consistent with the aircraft conditions at the last steering command, where the negligible turn rate recorded implies only a small bank angle present, i.e. sufficient to balance the lateral component of the wind. The other possible cause of the heading and track change is from a large left yaw command, which would be an unusual control input at the airspeed at which the aircraft was flying, but could be also explained by the last moment attempts to avoid impact. The pedal positions noted from the aircraft wreckage do appear to show that a large left yaw command had been made, however this evidence could be a result of the impact, and thus should not be considered as conclusive.

3.4 Vertical Flight Path Assessment

Before any discussion of the vertical flight path takes place, the potential effects of the resolution of the encoding altimeter must be noted. As documented in the original Thales report, and also in a subsequent clarification, the resolution of the encoding altimeter is 100ft, i.e. the altitude is “measured” in 100ft increments. Thus when two altitudes are compared, there exists a potential for a +/-100ft error to be introduced into the calculation. The immediate discussion below does not directly address the potential effects of such an error. These potential effects will, however, be addressed in a later section.

Figure 6 shows the two pieces of data that locate the aircraft vertical flight path from the point of last altitude measurement until the point of impact. Note that the actual measured altitude at that point was not recorded, but was derived from other related parameters that were recorded. Altitudes are shown as height above sea level. Both altitudes have been corrected to height above sea level using a correction factor of 145ft that was calculated as the difference between the surveyed altitude of the crash site and the data recorded at the time of impact, i.e. 810 (ft amsl) – 665 (ft baro) = 145 ft correction. This places the nominal altitude at the last measurement at 613ft amsl (= 468ft + 145ft). Also shown is the estimated aircraft flight path angle at the time of impact. The terrain profile was copied from the profile provided in paragraph 5.5 of the AAIB Report.

The location in space of the altitude measurement position was determined as a window, based upon the time counts and the accuracy of the altitude derivation. As documented in section 2.7.b, the time count stood at 30 at the time of impact, which places the time window between 30 and 31 counts, with each count being equivalent to ~0.6 seconds. The time counts were converted into distance using a groundspeed of 158.5kt, which is consistent with both the “average” course speed and the known speed at the last steering command calculation. The near edge of the window is set at 30 counts * 0.6 seconds per count, and the far edge is set at 31 counts * 0.6 seconds per count.

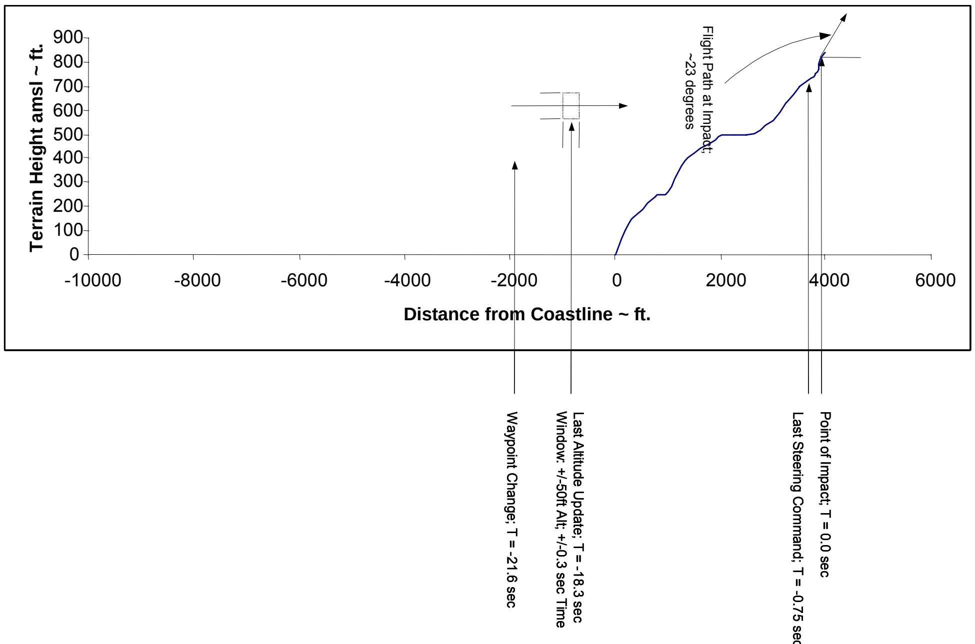

Figure 6. Vertical Flight Path Relative to Last Altitude Update

Other points shown are the aircraft position for the last steering command calculations and the position of the waypoint change selection. These latter two positions are located based upon their distances from the point of impact, which are known values. The time deltas associated with these positions were also determined using a groundspeed of 158.5kt.

The altitude of the aircraft at the last steering command position can be quickly determined to be within a range from ~740ft (the height of the ground) to 810ft (the height at the point of impact). It should be noted that tracing the 23 degree flight path angle from the point of impact back to the position of the last steering command places it at an altitude of ~730ft amsl, which is below the height of the ground at that position. This also lends credence to the conclusion that the final 23 degree flight path angle was achieved only in response to some last second control inputs.

This does not imply that the aircraft was in level flight prior to this point, rather that any prior climb rate was substantially lower. If the altitude at the last steering command position is set at 760ft amsl, as an example, the average aircraft rate of climb from the last altitude update to this position can be estimated as ~500fpm, this number then equates to a flight path angle of ~2 degrees at an airspeed of 135kt, which is not an abnormal climb rate. In total, the altitude gained from the time of the altitude update to the point of impact, using the data as recorded, is ~200ft, which effectively rules out any sustained period of high climb rate. This conclusion is also true when the potential accuracy effects of the altimeter resolution are factored in. Application of these effects essentially places a window of +/- 100ft around the height gain, i.e. the height gain could be as little as ~100ft, or as much as ~300ft, however neither of these values requires that the aircraft be climbing at an exceptional climb rate.

