

National Transportation Safety Board

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AIRCRAFT PERFORMANCE STUDY

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TABLE OF CONTENTS

A.	ACCIDENT	3
B.	AIRCRAFT PERFORMANCE GROUP	3
C.	SUMMARY	3
C.1.	Introduction	3
C.2.	Objective and scope of the <i>Aircraft Performance Study</i>	4
C.3.	Summary of results	5
C.3.1.	Approach to and landing on KPVC runway 7	5
C.3.2.	Takeoff and climb from KPVC runway 7	8
D.	DETAILS OF THE INVESTIGATION	10
D.1.	The Cessna 402C airplane	10
D.2.	Wreckage location and condition	10
D.3.	ADS-B data	10
D.4.	Surveillance video data	12
D.5.	Meteorological data	13
D.6.	Manufacturer-provided airplane performance data	15
D.6.1.	Climb performance presented in the POH/AFM	15
D.6.2.	Level acceleration data provided by Textron	16
D.7.	Climb performance over a range of airspeeds with non-zero acceleration	16
D.7.1.	Estimating drag characteristics from POH/AFM rate-of-climb data	17
D.7.2.	Thrust from engine power and propeller efficiency	18
D.7.3.	Calculating $\dot{h}$ at any V_T & $\dot{u}$: flaps up, gear up & flaps 45°, gear down	21
D.7.4.	Calculating $\dot{h}$ at any V_T & $\dot{u}$: flaps up, gear down	23
D.7.5.	Climb performance calculation results	23
D.8.	Regulations and guidance concerning operations on wet runways	25
D.8.1.	Overview	25
D.8.2.	Landing distance data in the Cessna 402C POH/AFM	26
D.8.3.	14 CFR Part 135 landing distance dispatch requirements	29
D.8.4.	FAA SAFO 19001	31
D.8.5.	Operational guidance to pilots provided by Cape Air	32
D.9.	Sequence of events during the approach, landing, and attempted takeoff	37
D.10.	The Owatonna BAe-800A accident and FAA InFO 17009	38
E.	CONCLUSIONS	39
F.	REFERENCES	42
G.	GLOSSARY	44
	FIGURES	46

A. ACCIDENT

Location: Provincetown, Massachusetts
Date: September 9, 2021
Time: 15:27 Eastern Daylight Time (EDT)
19:27 Coordinated Universal Time (UTC)
Airplane: Cessna 402C, registration N88833

B. AIRCRAFT PERFORMANCE GROUP

Chairman: John O'Callaghan
National Transportation Safety Board (NTSB), RE-60
Washington, D.C.

Members: N/A

C. SUMMARY

C.1. Introduction

On September 9, 2021, about 15:27 EDT, a Cessna 402C, N88833, was substantially damaged when it impacted trees after taking off from runway 7 at Provincetown Municipal Airport (KPVC), Provincetown, Massachusetts, immediately after having landed on the same runway. The pilot and the six passengers were seriously injured. The airplane was operated under the provisions of Title 14 Code of Federal Regulations Part 135 as a scheduled passenger flight.

The flight was being operated by Cape Air as flight 2072, and was on an instrument flight rules flight plan from Boston-Logan International Airport (KBOS), Boston, Massachusetts to KPVC. The flight departed KBOS about 15:04.

The pilot was cleared by air traffic control for the instrument landing system (ILS) approach to KPVC runway 7. Another Cape Air pilot was holding short of runway 25, waiting for the accident airplane to land. He said the captain of the accident airplane contacted him over the airport's common traffic advisory frequency to ask if the airport lights were on. The pilot holding short responded that the lights were on, that the visibility had improved, and that the rain was subsiding.

The pilot holding short first saw the accident airplane after it had landed and was about halfway down the 3,502-ft-long runway. As the airplane got closer to his position, he could tell that it was traveling "a little faster than it should be." The pilot could not estimate the airplane's speed, but it was traveling faster than he would have expected, and he said he knew it would not have room to stop on the remaining runway. The

airplane then took off and entered a slow climb. The pilot holding short said the attitude of the airplane appeared normal, but it was climbing slower than he thought it should. The airplane cleared the localizer antennas at the far end of the runway, then the perimeter fence, before it struck trees. The airplane disappeared into the trees, and he then saw a ball of flames.

A review of airport surveillance video revealed it was raining heavily at the time the accident airplane landed. As the airplane touched down on the runway, a splash of water was observed. During the landing rollout, as the airplane passed the airport's windsock, the windsock's movement was consistent with the airplane landing with a tailwind. The airplane then began to climb as it neared the end of the runway. The airplane entered a shallow climb and collided with trees. The video showed that the airplane disappeared into the trees and that a large fireball erupted shortly after.

Examination of the accident site revealed that the airplane came to rest upright approximately 200 ft. from its initial contact with the trees. A postimpact fire consumed portions of the left and right wings. All major components of the airplane were accounted for at the accident site.

The airplane was retained for further examination.

C.2. Objective and scope of the *Aircraft Performance Study*

The objective of this *Aircraft Performance Study* is to determine and analyze the motion of the airplane and the physical forces that produce that motion. In particular, the *Study* attempts to define the airplane's position and orientation during the relevant portion of the flight, and determine the airplane's response to control inputs, external disturbances, ground forces, and other factors that could affect its trajectory.

The data used to determine and analyze the airplane motion includes the following:

- Automatic Dependent Surveillance - Broadcast (ADS-B) data.
- Surveillance video recordings.
- Wreckage location and condition.
- Weather information.
- Airplane performance information in the Airplane Flight Manual.
- Supplemental performance information provided by the airplane manufacturer.

The airplane was not equipped (and was not required to be equipped) with a Flight Data Recorder (FDR) or Cockpit Voice Recorder (CVR). Consequently, the control inputs, engine power, speed, and acceleration of the airplane throughout the entire approach, landing, and go-around could not be determined with precision. In

addition, the lack of FDR data, and the unknown lift characteristics of the airplane at flaps 45° in ground effect, precluded a computation of the wheel braking friction coefficient achieved on the wet runway during the landing, and a comparison of the friction achieved with the friction levels achieved in other wet-runway landing accidents investigated by the NTSB.

However, the airplane's altitude, position, and speed during the approach to runway 7 could be computed from ADS-B data. Furthermore, as described in the NTSB *Video Study* (Reference 1), surveillance video of the airplane during the landing roll and go-around was used to determine the position and speed of the airplane on portions of the runway, as well as the time elapsed between the touchdown and the impact with the trees. This information, together with airplane performance data published in the Cessna 402C Pilot's Operating Handbook & Airplane Flight Manual (POH/AFM, Reference 2) and additional performance information provided by Textron (the manufacturer) is used in this *Study* to compare the conduct of the approach with the procedures outlined in the POH/AFM and Cape Air's operational guidance, and to evaluate the distance required to stop on the runway and the climb capability of the airplane during the go-around.

