National Transportation Safety Board
Office of Research and Engineering
Washington, D.C. 20594

Performance Study

Specialist Report
Marie Moler

A. ACCIDENT

Location:	Cleveland, Ohio
Date:	December 29, 2016
Time:	2257 EST, (0357 UTC, December 30, 2016)
Airplane:	Cessna 525,
NTSB Number:	CEN17FA072

B. GROUP

No vehicle performance group was formed.

C. SUMMARY

On December 29, 2016, at 2257 eastern standard time, a Cessna model 525C (Citation CJ4) airplane, N614SB, was destroyed on impact after descending into Lake Erie shortly after takeoff from runway 24R at the Burke Lakefront Airport (BKL), Cleveland, Ohio. The pilot and five passengers died. The airplane was registered to Maverick Air LLC and operated by the pilot under the provisions of 14 Code of Federal Regulations Part 91 as a personal flight. Night visual meteorological conditions prevailed for the flight, which was operated on an instrument flight rules (IFR) flight plan. The intended destination was the Ohio State University Airport (OSU), Columbus, Ohio.

D. PERFORMANCE STUDY

The aircraft was equipped with ADS-B (automatic dependent surveillance – broadcast), which recorded the time, the airplane's latitude and longitude, altitude, inertial speed, and other parameters. The ADS-B sampling was irregular, but position was sampled approximately once a second. ADS-B recorded pressure altitude[1], the barometric correction, and geometric altitude[2]. Altitude shown in this report will be the corrected altitude relative to mean sea level (MSL), which closely agreed with the geometric altitude up to 2,500 ft MSL. ADS-B also recorded selected altitude and selected heading parameters.

The airplane had a cockpit voice recorder (CVR), but no flight data recorder (FDR).

Weather Observation

The Meteorological Terminal Aviation Routine Weather Report (METAR) for BKL at 2245 EST was 33°F with 23 kts winds from 260° gusting to 32 kts. Visibility was six statute miles with a broken ceiling at about 1,900 ft MSL. Light snow was reported with no accumulation in the last hour. Altimeter setting was 29.73 inHg. A sounding conducted at 2300 EST for the airport reported winds and temperatures aloft which are shown in Table 1.

Table 1. Winds and temperatures aloft

Height (ft-MSL)	Pressure (mb)	Temperature (C)	Wind direction (deg)	Wind magnitude (kts)
587	987	1.1	278	17
627	986	1	278	17
732	982	0.8	278	23
951	973	0.4	278	27
1339	959	-0.4	279	29
1923	938	-1.5	280	31
2621	913	-4.4	281	32
3543	881	-6.2	287	33

Accident Flight

The flight path shown in Figure 1 and Figure 2 began at 22:56:47 and ended at 22:57:52 for a total recorded flight of 65 seconds. The elevation of runway 24R is 583 ft and ADS-B corrected altitude

[1] ADS-B recorded the pressure altitude, geometric altitude, and a barometric correction in feet. The barometric correction correlated with an altimeter setting of 29.7 inHg. Altitudes used in this report are barometric corrected altitude.

[2] Altitude parameters had a 32 bit limitation to what they recorded. For instance, an altitude of 2,000 ft would be recorded as 2,016 ft.

was recorded to the nearest 25 ft. The earliest recording on the runway showed about a 20 ft inaccuracy in the altitude[3]. The airplane had been instructed to fly at an altitude of 2,000 ft and a heading of 330° by air traffic control (ATC). The average surface elevation of Lake Erie is 570 ft, but that elevation will vary with location, weather, and season [1].

Figure 1. Flight path with time and altitude for selected points.

[3] The airport elevation is 583 ft and the ADS-B recorded altitude was 544 ft. Adding 25 ft still results in an altitude lower than the airport elevation by about 20 ft.

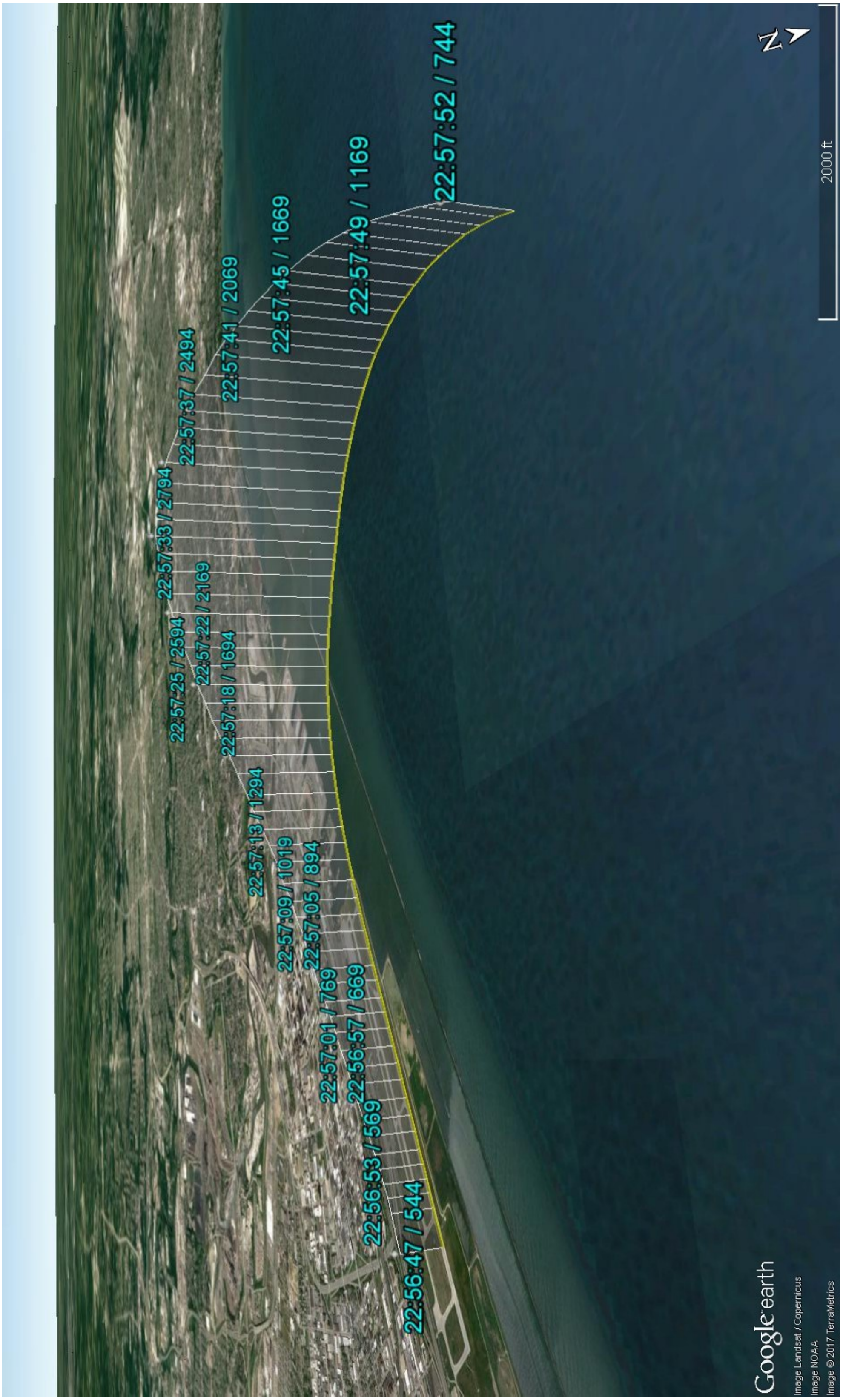

Figure 2. Flight path with time and altitude for selected points.

Speeds (Figure 3) were calculated from the airplane's location, altitude, and the winds aloft data provided. The airplane accelerated from take-off to about 215 kts airspeed as it passed over the end of the runway. The speed then leveled off until 22:57:29 when the airplane reached its maximum altitude of 2,893 ft. The airplane then began to rapidly descend and gain airspeed. The final ADS-B record at 22:57:52 was an altitude of 744 ft and the calculated airspeed was 300 kts.

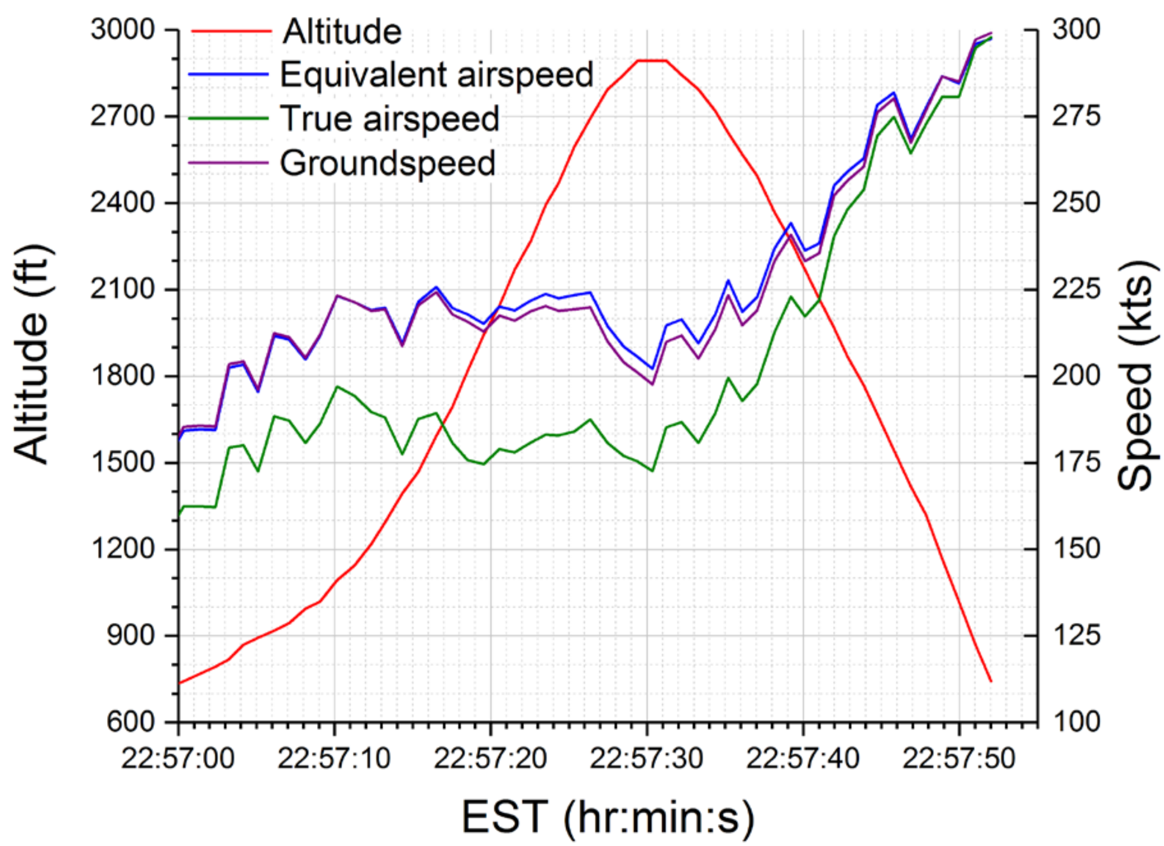

Figure 3. Altitude and calculated air and groundspeeds versus time.