4 Particular Analyses

The analyses documented in the previous sections appear to provide a consistent picture of what happened during the flight. These data appear to confirm that the flight, from the time of the ATC fix from Aldergrove to the point of impact, was probably made at a true airspeed that was, on average, higher than general practice. The aircraft then slowed somewhat as it approached the landmass. The aircraft groundspeed remained essentially constant over the flight, owing to the relative effects of the prevailing winds as the aircraft transitioned from the coast of Northern Ireland to the Mull.

The data indicate that the aircraft was also following its intended flight path from take off up to the point of the selection of waypoint change from Waypoint A to Waypoint B. From that point, the data indicate that the aircraft deviated from the selected course, and in fact changed course to the right when the directed change was left.

Note that all of the analyses conducted up to this point of the report have been based solely upon available data from the crash investigation, and have not require any actual knowledge of the performance capabilities of the Chinook aircraft. The analyses were also completed without requiring any speculative assumptions to fill in for missing data. The following analyses have been conducted in order to evaluate possible flight path timelines between known conditions. These analyses do require some knowledge of Chinook performance characteristics in order to be able to assess their viability.

4.1 Airspeed Conditions at Waypoint Change

Questions have been raised with respect to the aircraft speed profile over the last portion of the mission, i.e. from the selection of the waypoint change to the actual point of impact. Specifically, could the aircraft have slowed to a hover, for example, at the waypoint change? This question can best be answered by applying known Chinook performance capabilities against the known flight data.

The distance from the waypoint change selection to the last steering command calculation is 5582ft, or approximately 0.9nm. The additional distance to the point of impact is 195ft, making the total distance from the waypoint change to the point of impact 5777ft, or 0.95nm. If the aircraft is accelerated from a hover using maximum power, at a 10 degree nose down attitude, performance curves show that it can reach an airspeed of 135kt in about 36 seconds, and will travel a distance of about 4000ft with no wind assistance. With the tailwind component that existed at the time in question, the distance traveled would increase to about 5515ft. The additional time to cover the remaining ~262ft to impact at this speed would require ~1.0 seconds of elapsed time, thus placing the waypoint change at 37.0 seconds prior to impact rather than 21.6 seconds. Note that these calculations are based on level flight acceleration data, and would be modified somewhat by any aircraft rate of climb. However, for small flight path angles, these calculations are still essentially valid.

As a consequence, it can be concluded that it is indeed mathematically possible for the aircraft to have been in a hover at the position of the waypoint change and still attain the air/ground speed values known to have existed at the time of impact. However, such a maneuver, where the aircraft first must decelerate from its cruise speed to a hover, and then accelerate again, clearly requires that the average cruise speed for the remainder of the mission be increased. Since the established average speed for the mission, in total, is already approaching the limit level flight speed, any increase is likely to require this limit to be exceeded.

The means of calculating the effects of such a maneuver on average cruise speed, using standard equations of motion, are derived as follows:

$$\text{Distance traveled} = t_c{*}v_c + d_d + d_a = 34.7 \text{ nautical miles} \quad (1)$$

$$\text{Time Taken} = t_c + t_d + t_a = 791 \text{ seconds} \quad (2)$$

where: t_c = time at average cruise speed,

v_c = average cruise speed,

d_d = distance required for deceleration to waypoint change,

d_a = distance from waypoint change to impact = 5777 feet

t_d = time for deceleration to waypoint change, and

t_a = time from waypoint change to impact

The time and distance to decelerate to the waypoint change are dependent upon the average cruise speed as follows:

$$d_d = (v_{wp}^2 - v_c^2)/2a_d \quad (3)$$

$$t_d = (v_{wp} - v_c)/a_d \quad (4)$$

where: v_{wp} = speed at the waypoint change, and

a_d = deceleration constant

Finally, the time from the waypoint change, t_a, to the impact position must be calculated based upon two constraints. First, the distance traveled must be 5777 feet, and secondly, the groundspeed at a distance of 5582 feet from the waypoint change must be 158.5kt. Consequently, the calculation of t_a is given as:

$$t_a = [5777 - (v_f^2 - v_{wp}^2)/2a_a)]/v_f + (v_f - v_{wp})/a_a \quad (5)$$

where: a_a = acceleration constant,

v_f = the speed at the steering calculations = 158.5kt, and

$(v_f^2 - v_{wp}^2)/2a_a <= 5582$ feet

Note that these calculations necessarily use groundspeed, rather than airspeed, and thus the wind speed becomes a complicating factor, not the least because the wind speed and direction is not constant over the whole period of time. For the purposes of simplification and illustration therefore, and also to be consistent with previous calculations, the wind speed will be assumed to be, on average, a constant 15kt at 150 degrees prior to the waypoint change and a constant 30kt at 170 degrees from the waypoint change until impact.

Using the acceleration example described above, where the speed at the waypoint was 0kt true airspeed, i.e. v_{wp} = 23kts groundspeed (38.8ft/sec) using the 30kt wind component, and the acceleration constant, a_a, was 6.36ft/sec/sec, then t_a becomes 37.0 seconds. Consequently, for this case, the two primary equations shown above become:

$$t_c*v_c + (38.8^2 - v_c^2)/2a_d + 5777 = 210830 \text{ feet} \quad (6)$$

$$t_c + (38.8 - v_c)/a_d + 37 = 791 \text{ seconds, or} \quad (7)$$

$$t_c = 754 + (38.8 - v_c)/a_d \quad (8)$$

Substituting for equation (8) in equation (6) results in:

$$v_c^2 + A*v_c + B = 0 \quad (9)$$

where: $A = 1508*a_d - 77.6$, and

$B = 1505.44-410106*a_d$

If a deceleration rate of 0.1g (a_d = -3.2ft/sec/sec) is applied to this equation, the resulting value for v_c is 168kt. An average cruise speed over the mission was derived in section 3. This derivation showed a mean cruise groundspeed of ~158kts over the 34.7nm from the ATC fix to the point of impact, which required a true airspeed of ~149kt when the wind effects were subtracted. This true airspeed is already approaching V_h for the aircraft, which is set by the cruise guide indicator, but is expected to be in the region of 155kt. If the groundspeed for the constant speed portion of the mission increases to 168kt, as would be required by the aircraft slowing to a hover at the waypoint change, then the corresponding airspeed must also increase to a value of 159kt, which exceeds the V_h placard.