C.3. Summary of results

In this *Study*, the performance of N88833 during the accident is considered in two segments: 1) the approach to and landing on runway 7, including the deceleration performance on the runway; and 2) the acceleration and climb performance of the airplane following the pilot's decision to attempt to take off again.

C.3.1. Approach to and landing on KPVC runway 7

During its ILS approach to KPVC runway 7, N88833 might have exceeded the stabilized approach limits published in Cape Air's General Operating Manual (GOM, Reference 3) concerning glideslope deviation, and did exceed the limits concerning sink rate. Per the GOM, either of these exceedances should have triggered "an immediate go-around," but did not. Further, the airplane did not decelerate to 120 knots indicated airspeed (KIAS) (the final approach speed specified in Cape Air's Cessna 402C Normal Procedures Handbook (NPH, Reference 20)) until it descended below 600 ft. above ground level (AGL). In addition, N88833's airspeed at 50 ft. AGL was 110 knots KIAS, 15 knots faster than the 95 KIAS specified in the POH/AFM and NPH to obtain the landing distances (on a dry runway) published in the POH/AFM.

Figure 5-25 of the POH/AFM depicts a table of the required landing distance (at flaps 45°) as a function of airplane weight, pressure altitude, and air temperature. The table provides both the ground roll distance (the distance required to stop once the airplane has touched down), and the total distance required starting from 50 ft. above the

runway threshold (specified as the “total distance required to clear 50 feet”). A note in the table states, “for operations with tailwinds up to 10 knots, increase total distances by 14% for each 5 knots wind.” The table assumes a “level, hard runway,” but does not specify a runway surface condition (such as dry or wet). In response to an NTSB inquiry, Textron confirmed that the data in the table corresponds to a dry runway.

N88833 touched down about 500 ft. from the runway 7 threshold at about 104 knots ground speed, as determined from surveillance video evidence (see Section D.4 and Reference 1). Recorded Automated Weather Observation Station (AWOS) data from KPVC indicated that at the time of the accident, the wind was from 213° (true) at 12 knots, corresponding to about an 11 knot tailwind component for runway 7. With this tailwind component, the touchdown airspeed would have been 93 KIAS, 3 knots faster than the 90 KIAS at 50 ft. specified in the POH/AFM landing distance table for the airplane’s landing weight (6,215 lb.)¹ Assuming a 4% speed decay between 50 ft. and touchdown, the on-speed, zero-wind touchdown ground speed underlying the POH/AFM landing distance is about 86 knots. The actual touchdown ground speed was 18 knots faster.

Section 2.2.22 (“Tailwind / Short Runway IFR Operations”) of Cape Air’s GOM prohibits instrument approaches to short runways (defined as those shorter than 4,000 ft. for the Cessna 402C) when the tailwind component is greater than 5 knots. Since KPVC runway 7 is 3,502 ft. long, this limitation applied to the accident landing, and the actual tailwind component of about 11 knots exceeded the 5 knot tailwind limit in the GOM. However, in statements to the NTSB, the Captain reported that he remembered listening to the AWOS information at least twice before landing (though he could not recall the exact times he did so), and that the wind speed was 5 knots or less. Further, he stated that though he knew he would be landing with a quartering tailwind, the speed and direction of the wind were within the performance limits of the airplane and Cape Air’s policy. The recorded AWOS data shows that between 14:45 EDT and 15:10 EDT, the wind varied between 200° at 5 knots and 190° at 5 knots, corresponding to tailwind components of 4 and 3 knots, respectively. Between 15:15 EDT and 15:27 EDT the wind varied between 190° at 8 knots and 213° at 12 knots, corresponding to tailwind components of 5 and 11 knots, respectively (N88833 landed at about 15:27). Of note, the decision height for the ILS approach to runway 7 is 208 ft. MSL, whereas the minimum descent altitude for the RNAV (GPS) approach to runway 25 is 400 ft. MSL, which likely made the ILS approach to runway 7 preferable, if the winds allowed it.

At the airplane weight and atmospheric conditions of the accident, table 5-25 of the POH/AFM specifies a total landing distance (on a dry runway) of 2,305 ft., including a ground roll distance of 875 ft. and an in-air distance 1,430 ft. These distances assume

¹ For the accident conditions, both indicated and true airspeeds are about 1 knot higher than calibrated airspeed, and therefore approximately equal to each other.

an approach speed of 90 KIAS 50 ft. above the runway. At the time of the accident, the tailwind component on the runway was about 11 knots; with this tailwind, Table 5-25 specifies an on-speed landing distance of 3,015 ft. Consequently, without any adjustment for wet runway conditions, the 3,502 ft. runway was long enough to accommodate the landing within 86% of its length. The required distance at the 5-kt. tailwind limit allowed by the Cape Air GOM would be 2,628 ft. (75% of the runway length).

However, as noted above the touchdown ground speed was 18 kt. higher than the nominal ground speed implied in the POH/AFM. This difference is greater than the 10 kt. limit for which the tailwind adjustment to the landing distances published in Figure 5-25 of the POH/AFM is valid. Nonetheless, using the 14% increase in landing distance for every 5 knots of tailwind adjustment, the resulting required landing distance is $[1 + (18/5) \times (0.14)] \times (2,305 \text{ ft.}) = 3,467 \text{ ft.}$, close to the 3,500 ft. runway length available, and indicates that increases in the touchdown ground speed result in significant increases in the landing distance required.

The POH/AFM does not provide any adjustments to the landing distance to account for a wet runway. Any adjustments to the landing length to account for non-dry runway conditions would have to be made by operators themselves, based on other guidance. For example, 14 Code of Federal Regulations (CFR) §121.195 and §135.385 specify safety factors to be applied to the AFM landing distances when dispatching to dry and wet runways; however, these regulations only apply to transport-category or large normal-category airplanes (the Cessna 402C is a small normal category airplane).

Section 2.14.2 of Cape Air's GOM ("Preparation and Planning") states that

Before each flight, the pilot shall become familiar with all available information concerning that flight. For all flights, this includes, but is not limited to:

- Runway lengths, and takeoff and landing distances
- ...

This content reflects the language of 14 CFR §91.103. However, neither the GOM nor the NPH provide any additional guidance or instructions for adjusting the POH/AFM landing distances to account for non-dry runway conditions, though in correspondence with the NTSB Cape Air indicated that, in their experience, adding 15% to the dry runway landing distances to account for wet conditions provides sufficient safety margin. The additional 15% safety margin is presented to Cape Air pilots during adverse weather operations training, in connection with the FAA's Safety Alert for Operators (SAFO) 19001, and is discussed further below.