Figure 4 shows the calculated rate of climb for the take-off and descent. The maximum rate of climb was over 6000 ft/min.

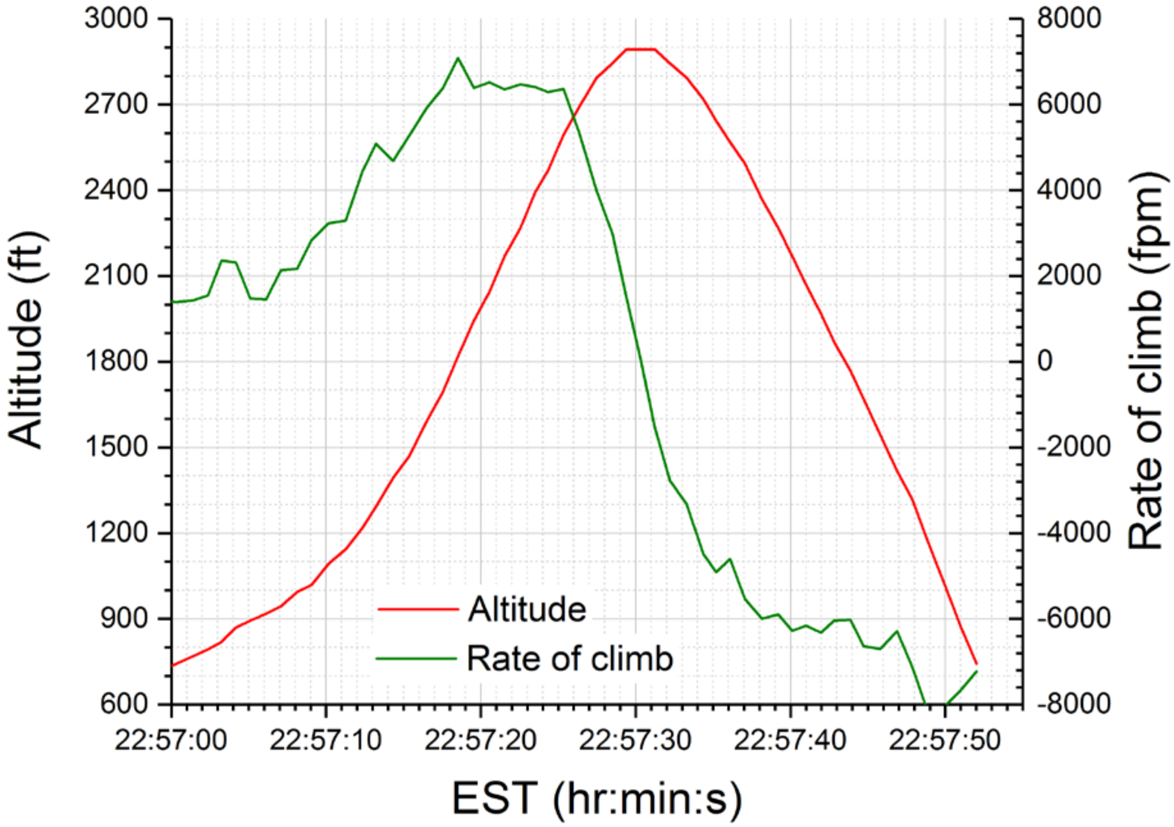

Figure 4. Altitude and calculated rate of climb versus time.

Figure 5 shows the airplane's path in Easting and Northing with the 330° heading that had been instructed by ATC noted. The airplane passed the 330° heading at about 22:57:37. At this point the airplane was descending below 2,500 ft and its speed was increasing.

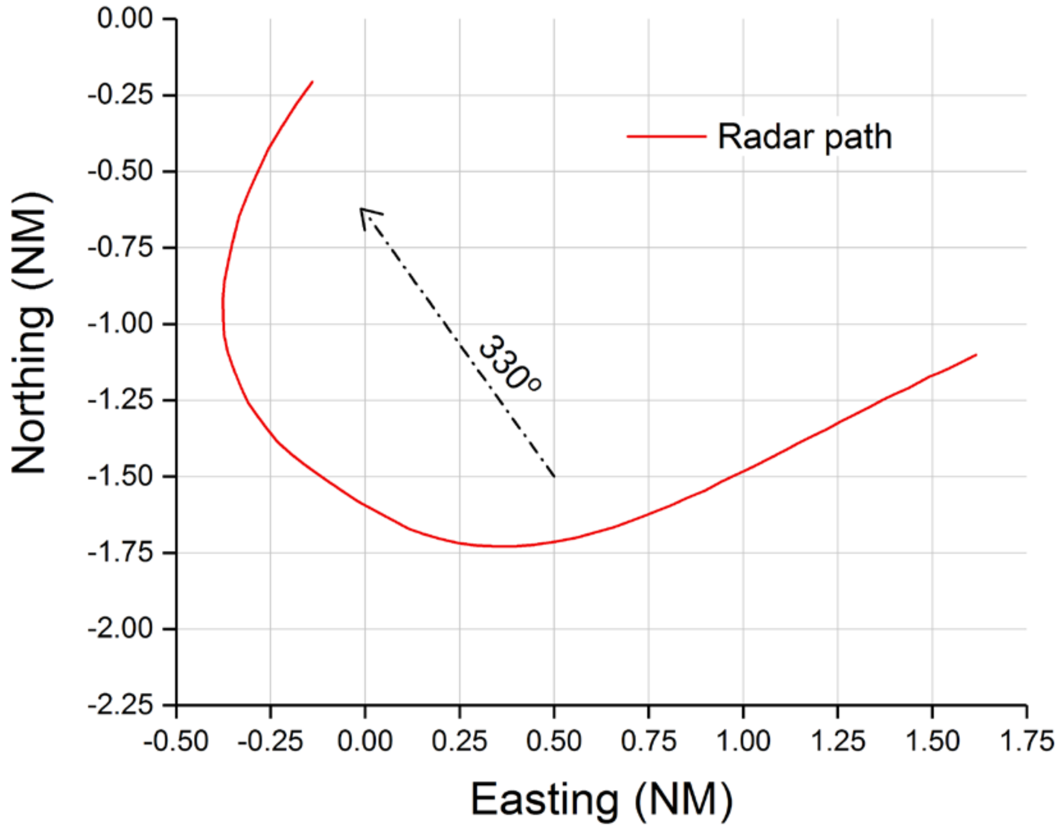

Figure 5. Radar path in Easting and Northing with 330° heading shown.

Airplane pitch and roll were calculated using a simplified aerodynamic model of the airplane and are shown in Figure 6. The airplane was increasingly nose up until 22:57:24. The airplane then rapidly pitched nose down and stayed nose down until the end of the recorded data. The airplane's right roll started shortly after take-off, reaching a maximum 62° right wing down at about 22:57:31. The airplane began to roll back toward wings level, but the last calculated bank angle was 25° right wing down.

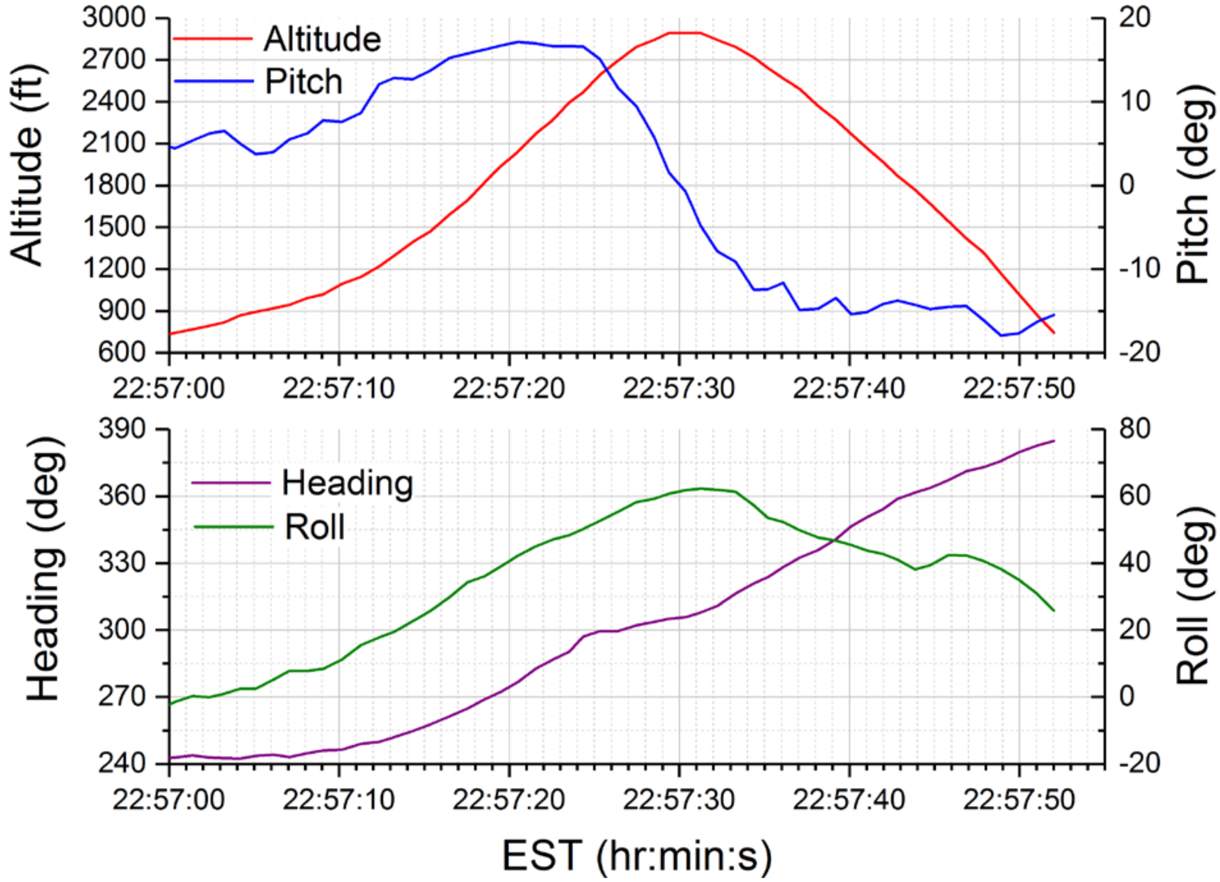

Figure 6. Airplane altitude and calculated pitch, heading, and roll.