Clearly, the assumed levels of acceleration and deceleration affect these calculations, i.e. more aggressive acceleration and deceleration rates would limit any required increases in cruise speed. The acceleration assumed above is equivalent to ~0.2g's and requires that the aircraft accelerate at a 10-degree nose down attitude, which is already considered aggressive. Higher levels of acceleration would require even more severe nose down aircraft attitudes, for example, doubling the acceleration rate to 0.4g's would require a nose down attitude of ~25 degrees, which is clearly improbable in this situation. Lesser levels of acceleration are obviously possible, but these would require that the minimum aircraft speed at the waypoint change increase significantly in order to be able to reach the final airspeed of 135kt. For example, an acceleration of 0.1g's would require a groundspeed of ~120kt at the waypoint change.

Similarly for the deceleration levels, where a higher deceleration rate would reduce the required value for v_c, while a lower deceleration rate would require a corresponding increase in v_c or an increase in the aircraft speed at the waypoint change. It should also be noted that, from pilot comments, a deceleration rate of 0.1g's would be considered aggressive for the Chinook, due to the aircraft's tendency to "balloon" during aggressive deceleration maneuvers.

To further illustrate the effects of aircraft acceleration and deceleration rates on required cruise speed, or alternatively on minimum waypoint speed, the equations provided above have been incorporated into a series of charts. These are provided as an attachment to this analysis.

In conclusion, while it is possible for the aircraft to have decelerated to a hover at the waypoint change, and then accelerated to reach the actual airspeed at the point of impact, this scenario does not pass the "common sense" test for a number of reasons. First, and perhaps most importantly, it leaves open the question as to why a pilot would bring the aircraft to a hover and then consciously accelerate towards an area of rapidly rising terrain, especially when that terrain is extensively masked by cloud or fog. Secondly, unless these deceleration and acceleration maneuvers were extremely aggressive, it would require that the remainder of the flight be conducted at speeds that are likely to exceed the aircraft speed placards. A more believable explanation of the aircraft speed profile is that the aircraft was traveling at a relatively high, constant, airspeed during the majority of the mission, and then decelerated as the landmass was approached. This explanation is certainly more consistent with the data discussed previously, which shows that the average airspeed over the complete extent of the flight was higher than the actual airspeed that was present during the last moments prior to impact.

4.2 Effects of Resolution Effects from Height Reporting

This analysis has been conducted in parallel with the simulation analysis documented in Enclosure 2. This simulation has attempted to define the immediate aircraft flight path leading up to the final impact with the ground. The measure of correctness of the simulation analysis was determined to be twofold: firstly, the ability to match the positions of the lower control actuators that were recovered from the aircraft wreckage; and secondly to match the aircraft flight path and pitch attitude at impact that were determined from the analysis of the wreckage by the AAIB. The results of that analysis determined that there are a number of aircraft initial condition sets that could result in these control positions and aircraft attitudes. Every condition evaluated required that a final pull-up maneuver be incorporated to meet the accident conditions. In general, the height attained during just this final pull-up maneuver was of the order of 100 – 150 feet, and required a maneuver duration of approximately 3.5 – 5 seconds.

The analysis has also determined a number of other parameters that could act as discriminators for determining the most likely flight path. One of these discriminators is the rate of climb of the aircraft prior to the final pull-up. The simulation showed that it was unlikely that this final pull-up maneuver was initiated from level flight. It showed that the ability to meet the measures of correctness improved as the initial climb rate was increased to 1000fpm or more. A climb rate of 2000fpm can be used as an approximate upper limit for the aircraft at an airspeed of 135kt.

Nominally, the aircraft climbed approximately 200ft in the 18 seconds from the last altitude calculation until the point of impact, which gives an average rate of climb of ~660fpm. However, this calculation does not recognize the effects of the pull-up maneuver, neither does it recognize the effects of altitude measurement errors. Consequently, the following analysis is presented as a means of trying to determine the most likely rate of climb of the aircraft at the onset of the pull-up maneuver, using the data recovered from the SuperTANS.

The aircraft pressure altitude is determined from the static pressure measured by the aircraft air data system. This pressure altitude is then corrected to barometric altitude based upon a correction factor (QNH) input by the flight crew.

The height recorded by the SuperTANS at power down differed significantly from the surveyed height corresponding to the point of impact. The recorded pressure altitude was 1100ft. Using the QNH entered by the flight crew, this pressure altitude converts to a barometric altitude of 665ft, which differs from the surveyed crash site altitude of 810ft. This difference was explained in detail in the response prepared by Thales to a question generated from the Mull of Kintyre Select Committee. This response identified that the difference of 145 feet between the SuperTANS baro-compensated reading at power down and the surveyed altitude could be attributed to three sources:

i. The accuracy of the pressure altitude measurement: +/-50ft
ii. A potential difference between the entered and actual QNH: +/-29ft
iii. The potential effects of the altimeter resolution: -100ft

The only other source that provides information about the altitude of the aircraft is embedded in the stored values of the surface winds. This was also discussed in the original RACAL report, firstly in section 2.8.9 and in more detail in section 4. This source places the aircraft barometric altitude at 468ft approximately 18 seconds before impact. It should be noted that this value is also potentially corrupted by the same error sources as listed above.