At the accident conditions, the airspeed at 50 ft. and the ground roll distance specified in Figure 5-25 of the POH/AFM imply a deceleration of about 12.2 ft/s², or 0.38 G.² The actual deceleration of the airplane following touchdown, as estimated from surveillance video evidence (see Reference 1), is about 5.15 ft/s², or 0.16 G. While the aerodynamic and thrust data for the Cessna 402C required to compute the wheel braking friction coefficient (μ_B) achieved during the landing roll is not available, the achieved deceleration is comparable to that achieved in other wet-runway landing accidents investigated by the NTSB. Hence, the reduction in deceleration from the 0.38 G level assumed in the POH/AFM for a dry runway, to the actual 0.16 G achieved on a wet runway, is not unexpected.

Further, N88833 touched down about 500 ft. from the runway threshold, 930 ft. closer to the threshold than the 1,430 ft. air distance implied in the POH/AFM. Consequently, after touching down the airplane had 3,000 ft. of runway available to stop. To stop in 3,000 ft. from a touchdown ground speed of 104 knots requires an average deceleration of about 0.16 G, matching the achieved deceleration estimated from the surveillance video. Consistent with this observation, Reference 1 notes that

Because of the ± 1.5 knots accuracy of the estimated speed and the ± 30 feet accuracy of the estimated distances, the actual stopping location could have been anywhere between about 68 feet before the end of the runway and 88 feet beyond the end of the runway.

Given the outcome of the attempted takeoff, in hindsight the better option would have been to accept an overrun into the open area beyond the end of runway 7.

C.3.2. Takeoff and climb from KPVC runway 7

Since N88833 did not climb steeply enough to clear the tree line about 660 ft. past the end of runway 7, it is of interest to determine if its achieved climb performance matches the expected performance of the airplane as published in the POH/AFM. Because the airplane was not equipped with an FDR, and because the video camera that captured its departure from runway 7 could not be calibrated accurately, the airplane's position, speed, acceleration, and rate of climb throughout the takeoff could not be determined precisely. However, the expected climb performance of the airplane across a speed range bounded by known data can be estimated based on POH/AFM information and simple aerodynamic models, and on computations of the airplane's straight-and-level acceleration capability provided by Textron. These estimates indicate that the climb rate of the airplane is drastically reduced with acceleration during the climb, as opposed to climbing at a constant airspeed. Surveillance video evidence indicates that

² "G" or "G's" is a non-dimensional unit of acceleration, equal to the dimensional value of acceleration divided by the acceleration due to gravity (32.2 ft/s² or 9.8 m/s²).

the airplane must have been accelerating during the takeoff, thereby reducing its climb performance.

Three surveillance video cameras at KPVC captured different portions of N88833's landing, ground roll, and takeoff. One of these cameras recorded N88833's liftoff from runway 7 and subsequent impact with trees (see Figure 3). However, according to Reference 1, it was not possible to compute the airplane's position and speed reliably from this video because the associated camera "could not be calibrated accurately and was only used for estimating the time when the airplane hit trees during the attempted go-around." Consequently, the exact liftoff point from the runway is unknown, though the location and time of the tree impact are known. Furthermore, the position and speed of the airplane at the end of a prior video segment recorded by a different camera (that could be calibrated accurately) are also known. Investigators at the scene estimated that the height of the tree impact point was about 20 ft. from the ground. The height of the top of the trees was not determined.

Based on the speed and position of the airplane at the time of the end of the prior video segment, and the known time and position of the impact point, the average acceleration of the airplane from the end of the prior video to the impact point can be determined (see Reference 1). The expected best rate of climb (at prescribed airspeeds) in the flaps up, gear up and the flaps 45°, gear down configurations are published in the POH/AFM. The straight-and-level acceleration information provided by Textron can be used to determine the excess power (that can also be used for climbing) in the flaps up, gear down configuration. With this information, simple flight mechanics models can be used to determine the expected rate of climb ($\dot{h}$) and flight path angle (γ) of the airplane in different configurations, across a range of airspeeds, for both zero acceleration (constant airspeed) and the average acceleration deduced from the video and impact location evidence. The results indicate that $\dot{h}$ and γ could have been much greater (and sufficient to clear the trees) if, instead of accelerating during the climb, the airspeed had been kept constant, even at a speed below the speeds for best rate of climb (V_y) or angle of climb (V_x).

The sections that follow present the data used in this *Study* (as listed above), and describe the methods used to calculate additional performance information from this data. The results of these calculations are presented in the Figures and Tables described throughout the *Study*.

D. DETAILS OF THE INVESTIGATION

D.1. The Cessna 402C airplane

The Cessna 402C is a 6 to 10 seat, unpressurized light airplane, powered by two wing-mounted Continental TSIO-520-VB engines producing 325 hp each, with a maximum gross weight of 6,850 pounds. N88833 was equipped with Supplemental Type Certificate (STC) numbers SA5131NM and SA01763SE, corresponding to the Micro AeroDynamics Inc. "MICRO VG SYSTEM" and the AeroAcoustics Aircraft Systems Inc. "Aircraft Payload Extender System," respectively (see References 18 and 19). These STCs increase the airplane's maximum gross weight to 7,200 lb., but do not affect the airplane performance tables published in the POH/AFM at the accident weight.

Figure 1 shows a 3-view image of the airplane, taken from Reference 2.

The airplane weight assumed in this *Study* is 6,215 pounds, corresponding to the planned landing weight specified in Cape Air's weight and balance form for the flight (see Figure 2).

D.2. Wreckage location and condition

KPVC runway 7 is 3,502 ft. long and 100 ft. wide, at an elevation of 8 ft.³ As measured in *Google Earth*, the trees impacted by the airplane are about 660 ft. from the departure end of the runway, and about 50 ft. past the localizer array for the runway 7 ILS. Investigators on-scene estimated that the airplane struck the trees at a height of about 20 ft. from the ground.

As noted above, the airplane came to rest upright approximately 200 ft. from its initial contact with the trees. A series of frames from the surveillance video showing the airplane's impact with the trees is shown in Figure 3. Photos of the accident site, along with a *Google Earth* image of the departure end of the runway, tree line, and road near the accident site, are shown in Figure 4. The *Google Earth* image was taken on 10/23/2021 (45 days after the accident). As shown in the image, the wreckage location area was apparently cleared of trees to facilitate the removal of the wreckage.

D.3. ADS-B data

Automatic Dependent Surveillance – Broadcast (ADS-B) capability enables aircraft to broadcast their three-dimensional position (latitude, longitude, and altitude) to other ADS-B equipped aircraft and to ADS-B ground stations.⁴ ADS-B data broadcast from

³ See <https://enasr.faa.gov/eNASR/nasr/Current/Airport/4336>.

⁴ For more information about ADS-B, see https://www.faa.gov/air_traffic/technology/adsb.

N88833 during its approach to KPVC runway 7 was received and recorded by Federal Aviation Administration (FAA) ADS-B ground stations, but no ADS-B data was received from the airplane while it was on the runway or during the attempted go-around.