CVR and Cockpit Annunciations

During the flight, the autopilot system and terrain avoidance warning system (TAWS) annunciated warnings, the tower contacted the airplane, and the pilot spoke. This information is documented in the Cockpit Voice Recorder transcript in full [2].

The Citation's autopilot system was installed to voice "ALTITUDE" 1,000 ft prior to a selected altitude and again if the airplane deviated over 300 ft past the selected altitude [3]. Two "ALTITUDE" annunciations were heard on the CVR: the first was at the CVR recorded time of 22:57:09.4 and the second at 22:57:23.4. The pilot's initial instruction was to turn right onto 330° and to maintain 2,000 ft and ADS-B recorded a selected altitude of 2,000 ft. For a selected altitude of 2,000 ft, the system would annunciate at 1,000 ft and 2,300 ft. Figure 7 shows the two "ALTITUDE" annunciations from the CVR and the ADS-B recorded altitudes. Both annunciations come less than 0.5 seconds after the airplane passed the 1,000 and 2,300 ft altitude marks. It was determined that the time recorded by the ADS-B and the CVR were in good agreement, assuming the autopilot annunciation had a short delay.

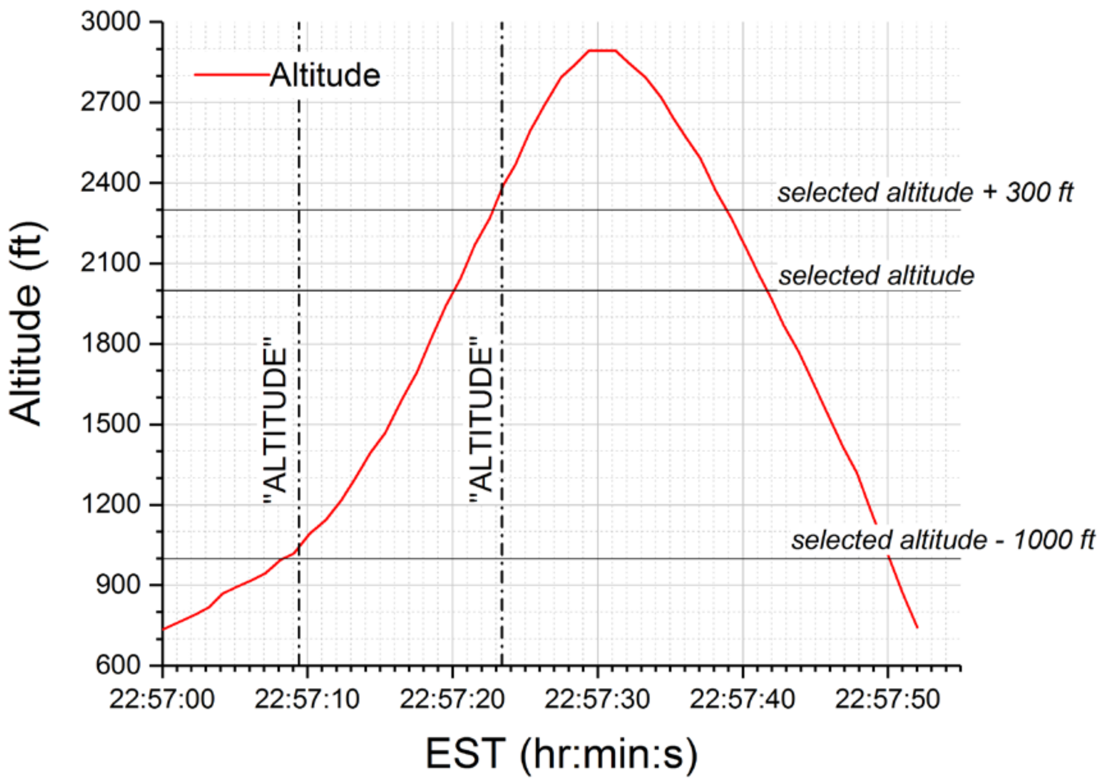

Figure 7. CVR “ALTITUDE” annunciations and ADS-B altitude.

ADS-B data also recorded selected heading which changed throughout the climb portion of the flight. The configuration of the input data is not known, but it was confirmed to the NTSB by Rockwell Collins that changes in the parameter indicated active pilot selection as the other avionics could not have changed the value of that parameter. Figure 8 shows four selected headings in yellow. The yellow line points towards the heading selected and intersects the flight path at the point in time when it was recorded. The last yellow line along the flight path is on the 330° heading.

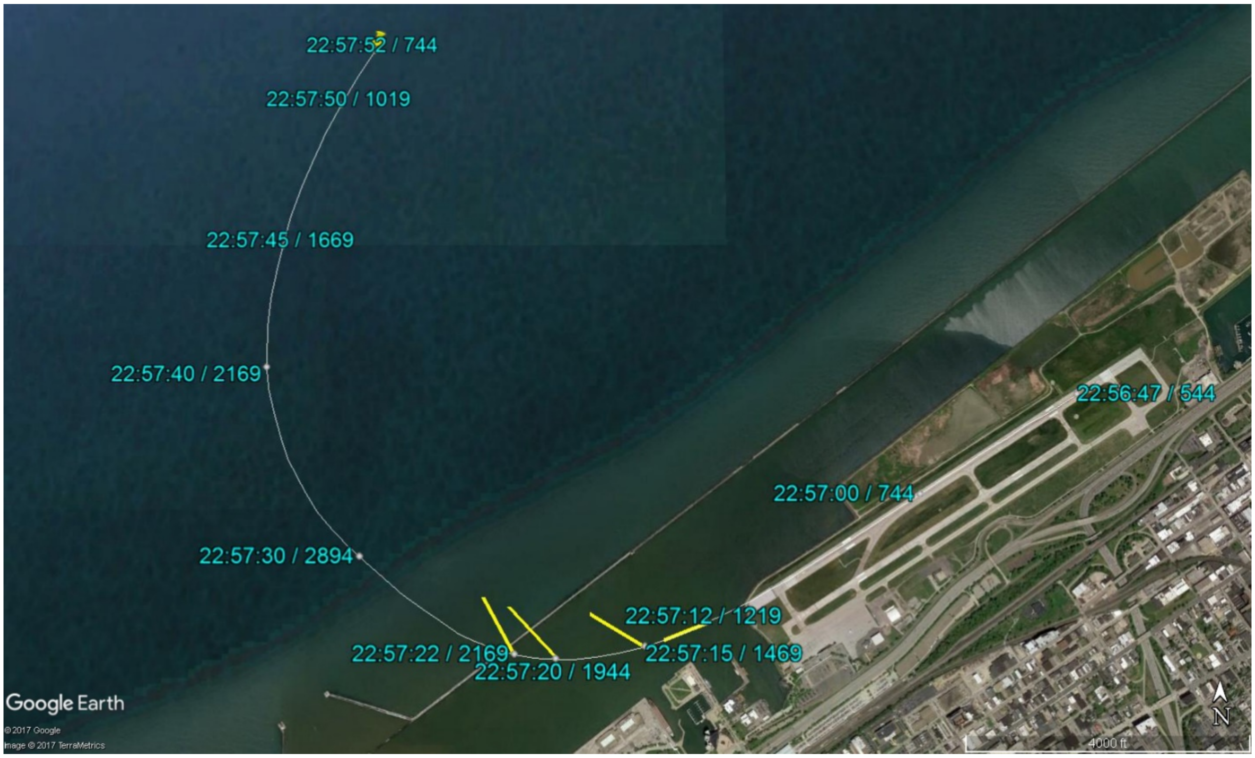

Figure 8. Selected heading shown as yellow lines at time of change/selection. The yellow line points towards the heading selected and intersects the flight path at the point in time when it was selected.

Figure 9 shows the calculated bank angle and altitude versus time. On the CVR, an automated annunciation of "BANK ANGLE" was heard at 22:57:27.2. According to the documentation for the ground proximity warning system (GPWS) warnings and cautions [3], the automated bank angle warning annunciates when the airplane reaches a bank angle greater than 55°[4]. This is consistent with the calculated bank angle, which surpassed 55° at 22:57:26. The peak roll angle was calculated to be 62° right wing down at about 22:57:31, about four seconds after the "BANK ANGLE" annunciation.

[4] This callout alerts the pilot to excessive bank angles. The bank angle that causes this alert varies linearly from 10° at 30 feet AGL to 40° at 150 feet AGL to 55° at 2,450 feet AGL.