In determining the aircraft vertical flight path prior to impact, however, only the relative altitude change is truly of interest. Therefore, those error sources that are not strictly random or time dependent are not germane to the analysis. This essentially removes errors due to sensor accuracy and entered QNH from the equation.

Thus, two conditions set the start and end points of the final 18 seconds of the aircraft vertical flight path as follows:

- Start – barometric altitude = 468ft (minimum), 567ft (maximum)
- End – barometric altitude = 665ft (minimum), 764ft (maximum)

Consequently, the altitude gained could be as little as 98ft, or as much as 296ft. However, the lower value is effectively negated by the results from the simulation described above, since these require a minimum altitude gain of ~100ft for the pull-up maneuver and essentially disbar a maneuver entry from level flight.

Figure 7 illustrates these vertical flight path constraints with respect to the terrain contour from the coastline to the point of impact. The terrain contour is the same as was used in Figure 6, except that now two windows are included. In addition, the horizontal scale is now presented in terms of time to impact, in seconds, rather than in feet. This conversion was made using a constant groundspeed of 158.5kt. Use of the time scale is considered to be more valuable than the distance scale in illustrating visually the rapid onset of events.

The first window boxes the possible range of aircraft altitudes at the last altitude update point. This window height is shown as being relative to the final impact point, i.e. the lower edge of the window is 296ft below the final impact point and the upper edge is 98ft below the impact point, using the measurement resolution analysis shown above. This is in comparison to the equivalent window from Figure 6, which showed the altitude accuracy only in terms of sensor measurement accuracy, i.e. +/-50ft. As before, the window width is shown as 0.6 seconds, with the window nominally placed at 18 seconds prior to impact.

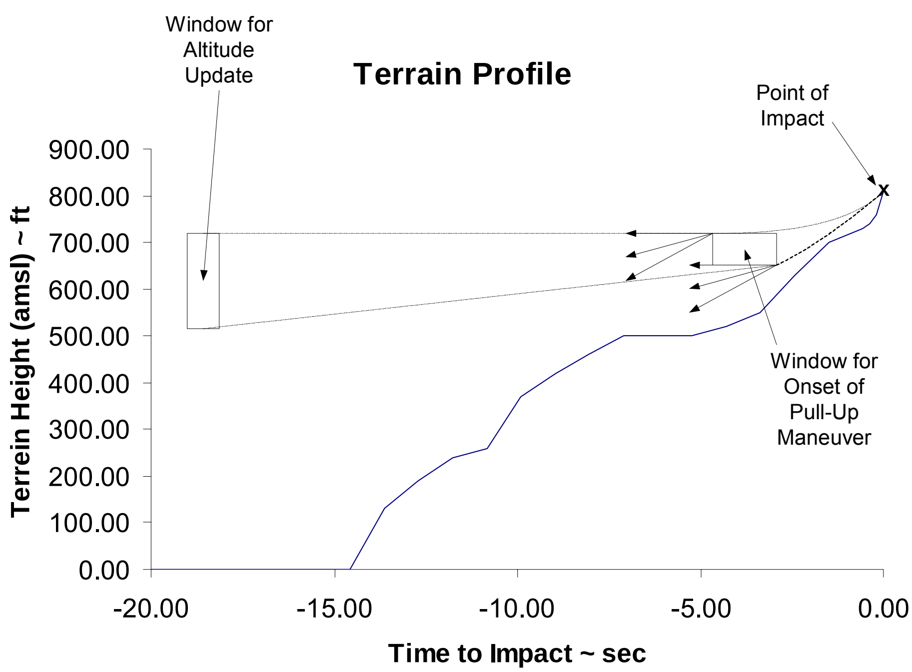

Figure 7. *Vertical Flight Path*

The second window boxes the range of entry points for the final pull-up maneuver, based on the results of the simulation as described above. The lower edge of the window is 150ft below the final impact point, and the upper edge is 100ft below. The width of the window extends from 3.5 to 5 seconds from impact. There are fan indications at two of the corners of this window. These indicate the angles associated with the entry flight path into the window being at 0, 1000, and 2000 feet per minute, respectively. For further illustration of the final pull-up maneuver, the corners of this window are connected with curved flight paths to the final impact point.

As can be surmised from this illustration, it is unlikely that the aircraft climb rate entering the "pull-up" window was much in excess of 1000fpm. For example, if the aircraft entered the window at its top edge at a climb rate of 2000fpm, it would probably be capable of clearing the terrain without having to initiate the pull-up maneuver. This possibility is also countered by other evidence, i.e. maintaining a climb rate of 2000fpm at an airspeed of 135kt requires that maximum power be applied to the rotor, and the evidence from the aircraft wreckage appears to show that the engines were not at maximum power at the time of impact.

The terrain features effectively preclude the aircraft from entering the window at the lower edge with a sustained climb rate of 2000fpm. However, it is possible that the aircraft was maintaining an essentially level flight path until approximately 7 seconds before impact, at which point the flight crew would have received an altitude warning from the radar altimeter, which was reportedly set at 69ft for one of the two instruments. The flight crew would be expected to then initiate a climb maneuver, which could place the aircraft at the lower edge of the window with a climb rate of 2000fpm or more. However, this explanation must also be tempered with the knowledge that the engines were not at maximum power at impact, whereas the flight crew would be expected to have commanded maximum engine power in conjunction with this initial climb command. This reasoning also does not explain why the flight crew would have been maintaining a level flight path with the knowledge that they were approaching rising terrain.

In discussing the probability of a low altitude warning being received from the radar altimeter, the anomaly raised by the AAIB where the radar altimeter could intermittently lose the ability to track the ground at terrain closure rates greater than ~100ft/sec should be addressed. Terrain closure rates are a result of the combination of aircraft climb or descent rate and the rate of change of terrain height with respect to the aircraft speed over the ground.