ADS-B latitude and longitude are determined using Global Navigation Satellite System (GNSS) signals, including those from Global Positioning System (GPS) satellites, and altitudes determined both barometrically and by GNSS are included in ADS-B messages. The GNSS positions are very accurate compared to radar data; radar range uncertainty alone (without even considering azimuth uncertainty) is about $\pm 1/16$ nm, or ± 380 ft., and GNSS positions are generally accurate to within 60 ft. (see Reference 4). Furthermore, ADS-B data are available at a higher frequency than radar data: typically at 1 sample/second for ADS-B, and at best, 1 sample every 4.5 seconds for radar.

The recorded ADS-B data includes the following parameters:

- UTC time of the ADS-B report, in hours, minutes, and seconds. EDT = UTC - 4 hours.
- Aircraft identifying information.
- Latitude and longitude, to a resolution of 0.01 arc-seconds (≈ 1 ft.)
- Pressure altitude in feet, to the nearest 25 ft. (an uncertainty band of ± 12.5 ft.)
- Geometric (GNSS) altitude in feet, to the nearest 25 ft. The GNSS altitude is the height above the WGS84 ellipsoid, which differs from MSL altitude by the height of the geoid.⁵ In this *Study*, GNSS altitudes are corrected to MSL altitude by adding 91 ft.⁶
- North-south and east-west components of ground speed, to a resolution of 1 kt.
- Rate of climb, to a resolution of 1 ft./min.
- Numerous parameters documenting the quality and accuracy of each reported GNSS position.

The time interval between ADS-B data points during the final approach to runway 7 is about 1 second, with the intervals between the last 5 points being as high as 1.5 seconds. Because the ADS-B ground stations rely on radio line-of-sight to the airplane to receive data broadcasts from the airplane, they will not receive data once the line-of-sight to the airplane becomes obscured by terrain or other obstructions. The last ADS-B data point from N88833 was received 15:27:04.5, at an altitude of 16 ft. MSL (about 8 ft. above and 93 ft. past the runway 7 threshold).

⁵ "The geoid ... is the shape that the ocean surface would take under the influence of the gravity of Earth, including gravitational attraction and Earth's rotation, if other influences such as winds and tides were absent." (Wikipedia.org, accessed 10/10/2022.)

⁶ Per <https://geographiclib.sourceforge.io/cgi-bin/GeoidEval>, the geoid at KPVC is 27.6 m (90.6 ft.) below the surface of the WGS84 ellipsoid.

The ADS-B data is presented in Figures 16 - 21, and discussed throughout the *Study*. In this *Study*, the position of the airplane is described by its "runway coordinates" relative to the KPVC runway 7 threshold. The runway x-coordinate runs from the origin (the runway 7 threshold) down the runway centerline towards the runway 25 threshold. The runway y-coordinate runs from the origin to the right side of runway 7, at 90° to the centerline. To convert from latitude / longitude coordinates to runway x / y coordinates, latitude and longitude are first transformed into east and north coordinates from the threshold using the WGS84 ellipsoid model of the earth, and the coordinates of the runway 7 threshold:

42° 04' 11.3870" N latitude / 70° 13' 34.6087" W longitude / elevation 7.6 ft. MSL

The east / north coordinates are then transformed into runway x / y coordinates by rotating them through the true heading of runway 7, which was measured in *Google Earth* as 59.23°.

D.4. Surveillance video data

Three separate surveillance video cameras at KPVC recorded different portions of N88833's landing, ground roll, and takeoff, with no overlap. The NTSB *Video Study* (Reference 1) describes how the video recordings are used to calculate the position and speed of the airplane on different portions of the runway, the time elapsed between the touchdown and the impact with the trees, and the average acceleration during the attempted takeoff. The *Video Study* 1 names the cameras "Camera 1," "Camera 2," and "Camera 3." "Camera 1" captured N88833's landing on runway 7. "Camera 2" captured the airplane rolling on the runway between the runway ends, and "Camera 3" captured the airplane lifting off from runway 7 and subsequently impacting the tree line 660 ft. from the runway end.

According to the *Video Study*, Cameras 1 and 2 could be calibrated accurately, and position and speed information for N88833 was obtained from the videos recorded by these cameras. However, as noted above, Camera 3 "could not be calibrated accurately and was only used for estimating the time when the airplane hit trees during the attempted go-around."

The results of the *Video Study* used in this *Aircraft Performance Study* are presented in Table 1. Note that the times and locations in Table 1 are those used in the *Video Study* (times are from the start of the Camera 1 video, and locations are distances down the runway 7 centerline from the runway 7 threshold).

Item	Value
Touchdown time	6 seconds
Touchdown location	500 feet
Touchdown ground speed	104 knots
Average deceleration from "Camera 2"	5.15 ft/s ² = 0.16 G
Time of last "Camera 2" position point	21.02 seconds
Location of last "Camera 2" position point	2,604 feet
Ground speed at last "Camera 2" position point	96.54 ft/s = 57.2 knots
Time of impact with trees	33.28 seconds
Location of impact with trees	4,163 feet
Average acceleration from the last "Camera 2" position point to impact with trees	5.0 ft/s ² = 0.155 G

Table 1. Video Study results used in this Aircraft Performance Study. Times are from the start of the Camera 1 video. Locations are distances down the runway 7 centerline from the threshold.

D.5. Meteorological data

The NTSB *Meteorology Factual Report* (Reference 6) presents meteorological data for this accident, collected from official National Weather Service sources. Items in Reference 6 most relevant to this Study are the altimeter setting, static temperature, winds, and precipitation at KPVC at the time N88833 landed. This information is provided to aviators through Aviation Routine Weather Reports (METAR) and Aviation Select Special Weather Reports (SPECI). The data for KPVC in these reports is recorded by the Automated Weather Observation System (AWOS) located at the airport.

Per Reference 6, the FAA Technical Operations Manager responsible for maintenance and service of the AWOS system at KPVC was also able to retrieve 1-minute AWOS data recorded between 14:46 and 15:37 EDT, including the average 2-minute wind direction and wind speed (updated every minute), the present weather, and the precipitation intensity (rate) estimation. The METAR, SPECI, and 1-minute AWOS data for KPVC at the times surrounding the accident are duplicated here in Tables 2 and 3.

Report Type Time (EDT)	METAR 13:56	SPECI 14:30	METAR 14:56	SPECI 15:37
Wind direction (°true)	230	210	200	210
Wind speed (knots)	6	7	5	10
Visibility (statute miles)	2.5	3	4	3
Present weather ⁷	Heavy rain Mist	Rain Mist	Rain Mist	Heavy rain Mist
Sky condition (ft. AGL ⁸)	3,000 few 5,000 broken 6,000 overcast	600 scattered 3,400 broken 4,600 overcast	200 broken 600 overcast	200 few 3,400 broken 5,000 overcast
Temperature (°C)	21	21	21	21
Dew point (°C)	21	21	21	21
Altimeter setting ("Hg)	29.81	29.81	29.79	29.79
Precipitation (inches) ⁹	0.28	0.23	0.27	0.22

Table 2. METAR and SPECI reports generated from KPVC AWOS data at times surrounding the accident, from Reference 6. N88833 landed at 15:27 EDT.