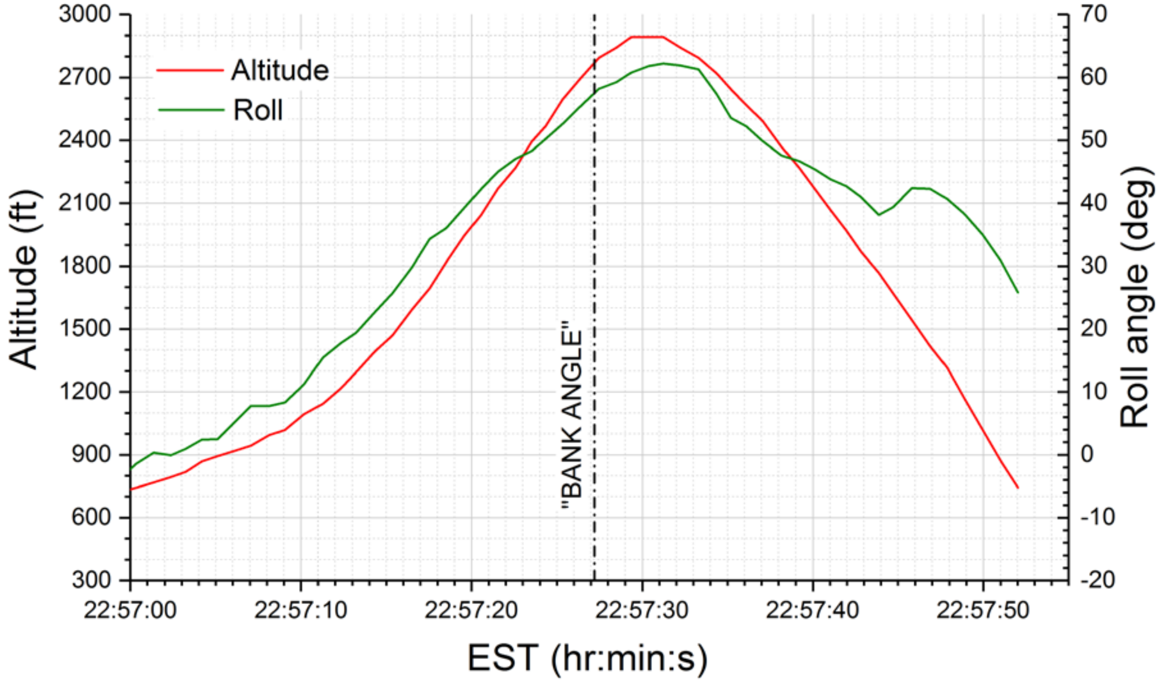

Figure 9. Altitude and roll versus time with bank angle call out from CVR.

Figure 10 shows all the annunciations and comments internal to the cockpit during the flight. The two "ALTITUDE" annunciations were followed by a sound consistent with a decrease in engine power two seconds later. The "BANK ANGLE" annunciation followed. ATC called (at 22:57:28.6 and 22:57:37.1) and the pilot spoke twice during the flight (at 22:57:30.8 and 22:57:39.7), in apparent response to radio calls from the tower, but the microphone was not keyed to transmit. At 22:57:39.1 there is an annunciation for "SINK RATE" which coincides with the rate of climb falling below -6,000 fpm and an altitude of 2,250 ft (Figure 4). Starting at 22:57:43.6, the TAWS annunciated "PULL UP" seven times, the last at 22:57:53.1. From 22:57:46.2, when the airspeed increased past 275 kts, until the end of the recording there was a sound similar to an overspeed warning.

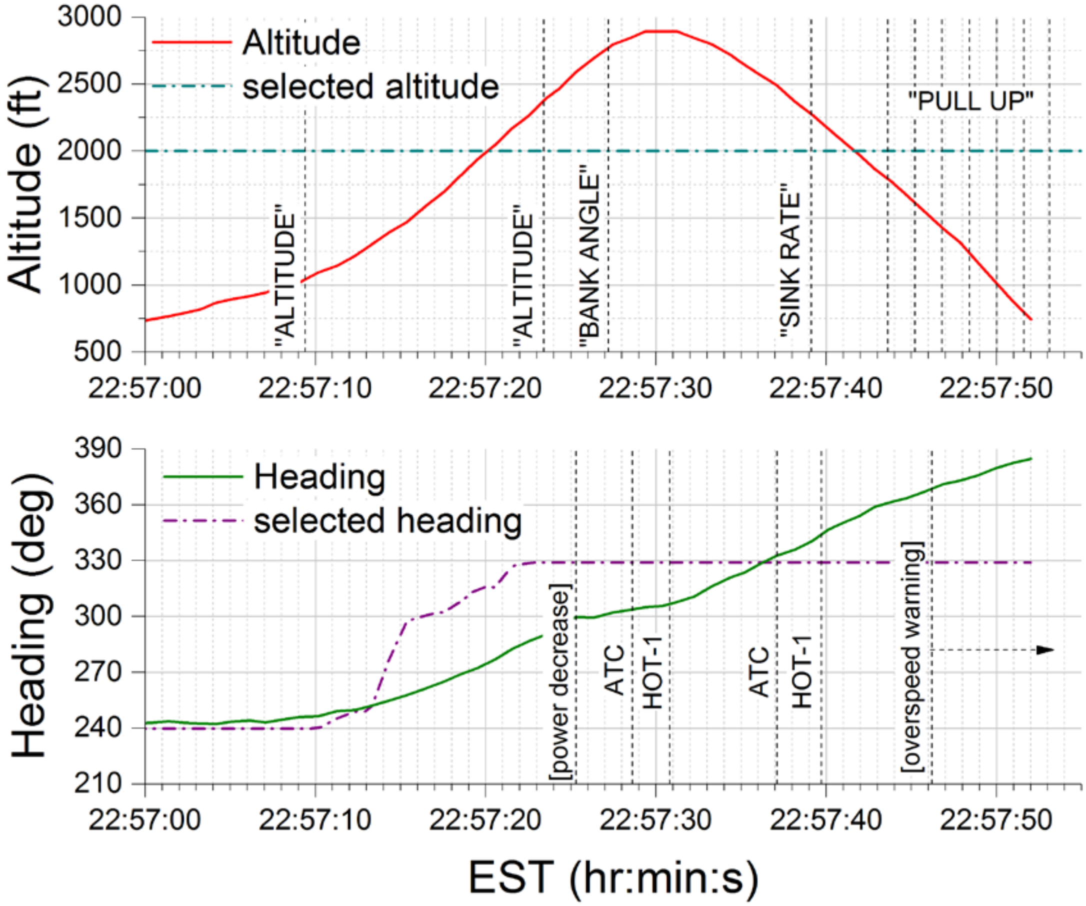

Figure 10. Altitude and heading with annunciations and comments from the CVR.

Flight Path Simulation

To obtain a more detailed estimate of performance throughout the flight and to confirm the consistency of the recorded ADS-B data with the performance capabilities of the airplane, a six degree-of-freedom (6-DOF) simulation of the flight was performed. The objective of the simulation was to obtain a physics-based estimate of the trajectory and orientation of the airplane throughout the flight that was consistent with the performance capabilities of the Cessna 525 and the ADS-B data. The simulation used a "math pilot" to generate control system inputs to produce pitch and roll angles that result in an approximate match of a target trajectory defined by a smoothed track through the recorded data. However, the pitch and roll angles that produced the accident trajectory may not have resulted entirely from control inputs but may have resulted entirely or in part from control failures or damage (such as that resulting from a bird strike) and consequently the simulation results, by themselves, do not provide information from which to determine the source of the rolling and pitching moments acting on the airplane. However, for this accident, no evidence of a control failure or damage prior to impact with the lake were found.

The results of the simulation are shown below in Figure 11. The simulation was run to best match ADS-B altitude, ADS-B position in northing and easting, and the aircraft's calculated groundspeed. The figure shows the simulation result that best matched all four parameters.

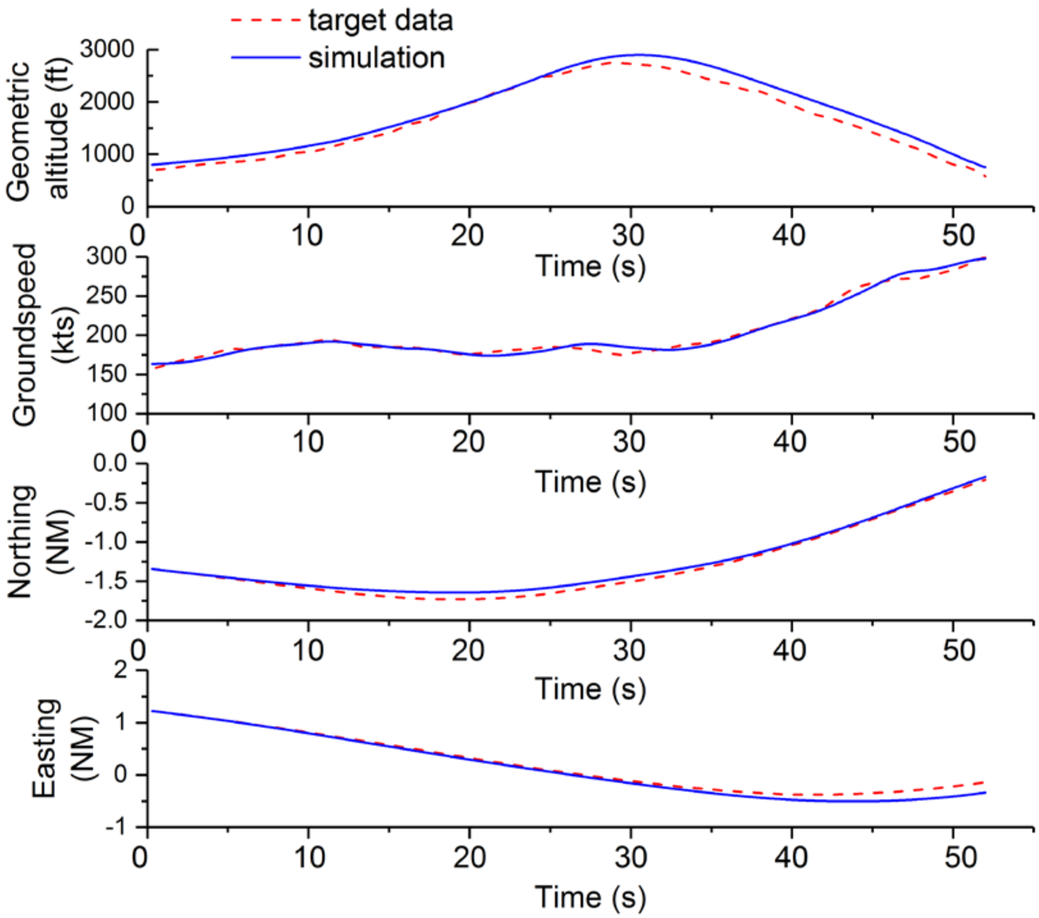

Figure 11. ADS-B and calculated target data and simulation results.

The simulation also calculated airplane load factors for the flight. Figure 12 shows the calculated longitudinal, lateral, and vertical load factors and the recorded altitude. The vertical load factor goes below 1g from 22:57:24.8 to 22:57:35.2 as the airplane transitions from climbing to descending and is highlighted in orange in the figure. The load factors calculated during the flight path simulation will be used to determine the "apparent" pitch and roll angles which are discussed in the next section.