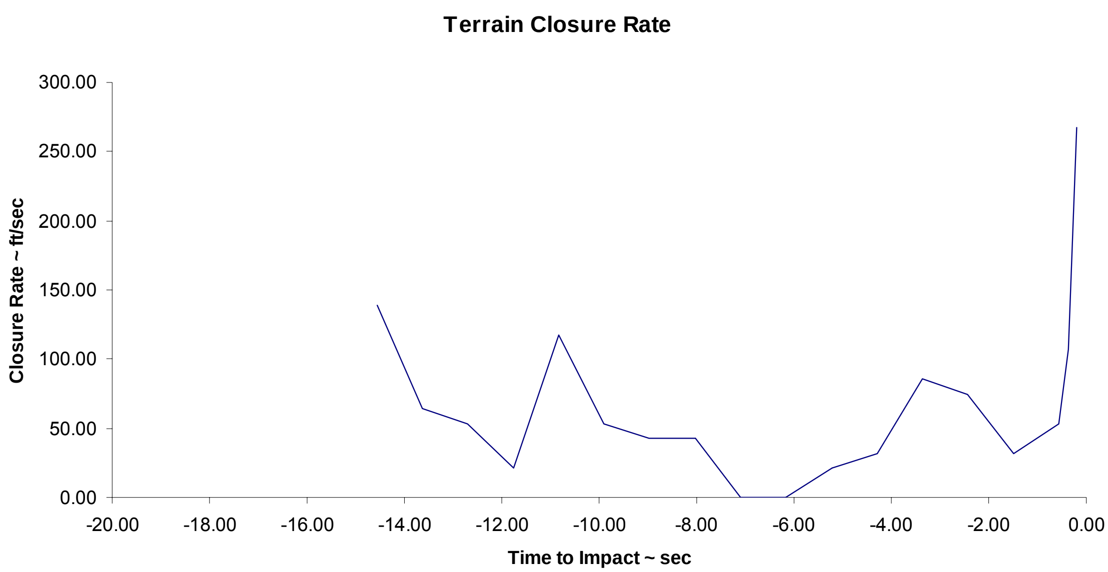

Figure 8. Terrain Closure Rate

Figure 8 shows the terrain closure rate that would be generated from the terrain profile shown in Figure 7. This closure rate is for an aircraft maintaining level flight with respect to the terrain, and again is shown versus time to impact. The effective closure rate is reduced by the aircraft climb rate: a climb rate of 500ft/min would reduce the closure rate by 8.33ft/sec and a climb rate of 1000ft/min would reduce the closure rate by 16.67ft/sec. Applying these factors to Figure 8, it can be seen that, although there are potentially some transient conditions where the net closure rate exceeds 100ft/sec, in the main the net value is less than this. Thus, the anomaly in radar altimeter performance detected by the AAIB should not have prevented a low altitude warning from being generated.

Consequently, the most likely explanation is that the aircraft was following a climbing flight path as it entered the pull-up window, at which point either the terrain was visually acquired, or the radar altitude warning was tripped, at which point the pull-up maneuver was initiated. The likely climb rate entering the window would have been in the order of 1000fpm, which can be maintained at an airspeed of 135kt without using maximum power. This sequence of events also provides an explanation for the engine power setting, where full collective would have been applied as a part of the pull-up maneuver, but there was insufficient time for the engines to spool up to maximum power prior to impact.

4.3 Effects of GPS Errors and Waypoint Entry Truncation

The previous two sections address issues related to the aircraft speed profile and vertical flight path profile. This section addresses some issues related to the horizontal flight path profile.

It is generally accepted that Waypoint A entered into the SuperTANS was intended to be the location of the lighthouse at the Mull. However, the longitude entered for the waypoint was in error in that the value entered was W00548.00, whereas the true position of the lighthouse was documented in the accident report as being ~0.15nm further to the west. If the directed course had been followed all the way to the selected waypoint, this error would place the aircraft further to the east, i.e. closer to the higher ground.

Similarly for the effects of any GPS errors. The AAIB established, using a handheld GPS and surveying measurements, that the actual point of impact was 0.15 minutes of longitude further to the east than that reported by the aircraft GPS. This error, which is equivalent to ~0.08nm, would also cause the aircraft to follow a flight path that is further to the east than intended. However, determination of the true impact of this error is prone to the same difficulties with establishing the differences in the recorded aircraft data between conditions at impact and conditions at power down.

The sum total of these errors would place the aircraft further into the coastline than intended. However, the flight crew had selected the change to Waypoint B prior to reaching Waypoint A, and, if the directed course had been followed from the waypoint change, the aircraft would probably have cleared the immediate terrain at landfall, albeit with minimal clearance. If a climb rate of ~1000fpm had been maintained, the aircraft would also clear the higher terrain that was approaching.

In light of the actual flight path that was followed, however, this discussion becomes moot. For, as shown in the previous discussions, instead of turning left to follow the directed course of ~12 degrees True to Waypoint B, the flight crew elected to turn right on a course of 26 degrees True. At the aircraft position corresponding to the last steering command calculation, the cross-track error to the directed flight path would have been ~0.16nm. This turn should not be considered as being the consequence of allowing the flight path to drift, as there was a clear aircraft heading change made, and the heading change was into the wind, rather than with the wind, which would have been more likely if the turn was purely due to drift. Consequently, the real issue that should be addressed with respect to the aircraft horizontal flight path is why this right turn was made.