Time (EDT)	Wind direction (°true)	Wind speed (knots)	Present weather	Precipitation intensity (in./hr.)
15:17	201	8.2	Rain	0.25
15:18	189	6.8	Rain	0.27
15:19	210	8.9	Rain	0.23
15:20	212	6.4	Rain	0.23
15:21	199	8.2	Rain	0.21
15:22	193	8.4	Heavy rain	0.40
15:23	203	8.9	Heavy rain	0.54
15:24	194	11.2	Heavy rain	0.72
15:25	212	8.5	Heavy rain	0.33
15:26	199	11.0	Heavy rain	0.59
15:27	213	12.4	Heavy rain	0.46
15:28	215	9.9	Heavy rain	0.61
15:29	219	10.7	Heavy rain	0.74
15:30	217	8.3	Heavy rain	0.75

Table 3. 1-minute reports from the KPVC AWOS at times surrounding the accident, from Reference 6. N88833 landed at 15:27 EDT.

⁷ Per Reference 17, the "rain" weather descriptor corresponds to rainfall rates between 0.11 and 0.3 inches/hour. The "heavy rain" descriptor corresponds to rainfall rates greater than 0.3 inches/hour.

⁸ AGL = Above Ground Level.

⁹ The recorded precipitation is that accumulated since the previous hourly METAR report was issued.

Reference 6 also presents winds-aloft data for the KPVC area at 15:00 EDT based on a High Resolution Rapid Refresh (HRRR) numerical model retrieved from the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory. Table 4 presents the HRRR model wind speed and direction, and the corresponding tailwind component for KPVC runway 7, up to an altitude of 2,829 ft. MSL (covering the final approach segment of the accident flight).

Altitude (ft. MSL)	Wind speed (knots)	Wind direction (°true)	Runway 7 tailwind component (knots)
28	3	199	2.3
113	4	188	2.5
284	5	182	2.7
541	8	170	2.9
945	10	164	2.6
1,492	14	159	2.4
2,128	19	158	3.0
2,829	22	164	5.7

Table 4. HRRR model of winds aloft near KPVC for the time of the accident, from Reference 6.

D.6. Manufacturer-provided airplane performance data

Textron Aviation acquired the Cessna Aircraft Company in 1992, and as the manufacturer is a party to NTSB investigations involving Cessna aircraft. Textron provided two types of performance information for the 402C to the NTSB in support of this investigation: the POH/AFM (Reference 2), and plots of the airplane’s straight-and-level acceleration capability in the flaps up, gear down configuration. The latter was provided in response to an inquiry from the NTSB concerning the acceleration the airplane could have achieved during the attempted takeoff from runway 7.

D.6.1. Climb performance presented in the POH/AFM

Textron also provided the NTSB the zero-lift drag coefficient (C_{D0}) and aerodynamic efficiency factor (e) for the Cessna 402C for the flaps up, gear up and flaps 45°, gear down configurations. These parameters can be used to compute the airplane’s “drag polar” in a given configuration, that is, its drag coefficient (C_D) as a function of its lift coefficient (C_L):

$$C_D = C_{D0} + \frac{C_L^2}{\pi(AR)e} = C_{D0} + kC_L^2 \quad [1]$$

Where AR is the aspect ratio of the wing. However, it was found that modeling the drag in this way did not result in a match of the best-rate-of-climb data published in the POH/AFM (the calculation of the rate of climb based on the airplane’s engine power and drag characteristics is presented in Section D.7). The reason for this discrepancy is unknown, though it might be that the theoretical C_{D0} and e values provided were

selected to best match the airplane's performance in cruise flight, rather than at lower climb speeds. In any case, since the climb performance of the airplane is of most interest in this accident, alternative values for C_{D0} and k in Equation [1] were computed using the POH/AFM climb data itself, as described in Section D.7. Modeling C_D with these alternative values of C_{D0} and k allows the climb performance of the airplane to be estimated for a range of airspeeds, while matching the rate of climb published in the POH/AFM at the specified best-rate-of-climb airspeed (V_y).

The POH/AFM presents the maximum climb performance of the airplane at takeoff power with flaps up and gear up in Figure 5-13, which is duplicated here as Figure 5, as modified by STC SA5131NM (MICRO VG SYSTEM). The maximum climb performance at maximum power with flaps 45° and gear down (the "balked landing climb" configuration) is presented in Figure 5-16, duplicated here as Figure 6, as modified by STC SA01763SE (AeroAcoustics Aircraft Payload Extender System). Per Reference 2, the takeoff power of the engines is 310 SHP/engine, and the maximum power of the engines is 325 SHP/engine.

D.6.2. Level acceleration data provided by Textron

In response to an inquiry from the NTSB concerning the acceleration N88833 could have achieved during the attempted takeoff from runway 7, Textron provided the information presented in Figure 7. This figure plots the maximum-power acceleration of the Cessna 402C in level flight, with the flaps up and the gear down (the configuration found in the wreckage of N88833). Textron's document transmitting this data states

The documented POH takeoff distance calculations were performed using only parasitic drag (C_D) and ignored induced drag as a means to account for ground effect. The acceleration analysis was performed twice, with and without induced drag. Rolling friction was ignored in the drag analysis as it was assumed that the airplane was either off the ground or at the point in the run where the normal force on the tire would be close to zero.

...

[The provided data] should be considered the range of the expected acceleration between in ground effect and in free stream flight for an airplane with engines making rated power. ... The step change in the acceleration profile around the 74 knot point is due to the modelling of [propeller efficiency] and may not be [a] real effect.

D.7. Climb performance over a range of airspeeds with non-zero acceleration

The POH/AFM rates of climb presented in Figures 5 and 6 correspond to unaccelerated flight at the constant, best-rate-of-climb speed (V_y) in each configuration. (V_y depends on gross weight, as shown in the airspeed vs. weight tables embedded in the Figures.) Table 1 indicates that during the attempted takeoff, N88833's average acceleration was 5 ft/s²; its airspeed was not constant, but increasing. Consequently, the rate (and angle) of climb capability of the airplane across

a range of airspeeds, and with non-zero acceleration, is of interest. The rate of climb at non-zero acceleration is particularly significant, since the portion of engine power used to accelerate the airplane (increase its kinetic energy) will not be available to increase its altitude (potential energy). The rate of climb as a function of airspeed and acceleration can be determined given the airplane's weight, engine power, and drag characteristics.