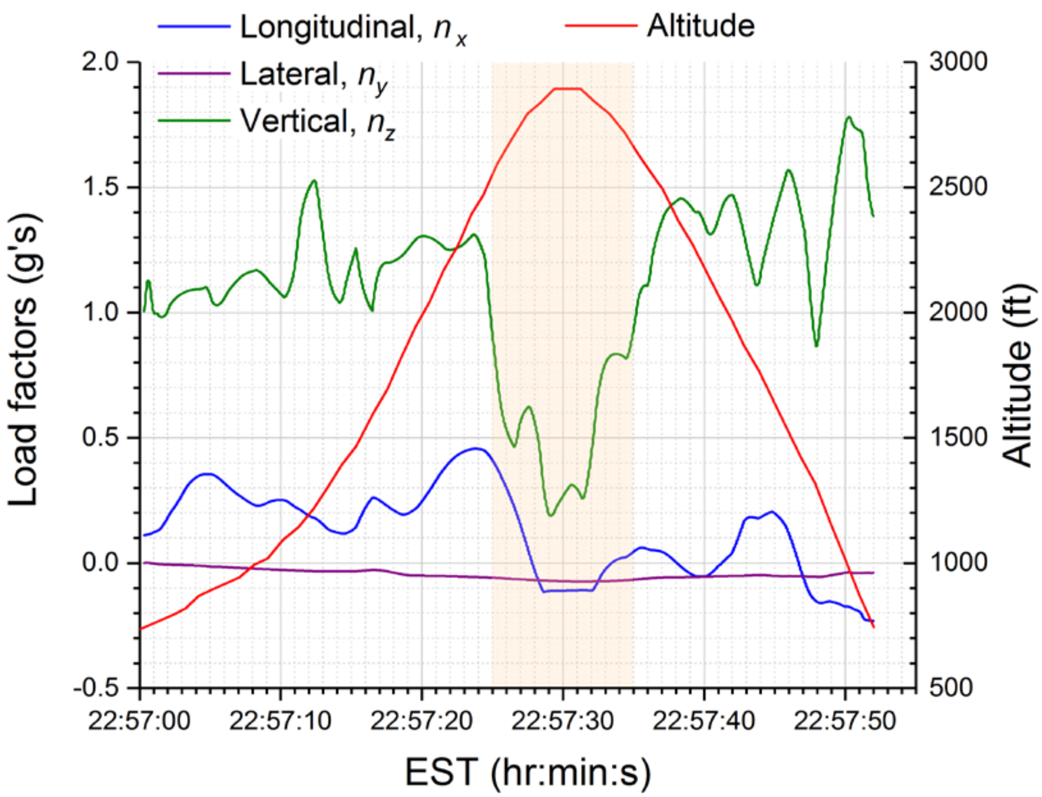

Figure 12. Longitudinal, lateral, and vertical load factors from the simulation and altitude.

Apparent Angles

The vestibular system of the inner ear allows a person to have a sense of balance and spatial orientation. However, like all accelerometers, the vestibular system cannot distinguish between load factors due to motion versus load factors due to gravity. Simply put, on its own, the inner ear cannot differentiate between accelerations and tilt. Additional sensory inputs, such as visual cues, are needed to correctly perceive attitude and acceleration. When a pilot misperceives attitude and acceleration it is known as the "somatogravic illusion" and can cause spatial disorientation. Further information is available in the Human Performance Report [4].

Figure 13 shows the orientation of the resultant load factor vector $\vec{n}$ for two cases. In the left image, the airplane is unaccelerated, and $\vec{n}$ is aligned with the gravity vector g, along the earth's vertical axis (z_e). In the right image, the airplane is in accelerated flight, and $\vec{n}$ has a component along the x_b axis (n_x). In both cases, the angle of the vector $\vec{n}$ relative to the airplane's vertical axis (z_b) is the same: θ_{APP}, or the "apparent" pitch angle. While in the left image, θ_{APP} is the actual pitch angle of the airplane ($\theta_{APP} = \theta$), in the right image the actual pitch angle is less than θ_{APP}. However, in both cases the pilot's vestibular/kinematic system alone would perceive the pitch angle as θ_{APP}.

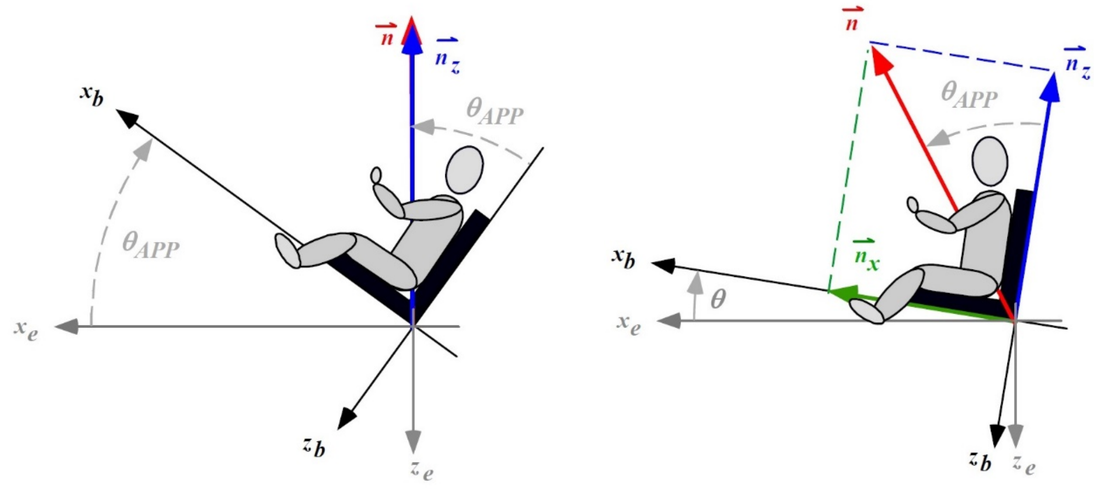

Figure 13. Apparent angles in an unaccelerated (left) and accelerated (right) reference frame.

The following equations represent the apparent pitch and roll angles for a worst-case scenario where acceleration is wholly mis-equated for gravity, but the actual pilot perception could range between an accurate attitude to one where the airplane attitude is wholly mis-equated. The pitch and roll angles in an unaccelerated axis system that will produce a vector $\vec{n}$ parallel (in airplane body axes) to the vector $\vec{n}$ in the accelerated system are needed to compute θ_{APP} and ϕ_{APP}. In the unaccelerated system, $\vec{n}$ has Earth-axis components {0, 0, -g}, or equivalently

$$\vec{n} = \begin{pmatrix} 0 \\ 0 \\ -|\vec{n}| \end{pmatrix}_{EARTH}$$

Where

$$|\vec{n}| = \sqrt{(n_x)^2 + (n_y)^2 + (n_z)^2} = g$$

Transforming these components into airplane body axis for the unaccelerated system gives

$$\vec{n} = -|\vec{n}| \begin{pmatrix} -\sin\theta \\ \sin\phi\cos\theta \\ \cos\phi\sin\theta \end{pmatrix}_{BODY}$$

For the accelerated system, θ_{APP} and ϕ_{APP} are such that when the airplane body axis is aligned with these angles in an unaccelerated system, the resulting body-axis components of $\vec{n}$ will match the load factors n_x, n_y, and n_z from the accelerated case. So, the last equation is set as

$$|\vec{n}| \begin{pmatrix} -\sin\theta_{APP} \\ \sin\phi_{APP}\cos\theta_{APP} \\ \cos\phi_{APP}\sin\theta_{APP} \end{pmatrix}_{BODY} = \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}$$

And θ_{APP} and ϕ_{APP} can be calculated as

$$\theta_{APP} = \sin^{-1}\left(\frac{n_x}{|\vec{n}|}\right)$$

$$\phi_{APP} = \sin^{-1}\left(\frac{-n_y}{|\vec{n}|\cos\theta_{APP}}\right)$$

Figure 14, below, shows the actual and calculated apparent pitch and roll angles. The orange highlighted area is the same as Figure 12, when n_z dropped while the airplane reached its maximum altitude and nosed over. As the load factor $\vec{n}$ became less than one (1), the apparent roll angle increased and the apparent pitch dropped. This portion of the apparent angle calculation should be treated as more uncertain than the initial climb and later descent.

During the descent, it was possible that the pilot perceived that the aircraft was nose-level rather than nose-down. Throughout the whole of the flight, it was possible that the roll angle could have felt much less extreme than it actually was.

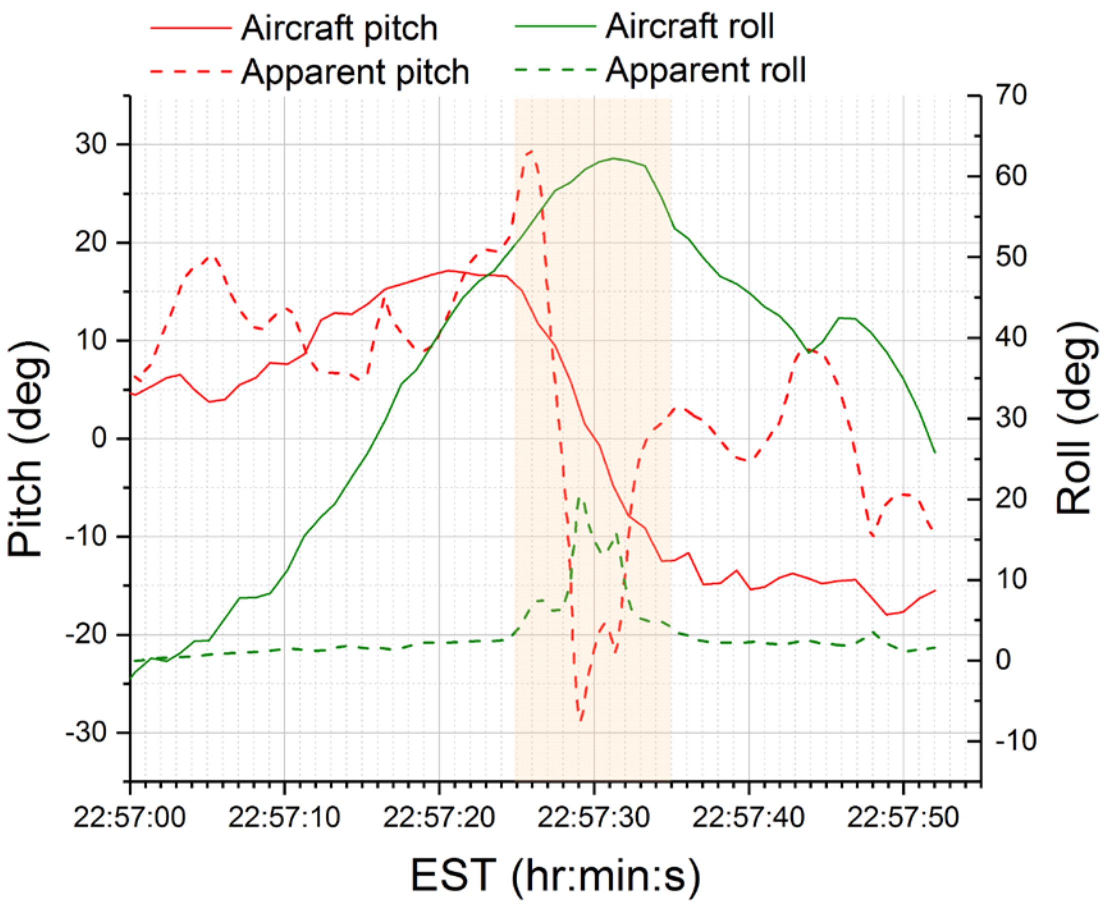

Figure 14. Actual and apparent pitch and roll angles.