A possible answer can be determined from the setting of the TACAN Control Unit (CU), this was set to Channel 107x, which is the channel for the TACAN beacon at RAF Macrihanish. If the flight path of the aircraft is extrapolated from the position of the aircraft corresponding to the last steering command calculation, along the course it was then following, the flight path arrives at RAF Macrihanish, although not on a direct course to the TACAN beacon. This information provides a possible explanation for the right turn, but does not explain why this turn was made. It is possible that the flight crew had determined from the existing weather conditions that continuation of the flight plan under VFR rules was no longer possible, and that they were transitioning to IFR conditions using the Macrihanish beacon for direction. Certainly, making this turn placed the aircraft flight path across the highest points of the local terrain, with the sectional map showing the terrain rising to ~1500ft before it descends at Macrihanish.

5 Conclusions

The data related to the Mull of Kintyre crash investigation has been evaluated for correctness, and a number of analyses performed in order to develop a coherent picture of the aircraft flight path from takeoff until the point of impact with the Mull. This data has been assembled from a number of different sources, such that any data inconsistencies would be expected to become apparent as the analyses are conducted.

In general, there is a high degree of consistency in the data evaluated. Some minor inconsistencies were established in the data retrieved from the SuperTANS related to aircraft conditions at impact, or power down. These inconsistencies were satisfactorily explained as being attributable to the “sampled data” effects inherent on the operation of the unit, and had no impact on the ability of this report to develop a coherent definition as to the most probable timeline for the aircraft flight path.

It was concluded that the flight was proceeding as planned until the aircraft neared the first entered waypoint, Waypoint A. The selection of the new waypoint, Waypoint B, was made some distance prior to Waypoint A actually being reached. This is considered normal, as the SuperTANS is conditioned to provide the flight crew with a Leg Change Alert prior to reaching the waypoint location. However, instead of following the directed course to the new waypoint, which would have required a left turn, the flight crew made a course correction to the right. In addition to being in conflict with the directed course to the next waypoint, this course change also oriented the aircraft flight path more directly towards the Mull.

An average ground speed for the flight, from the Aldergrove ATC fix until the point of impact, was determined by simply dividing distance traveled by time taken. This ground speed was converted to true airspeed by correcting for the effects of wind. The resulting value for average true airspeed was at the higher end of the normal cruise airspeed range.

A more precise, local, value of true airspeed just prior to the point of impact was determined from data retrieved from the SuperTANS that was related to the last steering calculations the unit had performed. This value was lower than the average value determined from the time and distance calculations, and was more consistent with the airspeed value normally used for a cruise climb profile. This leads to a conclusion that the airspeed was reduced as the landmass of the Mull was approached; from a relatively high cruise airspeed to a more normal airspeed as a cruise climb was initiated. It was also determined from the same set of data that, even with this lower airspeed, the aircraft ground speed remained essentially constant as the aircraft approached the Mull. It was concluded that this was due to the effects of the increase in wind strength at the Mull when compared with the wind strength over Northern Ireland and during the sea crossing.

A more detailed analysis was conducted to determine if it was possible for the aircraft to slow dramatically at the waypoint change whilst remaining within the overall mission time constraints. It was concluded from this analysis that any large variations in airspeed during the mission are generally precluded by the compensating actions that would have been necessary to achieve the high average mission speeds. These compensating actions would have required overly aggressive decelerations and accelerations to and from the waypoint change, as well as requiring cruise speeds for the remainder of the mission that would probably exceed the aircraft level flight speed placards. It was also concluded that such an aggressive acceleration towards the Mull would have been highly unusual, given the proximity of the waypoint change to the landmass and the fact that the landmass was, at least partially, obscured by clouds.

Finally, a determination was made of the climb rate that was established by the aircraft as it approached the Mull. It was concluded, that up until the last seconds of the flight, the average climb rate was insufficient to clear the terrain. This was made worse by the unexplained course change to the right that had been made, which placed the aircraft flight path over the area of highest local terrain. An emergency pull-up maneuver was attempted in the final seconds, but it was initiated too late to avoid impact.

Attachment A - Effects of Speed Variations at Waypoint Change

This attachment is provided as an expansion of the analysis presented in Section 7(a), which addressed the possibility that the aircraft slowed as the waypoint change was made and then accelerated to the final speed reached at impact.

The following figures illustrate the effects of the aircraft acceleration from a minimum speed at the waypoint change to the final speed just prior to impact. These calculations describe the results from equation (5), and also reflect that the minimum groundspeed at the waypoint change of 23kt, based upon the wind speed contribution.