D.7.1. Estimating drag characteristics from POH/AFM rate-of-climb data

Figure 8 depicts a free-body diagram of the forces on the airplane in a climb. The equation of motion along the stability x -axis is

$$-g \sin \gamma + F_{x|aero} + F_{x|thrust} = m(\dot{u} + wQ + vR) \quad [2]$$

Where:

g = acceleration due to gravity

γ = flight path angle

$F_{x|aero}$ = aerodynamic forces along stability x axis = $-D$, where D = drag

$F_{x|thrust}$ = thrust forces along stability x axis

m = airplane mass (= W/g , where W = weight)

$\dot{u} = du/dt$ = rate of change of u , where u = linear velocity along the stability x axis¹⁰

v = linear velocity along the stability y axis

w = linear velocity along the stability z axis

Q = pitch rate (angular velocity about the stability y axis)

R = yaw rate (angular velocity about the stability z axis)

For wings-level steady climb, $Q = R = 0$. Assuming that the angle of attack (α) is small, then

$$F_{x|thrust} = T \cos \alpha \cong T \quad [3]$$

Where T is the total thrust from the engines, and it is assumed that the thrust acts along the body x -axis.

With these assumptions and simplifications, Equation [2] becomes

$$\left(\frac{T-D}{W}\right) = \frac{\dot{u}}{g} + \sin \gamma \quad [4]$$

The rate of climb is given by multiplying Equation [4] by the true airspeed, V_T :

¹⁰ From Figure 8, u is aligned with V_T and so in calm wind $\dot{u} = \dot{V}_T$. However, u is the inertial velocity along the stability x axis, and V_T is the true airspeed along that axis, which depends on both u and the wind. Changes in wind directly change V_T but not u , so to be rigorous, $\dot{u}$ is written here instead of $\dot{V}_T$.

$$\dot{h} = V_T \sin \gamma = V_T \left[\left(\frac{T-D}{W} \right) - \frac{\dot{u}}{g} \right] \quad [5]$$

For climbs with zero acceleration (such as those corresponding to the climb rates published in the POH/AFM), $\dot{u} = 0$, and the drag (D) can be computed from Equation [5] knowing $\dot{h}$, W , V_T , and T . $\dot{h}$, W and V_T are specified in the POH/AFM data,¹¹ and T can be estimated using the known engine power, an assumed propeller profile efficiency, and the ideal propeller efficiency determined from propeller thrust momentum theory.

D.7.2. Thrust from engine power and propeller efficiency

Figure 5 shows the flaps up, gear up climb rate at “takeoff power,” corresponding to 310 shaft horsepower (SHP) per engine, at a manifold pressure of 39 “Hg and a propeller speed of 2,600 RPM. Figure 6 shows the flaps 45, gear down climb rate at the engines’ maximum “rated power,” corresponding to 325 SHP per engine, at a manifold pressure of 39” Hg and a propeller speed of 2,700 RPM.

The actual power delivered to the airframe is less than the SHP produced by the engines because of losses involved in producing thrust with the propellers. The power delivered to the airframe (that increases the energy state of the airplane) by one engine is equal to the thrust produced by that engine’s propeller multiplied by the true airspeed of the airplane. This is less than the SHP produced by the engine; the *propeller efficiency* is defined as

$$\eta_P = \frac{HP}{SHP} = \frac{(T)(V_T)}{SHP} \quad [6]$$

Where:

η_P = propeller efficiency

HP = horsepower delivered to airframe

SHP = shaft horsepower produced by engine

T = thrust produced by propeller

V_T = true airspeed

η_P is less than 1 as a result of both the limited *ideal efficiency* of the propeller (η_i , associated with the physics of producing thrust by accelerating air through the propeller), and the propeller *profile efficiency* (η_0 , associated with drag losses in the boundary layer of the propeller itself). Consequently,

$$\eta_P = \eta_i \eta_0 \quad [7]$$

¹¹ Actually, calibrated airspeed is specified in the POH/AFM climb data, but true airspeed can be computed from calibrated airspeed and the specified pressure altitude and ambient temperature.

η_0 is assumed to be 0.9 in this *Study*, following the practice observed at a manufacturer of propeller-driven airplanes.¹² η_i depends on the flight condition and propeller diameter, and can be computed along with the thrust produced by the propeller by considering the changes in momentum and kinetic energy of the air passing through the propeller.

Figure 9 shows air flowing through a thrusting propeller. The air approaches the propeller at the airplane's true airspeed V_T ; it accelerates and passes through the propeller with velocity V_1 ; and it accelerates further to a final velocity of V_2 . Since the air density (ρ) is constant, conservation of mass requires that the stream tube of air accelerated by the propeller shrink in diameter as the air is accelerated, as shown in Figure 9.

The thrust produced by the propeller is equal to the change in momentum of the air in front of and behind the propeller:

$$T = \frac{d}{dt}(mv) = v \frac{dm}{dt} + m \frac{dv}{dt} \quad [8]$$

Since mass is constant,

$$\frac{dm}{dt} = 0 \quad [9]$$

The mass of air in a differential length dx at the propeller disk is

$$m = \rho A dx \quad [10]$$

Where A is the propeller disk area ($A = \pi(d/2)^2$, where d is the propeller diameter). The air velocity at the propeller disk is

$$\frac{dx}{dt} = V_1 \quad [11]$$

Consequently

$$m \frac{dv}{dt} = \frac{\rho A dx dv}{dt} = \rho A V_1 dv \quad [12]$$

The total change in air velocity dv is

$$dv = V_2 - V_T \quad [13]$$

¹² An η_0 of 0.9 was used initially to compute thrust and drag from the POH/AFM rate of climb data, incorporating the approximation given in Equation [3]. When the rate of climb was later computed across a range of airspeeds using the resulting C_D , the effect of non-zero α was accounted for, and an adjusted η_0 of 0.892 was used to match the POH/AFM climb rates at the corresponding airspeeds.

Combining Equations [8], [9], [12], and [13] gives

$$T = \rho A V_1 (V_2 - V_T) \quad [14]$$

Now consider the work done on the air passing through the propeller, which increases the air's kinetic energy. The work done is equal to the thrust of the propeller multiplied by the differential distance dx at the propeller disk. Consequently,

$$T dx = \frac{1}{2} \rho A dx V_2^2 - \frac{1}{2} \rho A dx V_T^2 \quad [15]$$

$$T = \frac{1}{2} \rho A (V_2^2 - V_T^2) \quad [16]$$

The right-hand side of Equation [15] is the change in the kinetic energy of the air. Combining Equations [14] and [16] gives, after some algebraic manipulation,

$$V_1^2 = V_T V_1 + \frac{T}{2\rho A} \quad [17]$$

The engine power (SHP), multiplied by the propeller profile efficiency η_0 , is the power delivered to the air at the propeller disk, and is equal to the thrust of the propeller multiplied by the speed of the air passing through the propeller disk:

$$(SHP)\eta_0 = T V_1 \quad [18]$$

Solving Equation [18] for V_1 , substituting into Equation [17], and rearranging terms results in the following cubic polynomial for the propeller thrust T , in terms of the known quantities ρ, A, V_T, SHP , and η_0 :

$$T^3 + [2\rho A V_T (SHP)\eta_0]T - 2\rho A [(SHP)\eta_0]^2 = 0 \quad [19]$$

Equation [19] can be solved numerically for T . The propeller efficiency η_p can then be computed using Equation [6].