Sightlines

Of interest was when during the ascent and roll the pilot would have lost sight of the Cleveland skyline and an outside visual reference. The geometry of the CJ4 was used to determine that when centered in the window, the angle from the pilot's eyes to the bottom of the window is between 28° and 37° from the horizontal (see upper image in Figure 15) [5]. The lower image of Figure 15 shows how a right roll affects the pilot's sightline. As the airplane rolls to the right, the pilot sees less and less of the ground to the left. When the roll angle is greater than the angle out the window, the ground could no longer be seen without the pilot moving his head towards the window[5].

[5] Due to the low altitude, the distance along the sightline from the airplane to the ground was not enough to be limited by weather visibility which was reported to be six statute miles.

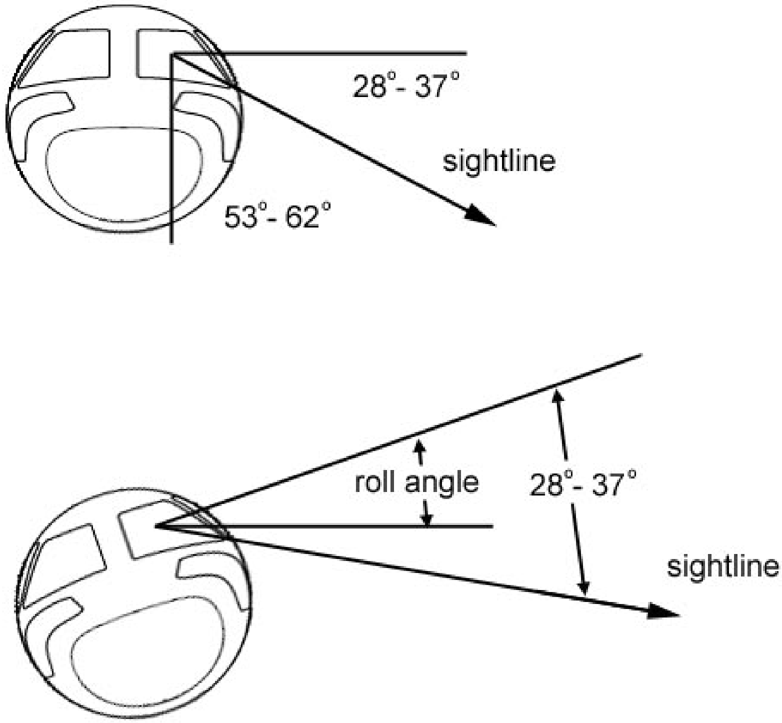

Figure 15. Sightlines from CJ4 cockpit. Top picture is wings level; lower picture in a bank.

The airplane's roll exceeded 28° by 22:57:16.5 (1,600 ft altitude) and 37° by 22:57:19.5 (1,950 ft). Meteorology recorded a broken layer at 1,900 ft. The loss of the pilot's sightline and the entrance into a layer of broken clouds, snow, and mist occurred within a 3.5 second window (Figure 16). The roll angle remained above 37° until 22:57:49, about 3 seconds before the data ended. The airplane remained above the broken cloud layer until 22:57:50, about 2 seconds before the data ended.

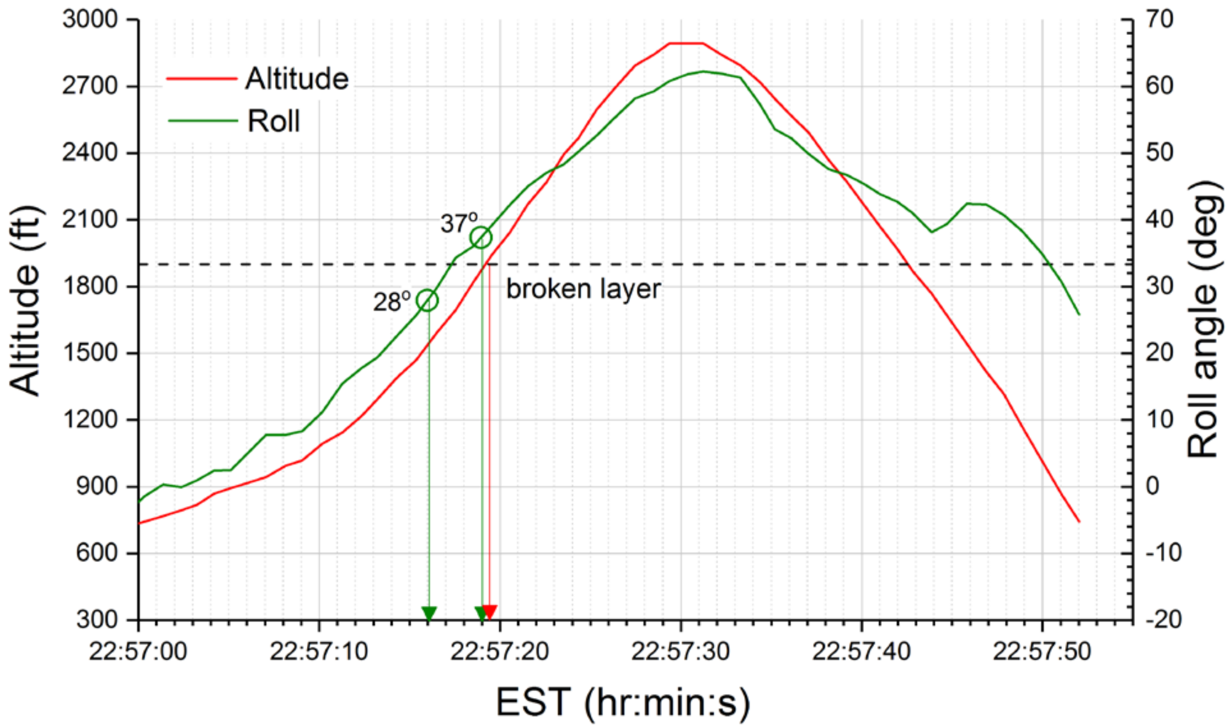

Figure 16. Altitude and roll versus time with sightline and cloud layer noted.

Prior Take-offs

The ADS-B data were available for six earlier flights that occurred in the month of December. The altitude, rate of climb, and groundspeed for about the first five minutes of each flight are shown in Figure 17 through Figure 22. Flights were not necessarily consecutive. All flights except for the accident flight are shown in UTC. Figure 23 shows the accident flight data in EST to the same scale as the other flights for comparison. Rates of climb are calculated between each altitude reading, but the general trends should be considered more than short instances of extremely high rates of climb.

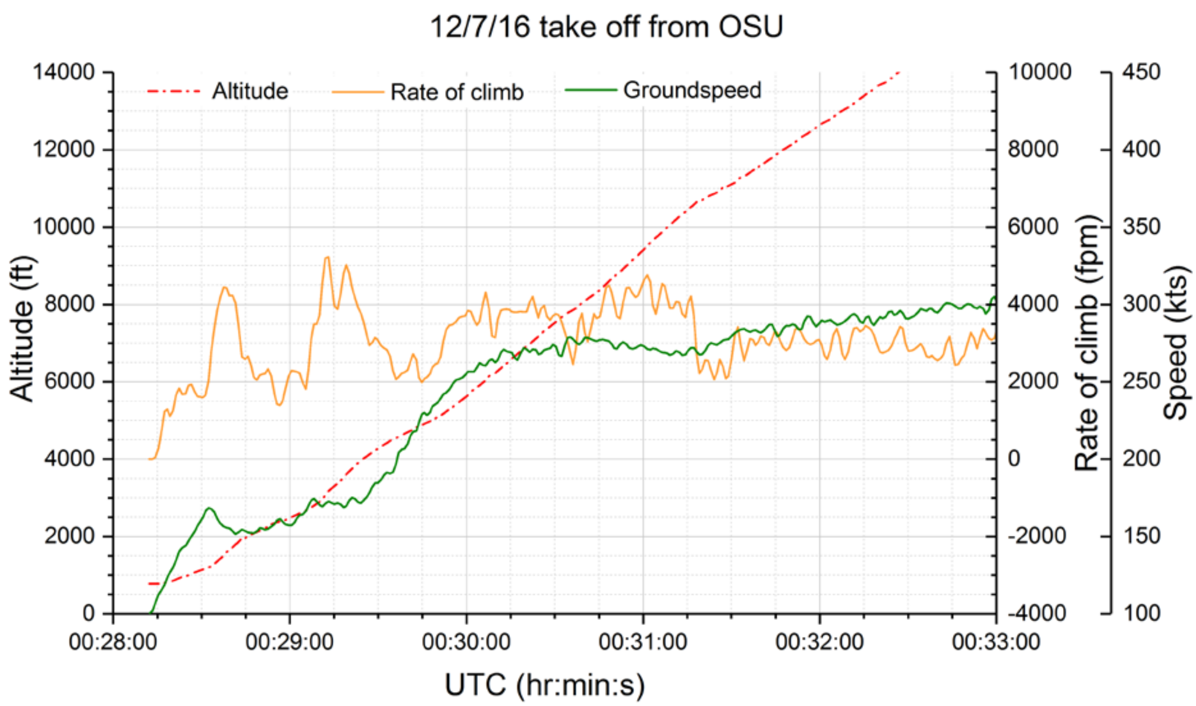

Figure 17. Altitude, rate of climb, and groundspeed of 12/7/16 take-off from OSU.