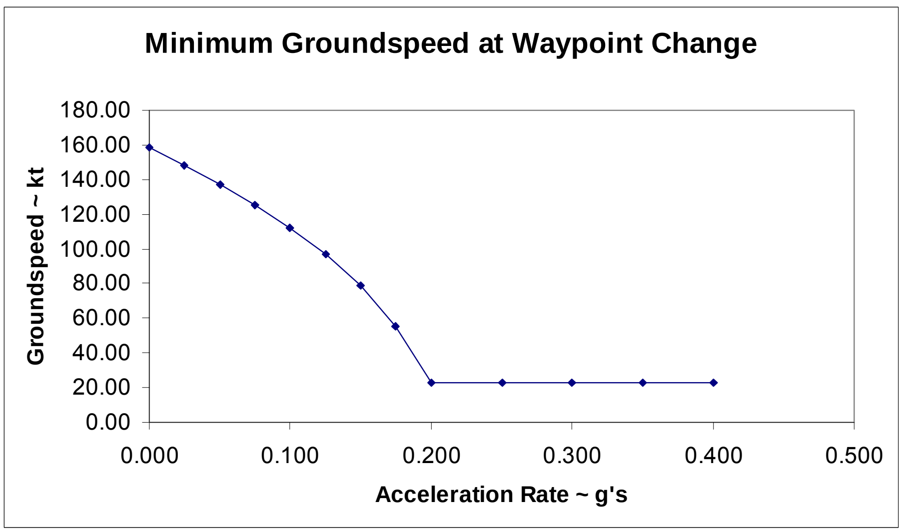

Figure A1

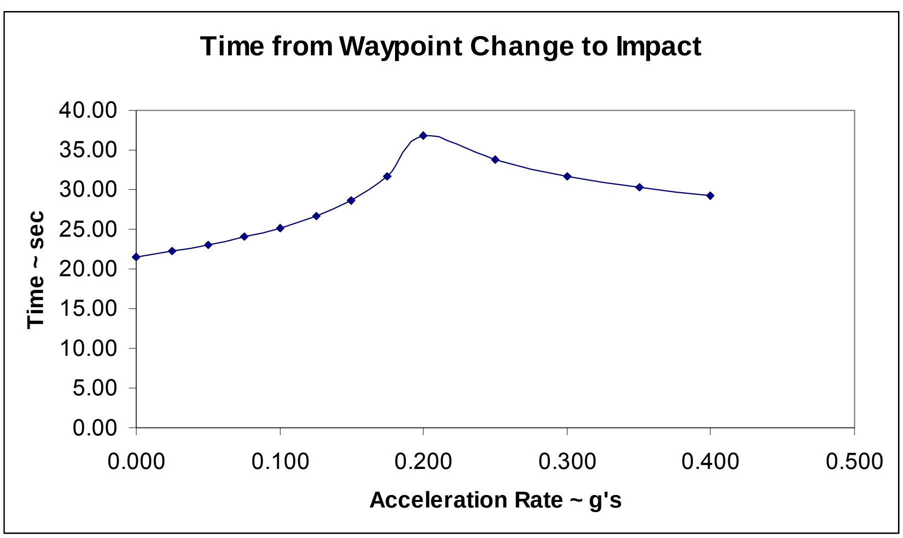

Figure A2

Note that the maximum time from the waypoint change to impact coincides with the minimum acceleration for which the minimum groundspeed at the waypoint change corresponds to the aircraft being at zero airspeed. The minimum time coincides with the aircraft traveling at constant speed from the waypoint change to impact.

The following figures illustrate the cruise groundspeed required versus speed at the waypoint change for a variety of aircraft acceleration and deceleration rates. Again, the minimum groundspeed at the waypoint change is shown as 23kt, which is the wind speed component assuming a wind of 30kt at 170degrees.