η_p increases with the airplane's airspeed V_T and with propeller disk area A . The thrust of the propeller is proportional to the change in the momentum (velocity) of air produced by the propeller, but the energy required to produce this thrust is proportional to the *square* of the velocity change (change in kinetic energy). Hence it is more efficient to produce a given amount of thrust by accelerating a greater volume of air through a smaller velocity change, than a smaller volume of air through a greater velocity change.

The total thrust from the engines at the climb airspeeds and engine SHP settings indicated by Figures 5 and 6 can be computed using Equation [19]. The resulting thrust

can be used in Equation [5] to solve for D . The drag coefficient C_D and lift coefficient C_L in the climb conditions corresponding to Figures 5 and 6 then follow from

$$C_D = \frac{D}{\bar{q}S} \quad [20]$$

$$C_L = \frac{L}{\bar{q}S} \quad [21]$$

Where S is the airplane's reference wing area (225.8 ft.²), and $\bar{q}$ is the dynamic pressure of the air meeting the airplane, defined as

$$\bar{q} = \frac{1}{2}\rho V_T^2 \quad [22]$$

From Figure 8, the lift L is given by

$$L = W \cos \gamma - T \sin \alpha \quad [23]$$

As a first approximation, Equation [23] can be evaluated assuming $\sin \alpha \cong 0$. The α corresponding to the resulting L (and C_L) can then be estimated if the lift-curve (C_L as a function of α) at the corresponding configuration is known, and used in Equation [23] to update the calculation of L (and C_L). For this *Study*, the lift-curve of the Cessna 402C at flaps up and flaps 45° was estimated based on the airplane geometry, the wing efficiency (e) provided by Textron, and textbook methods.

D.7.3. Calculating $\dot{h}$ at any V_T & $\dot{u}$: flaps up, gear up & flaps 45°, gear down

Equation [5] can be used to compute the rate of climb $\dot{h}$ at any airspeed V_T and acceleration $\dot{u}$, if the thrust T and drag D are known. T can be computed from engine power and the flight condition using Equation [19], and D is given by Equation [20] if C_D is known. The C_D can be computed from C_L (itself given by Equations [23] and [21]) if the drag polar of the airplane in a given configuration is known.

As noted above, drag polars are classically modeled using Equation [1] (see, for example, References 8 and 9), but the C_{D0} and k values provided by Textron did not result in a good match of the $\dot{h}$ shown in Figures 5 and 6. However, the C_L and C_D in the POH/AFM climb condition (C_{Lc} and C_{Dc}), which are computed as described above, can be used to determine alternative values of C_{D0} and k that do result in a match of the $\dot{h}$ shown in Figures 5 and 6. From Equation [1], in the climb condition

$$C_{Dc} = C_{D0} + kC_{Lc}^2 \quad [24]$$

This is one equation containing two unknowns, C_{D0} and k . But C_{Lc} and C_{Dc} correspond to the airspeed for which $\dot{h}$ is a maximum (V_y), and the airplane is not accelerating. This fact can be used to find a second equation to help solve for the two unknowns.

For $\dot{u} = 0$, Equation [5] can be written

$$\dot{h} = V_T \left(\frac{T-D}{W} \right) \quad [25]$$

For small α and γ , $L \cong W$ (see Equation [23]) and Equation [25] becomes

$$\dot{h} \cong V_T \left(\frac{T}{W} - \frac{C_D}{C_L} \right) \quad [26]$$

For a given T/W , $\dot{h}$ is maximized when C_D/C_L is minimized. From Equation [1],

$$\frac{C_D}{C_L} = \frac{C_{D0}}{C_L} + k C_L \quad [27]$$

The C_L (and airspeed) at which C_D/C_L is minimized is that at which the derivative of C_D/C_L with respect to C_L is equal to zero. Taking the derivative of Equation [27] with respect to C_L and setting it equal to zero gives

$$\frac{\partial(C_D/C_L)}{\partial C_L} = -\frac{C_{D0}}{C_L^2} + k = 0 \quad [28]$$

But the C_L at this condition is simply the C_L at V_y , or C_{Lc} . Hence

$$k = \frac{C_{D0}}{C_{Lc}^2} \quad [29]$$

Combining Equations [24] and [29],

$$C_{Dc} = C_{D0} + k C_{Lc}^2 = C_{D0} + \left(\frac{C_{D0}}{C_{Lc}^2} \right) C_{Lc}^2 = 2C_{D0} \quad [30]$$

$$C_{D0} = \frac{C_{Dc}}{2} \quad [31]$$

Finally, substituting Equation [31] into Equation [29] gives

$$k = \frac{C_{Dc}}{2C_{Lc}^2} \quad [32]$$

And a drag polar that matches the climb data in the POH/AFM can be constructed using Equation [1] and values of C_{D0} and k given by Equations [31] and [32]. The values of C_{Dc} and C_{Lc} in these Equations are computed as described in Section D.7.2.

D.7.4. Calculating $\dot{h}$ at any V_T & $\dot{u}$: flaps up, gear down

The POH/AFM does not provide any climb charts (such as those shown in Figures 5 and 6) for the airplane in the flaps up, gear down configuration. Therefore, the method described in Section D.7.3 cannot be used to determine a drag polar for that configuration. However, the level-flight acceleration data provided by Textron (see Figure 7) can be used, along with Equation [5], to determine the rate of climb at any airspeed and acceleration in the flaps up, gear down configuration.

The data in Figure 7 corresponds to a level-flight condition for which $\gamma = 0$. For this condition, Equation [5] becomes

$$\left(\frac{T-D}{W}\right) = \frac{\dot{u}}{g} \quad [33]$$

Since $\dot{u}$ is given as a function of V_T in Figure 7, $(T - D)/W$ is also known over a range of airspeeds. With this information, Equation [5] can be solved for $\dot{h}$ and γ for any $\dot{u}$ (including $\dot{u} = 0$) over that same range, providing climb performance data for the flaps up, gear down configuration.

D.7.5. Climb performance calculation results

Figures 10a and 10b present the results of the climb performance calculations described in the previous sections. Figure 10a presents the results for zero-acceleration (constant-speed climb), and Figure 10b presents the results for an acceleration of 5 ft/s², the average acceleration between the last position derived from the Camera 2 video and the impact with the trees (see Section D.4 and Table 1).