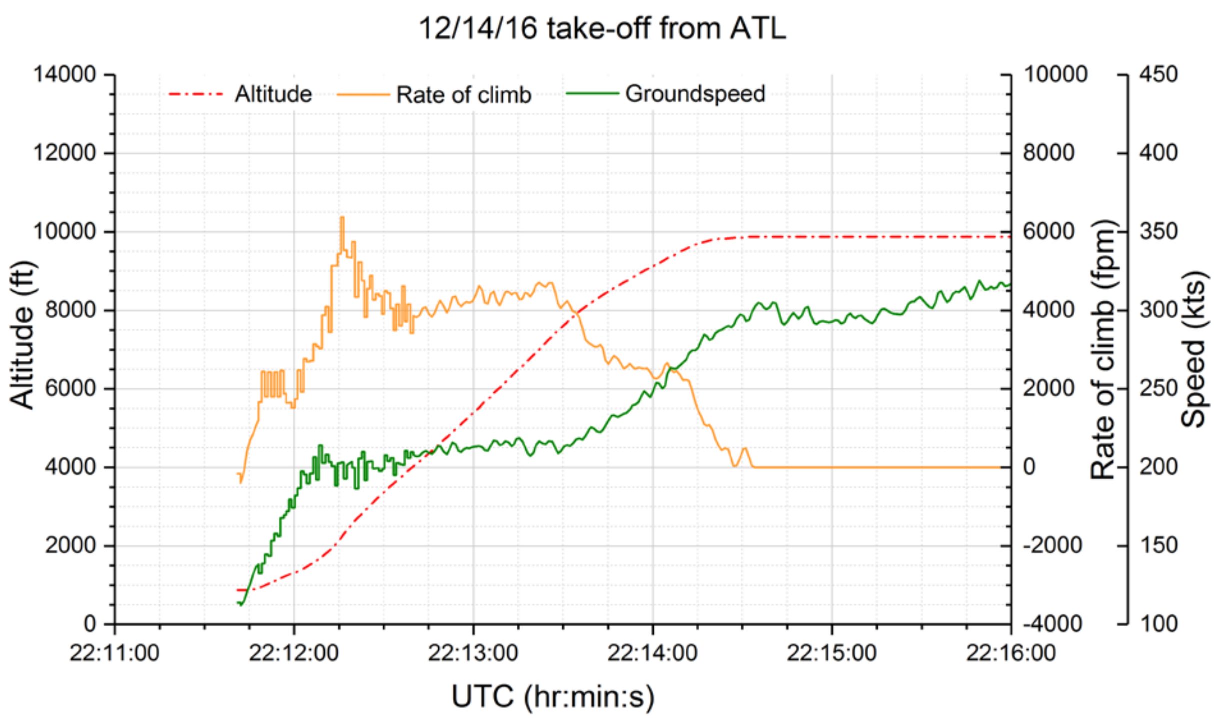

Figure 18. Altitude, rate of climb, and groundspeed of 12/14/16 take-off from ATL.

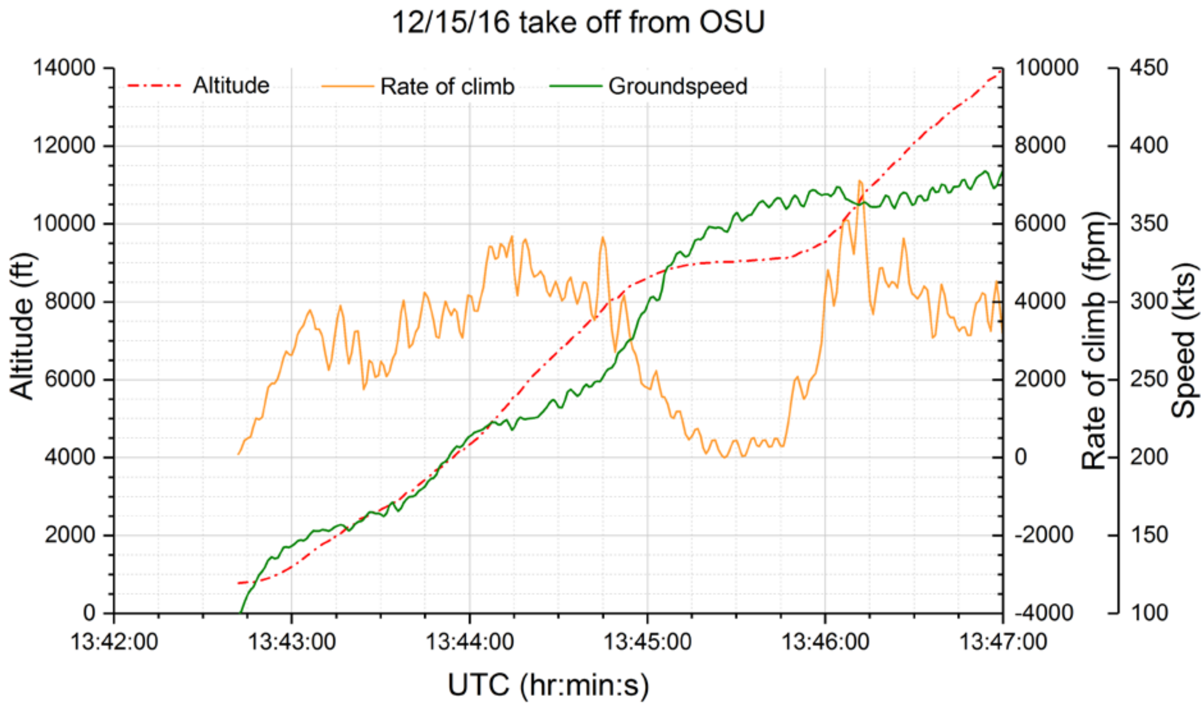

Figure 19. Altitude, rate of climb, and groundspeed of 12/15/16 take-off from OSU.

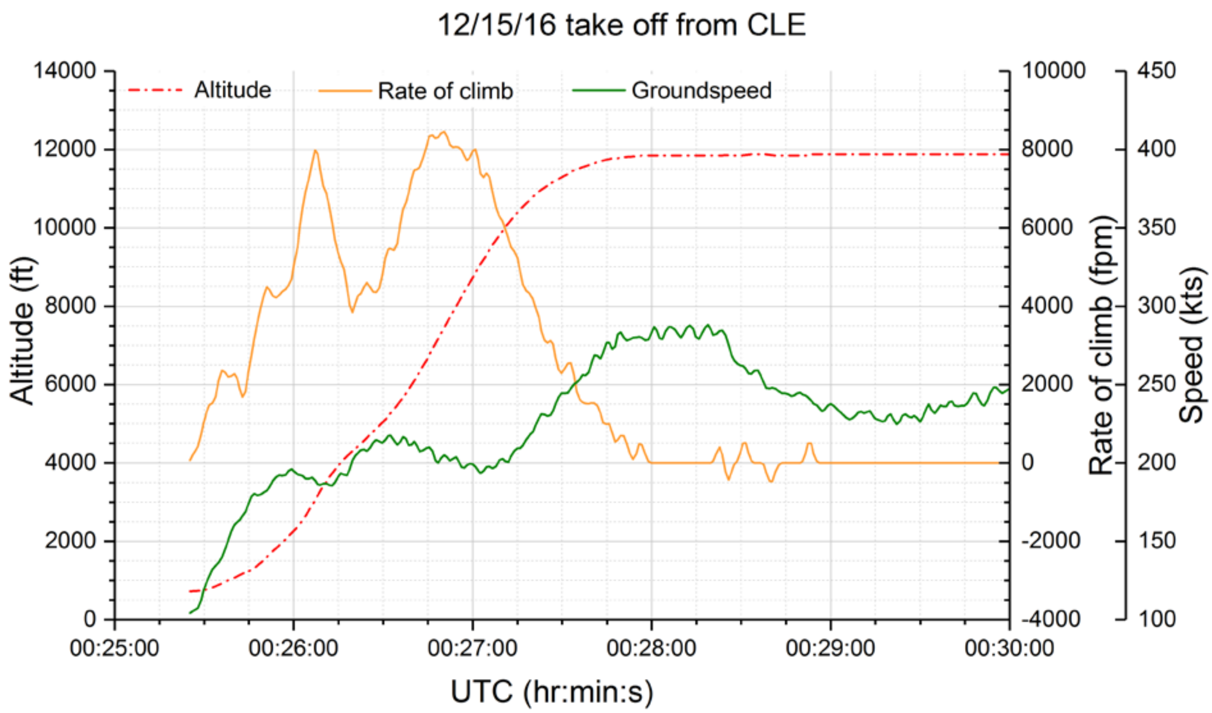

Figure 20. Altitude, rate of climb, and groundspeed of 12/15/16 take-off from CLE.