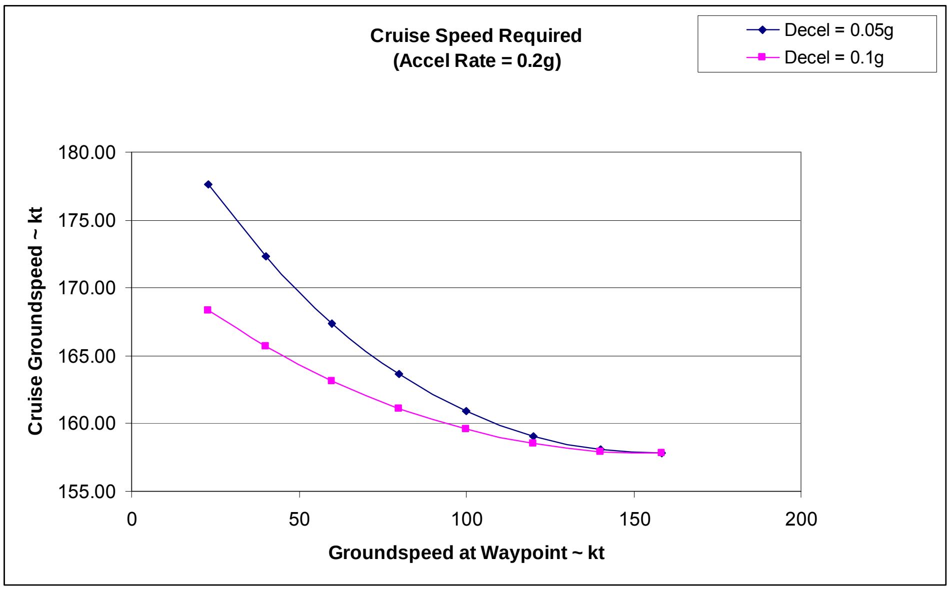

Figure A3

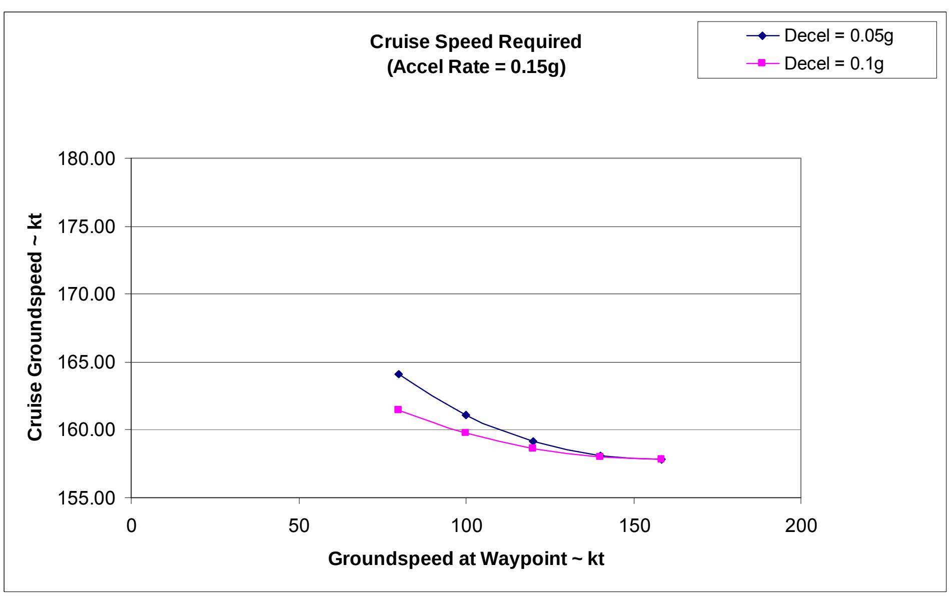

Figure A4

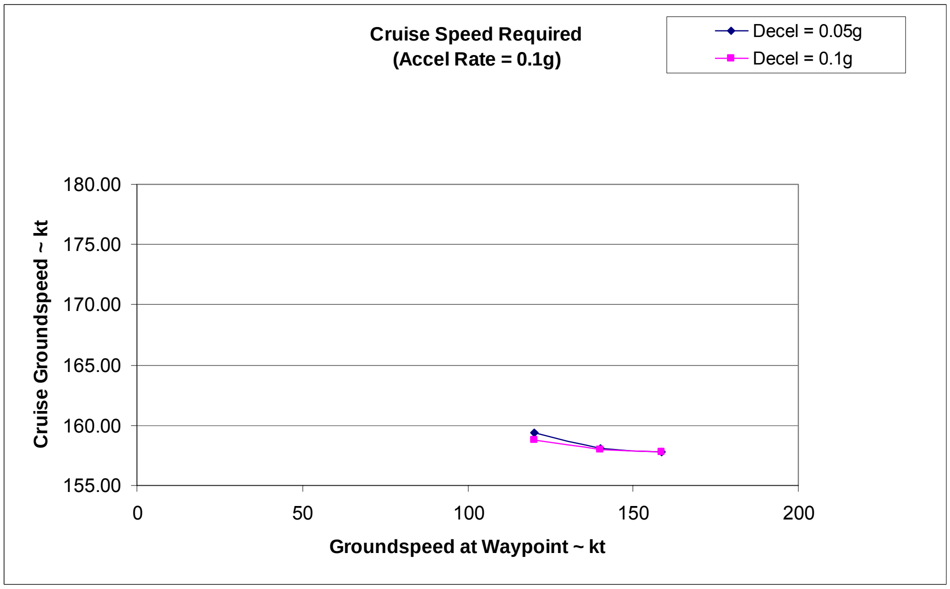

Figure A5

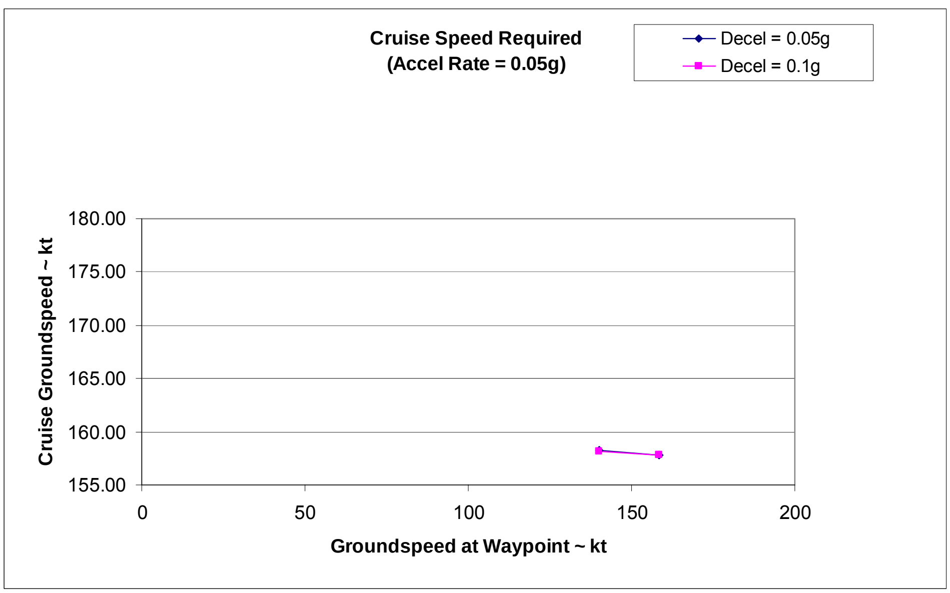

Figure A6

It can be seen that the curve of cruise groundspeed versus the groundspeed at the waypoint change is not significantly affected by acceleration rate. This is because, as seen in Figure A2, the variations in time required to cover the distance from the waypoint change to the impact point are not sufficient, in a relative sense, to affect the cruise speed calculations. Specifically, the variation is approximately 15 seconds between minimum and maximum times. Relative to the total ATC fix to impact flight time of ~800 seconds, this variation is equal to less than 2 percent of the total.

In reviewing the data, it can be clearly seen that the number of conditions that satisfy all constraints shrinks dramatically as the acceleration rate reduces. This is because, as seen in Figure A1, the aircraft cannot attain the final groundspeed at impact with a low acceleration rate unless there is an appreciable groundspeed at the waypoint change.

Similarly, if these cruise groundspeed values are reduced by ~ 9kt to account for the wind speed contribution over the cruise portion of the flight, it can also be seen that many of the high acceleration rate conditions will fail the maximum airspeed limit, i.e. airspeed values of ~155kt and greater are in excess of the aircraft level flight speed limits.

Consequently, it can be determined from this data that the possibility of the aircraft being at a hover (zero airspeed) at the waypoint change is highly unlikely, unless the deceleration and acceleration maneuvers were aggressive, or unless the aircraft level flight speed placards were exceeded during other portions of the flight.

In summary, this data supports the contention that the majority of the flight was performed at an essentially constant speed that tended towards the higher end of the normal cruise speed range. As the aircraft approached the landmass, this speed reduced to a value more consistent with the aircraft initiating a cruise climb profile.