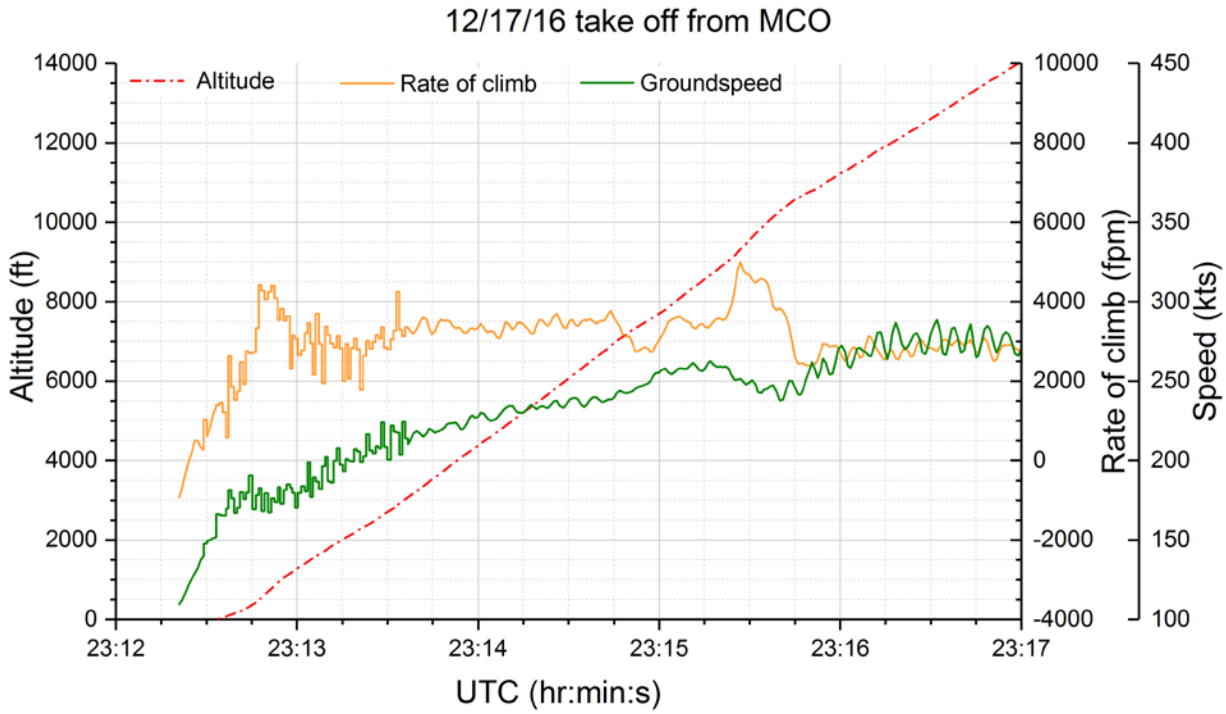

Figure 21. Altitude, rate of climb, and groundspeed of 12/17/16 take-off from MCO.

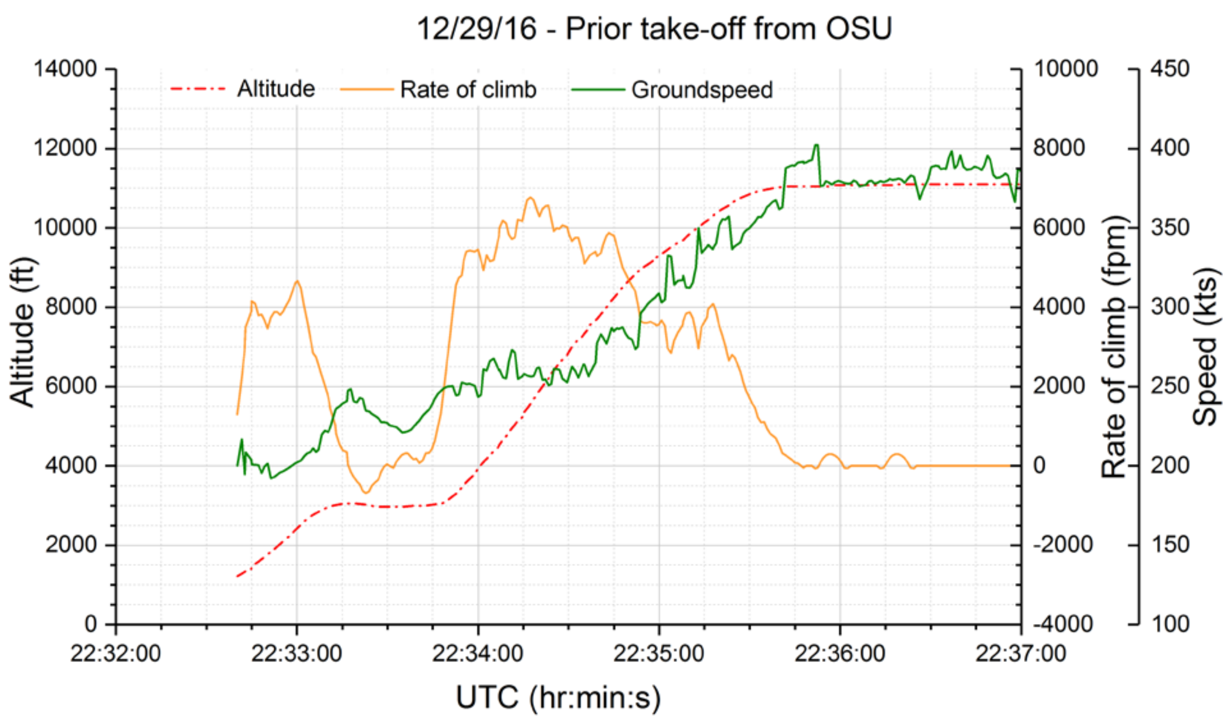

Figure 22. Altitude, rate of climb, and groundspeed of 12/29/16 take-off from OSU.

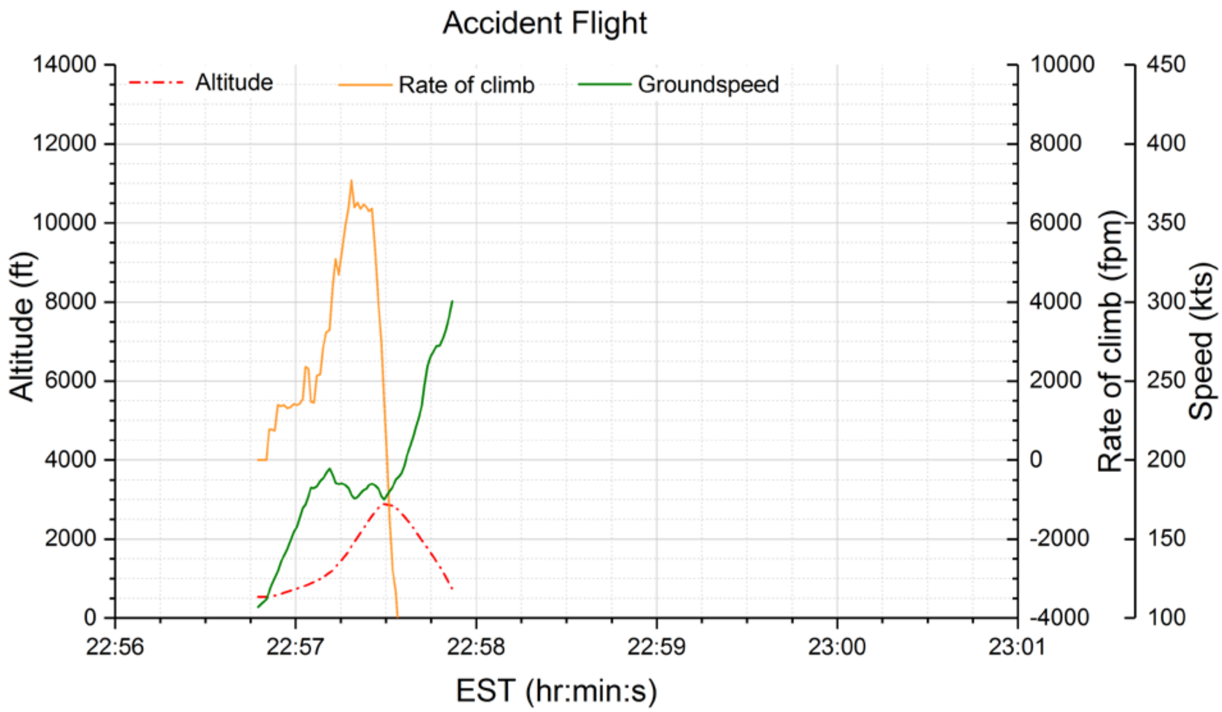

Figure 23. Altitude, rate of climb, and groundspeed of accident take-off for comparison.

The take-off just prior to the accident flight (December 29th out of OSU) had an initial rate of climb around 4,000 fpm, before increasing to between 5,000 and 6,000 fpm for about a minute of the early climb. The highest climb rate seen in these flights was on December 15, 2016 out of CLE when climb rates of nearly 8,000 fpm were seen. The other four take-offs showed climb rates near 4,000 fpm with some faster rates of climb for short periods of time.

During the accident flight, the airplane gained 100 kts of groundspeed (100 kts to 200 kts) in just over 23 seconds of flight. The December 14th flight (Figure 18) showed a similar increase in groundspeed from 100 kts to 200 kts in 25 seconds. The other flights showed significantly lower gains in groundspeed.

E. CONCLUSIONS

The airplane took off from Burke Lakefront Airport (elevation 583 ft) at 22:56:47 and climbed to an altitude of 2,893 ft by 22:57:29 at a maximum rate of climb over 6,000 fpm. After two “ALTITUDE” annunciations (first for 1,000 ft under the selected altitude of 2,000 ft, the second for 300 ft above the selected altitude) there was a cockpit sound consistent with the decrease of power and the airplane stopped climbing and began descending.

The airplane, which had been instructed onto a heading of 330°, began banking into a right turn upon take off. At 22:57:27 there was an annunciation of “BANK ANGLE” as the airplane passed through 55° right wing down. It reached a maximum bank angle of 62° right wing down at about 22:57:31 before the airplane began to roll back left, but the last calculated bank angle was 25° right wing down.

At 22:57:39.1 there was an annunciation for “SINK RATE” which coincides with the rate of climb falling below -6,000 fpm. Starting at 22:57:43.6, the TAWS annunciated “PULL UP” seven times, the last at 22:57:53.1. The descent rate reached a maximum downward speed of -8,000 fpm before the ADS-B data ended and the airplane impacted the lake. Pitch calculations showed that the airplane was 15° nose down at the end of the ADS-B data.

The flight path was consistent with the performance of airplane and no loss of control was evident from the data.

The airplane near simultaneously entered a broken layer of clouds and banked to the right so that the city lights were no longer visible from the cockpit. Both events would have limited any outside visual references of the ground. When the airplane impacted the lake, it was 15° nose down and 30° right wing down, but calculated apparent angles were near wings and nose level. If acceleration and gravity were misinterpreted, and there were no visual cues to the contrary, the pilot could have mis-perceived that the airplane was wings and nose level before impact.

ADS-B data for six earlier flights were available. No pattern could be determined from this small data set, but the pilot had completed take-offs with climb rates of over 6,000 fpm within the past thirty days.

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F. REFERENCES

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2. Cockpit Voice Recorder Factual Report, CEN17FA072. National Transportation Safety Board, 2017.
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4. Human Performance Factual Report, CEN17FA072. National Transportation Safety Board, 2017.
5. Model 525C Maintenance Manual. Cessna Aircraft Company, Revision 6.