In the zero-acceleration results (Figure 10a), the computed rate of climb matches the POH/AFM rate of climb at the best-rate-of-climb airspeed (V_y) for the flaps up, gear up configuration at takeoff power (310 SHP/engine), and for the flaps 45°, gear down configuration at maximum power (325 SHP/engine), as expected. In the flaps 45°, gear down case, the computed rate of climb actually exceeds the POH/AFM maximum rate of climb at a lower airspeed by about 50 ft./min.; this results from the higher thrust computed at the lower airspeed (see Equation [18]). C_{D0} and k in Equation [1] were derived by assuming that $\dot{h}$ in Equation [26] was maximized by minimizing C_D/C_L with T/W constant, but in fact, T/W also varies with airspeed. Nonetheless, the 50 ft./min. "exceedance" is relatively small, and Figures 10a and 10b provide a reasonable estimate of how the airplane's rate of climb varies with airspeed.

The speed range between 65 and 84 knots highlighted in Figures 10a and 10b corresponds to that possibly achieved by N88833 while airborne during the attempted takeoff. The lower bound of the range (65 KCAS) is the flaps 45° stall speed at 6,215

lb. (the lowest possible airborne speed). The upper bound (84 KCAS) is the speed at tree impact computed as shown in Figure 11, and is also the best-angle-of-climb airspeed (V_x) published in the POH/AFM.¹³ The top plot of Figure 11 shows N88833's ground speed as a function of the *Video Study* time, starting at the speed of the last Camera 2 position point (57.2 kt.), assuming a constant acceleration of 5 ft/s², and ending at the time of impact. The true airspeed and calibrated airspeed shown in Figure 11 are computed from the ground speed assuming a 9-knot tailwind.

The results in Figures 10a and 10b were computed with the METAR winds reported at 15:37 (210° at 10 knots, a 9 knot tailwind for runway 7), whereas the AWOS 1-minute data for 15:27 (closer to the landing time) recorded winds from 213° at 12 knots (an 11 knot tailwind). Thus, the actual tailwind was likely 2 knots greater than that used to compute the results shown in Figures 10a and 10b, which would affect the flight path angle relative to the Earth shown in the Figures slightly. In addition, the true and calibrated airspeeds shown in Figure 11 would be 2 knots lower with an 11 knot vs. 9 knot tailwind. (Additional weather data is presented in Section D.5 and Reference 6.)

Figures 7, 10a, and 10b indicate that both ground effect and achieved acceleration have a significant effect on the airplane's climb performance. As Textron noted when communicating the data in Figure 7 to the NTSB, "the documented POH takeoff distance calculations were performed using only parasitic drag (C_D) and ignored induced drag as a means to account for ground effect."

The physical basis and qualitative effects of ground-effect on an airplane's aerodynamics are well understood (see, for example, References 7-9). The airflow around the airplane cannot have a vertical component at the ground plane (i.e., air cannot flow into or out of the ground), and so the streamlines around the airplane are altered from what they would be in free air. Specifically, the downwash produced by the wing trailing vortices is reduced by the proximity of the ground plane, which in turn reduces the induced angle of attack and induced drag, and increases the C_L at a given α . These effects are sketched in Figure 12, which is taken from Reference 7.

Figure 1 shows that with the airplane resting on its landing gear, the wing is about 3.4 ft. from the ground. With a wingspan of 44.12 ft., the corresponding wing height to wingspan ratio (h/b) is about 0.076. Per Figure 12, ground effect would consequently reduce the induced drag by about 60% when the airplane is on the ground. Hence, the "no induced drag" line in Figure 7 (which represents a 100% reduction in induced drag) likely exaggerates the ground effect. At the tree impact height of 20 ft., $h/b \cong 0.5$ and Figure 12 indicates that the induced drag would only be reduced by about 10%. Nonetheless, ground effect improves acceleration on the ground and the initial climb rate because it reduces induced drag substantially.

¹³ POH/AFM presents V_x for flaps-up only.

Figure 10b indicates that while accelerating at 5 ft/s^2 (0.155 G) with the flaps up and the gear down, some ground effect is required to lift off; in free air (out of ground effect) all the engine power is required to overcome drag and accelerate the airplane. In the wreckage of N88833, the flaps were found up and the gear down. It is not known when the flaps were retracted, but it was likely on the ground soon after the pilot decided to abort the landing and attempt to take off again. This timing would be consistent with the procedures for a "touch-and-go," and the negative climb rate depicted in Figure 10b indicates that it is unlikely that the airplane could have accelerated and taken off with flaps 45° .

The results in Figures 10a and 10b suggest that N88833 was able to accelerate and take off from runway 7 with the assistance of ground effect, but as the height above the ground increased and ground effect decreased, the airplane could not maintain both its acceleration and its climb. Figure 10a suggests that if the lift-off airspeed had been maintained (without further acceleration), the airplane should have been able to achieve a flight path angle (γ) between 6° and 8° , which would have been sufficient to clear the trees (a normal glide path angle to landing on runway 25 would be only 3°). However, it is understandable if after having lifted off, the pilot would have wanted to accelerate to V_x before attempting to climb clear of obstacles, since γ is maximized at V_x . (Figures 10a and 10b show γ increasing below V_x , but the published flaps-up V_x might also have been selected to provide an adequate margin from stall warning.) In comments on a draft version of this *Study*, Cape Air noted that "it is not common to train crews to climb at speeds below V_x and V_y in twin-engine reciprocating aircraft."

D.8. Regulations and guidance concerning operations on wet runways

D.8.1. Overview

The surveillance video of the accident indicates that after touching down on runway 7 about 500 ft. from the threshold at 104 knots and decelerating to 57 knots (see Table 1), N88833 accelerated and lifted off in an apparent attempt to abort the landing and take off again. The deceleration achieved on the runway was substantially lower than the deceleration implied by the landing ground roll distances published in the POH/AFM (see below); consequently, it is reasonable to conclude that the pilot decided to abort the landing after perceiving that the airplane might overrun the runway before coming to a stop. Considering the lower-than-expected deceleration (or longer-than-expected landing roll), this accident has some similarities to several wet-runway landing overrun accidents investigated by the NTSB and described in Reference 10.

The accidents described in Reference 10 all involve transport or commuter category turbine-powered airplanes operated under 14 CFR 135 or 121. These operational regulations specify dry and wet runway landing distance safety margins for dispatching

turbine-powered airplanes (in §135.385 and §121.195), but these regulations do not apply to small, piston-powered, normal category airplanes with fewer than 10 passenger seats, such as the Cessna 402C. Furthermore, although not required by regulation, manufacturers of turbine-powered airplanes often include supplemental or “advisory” information in their AFMs for computing landing distances on wet or contaminated runways. AFMs of non-turbine powered airplanes rarely include such information. For example, the 2018 revision of the AFM of the Pilatus PC-12 (Reference 11), a single engine turboprop airplane, only states the following concerning landing performance on non-dry runways:

The take-off, accelerate-stop and landing distance performance chart data is based on a DRY TARMAC RUNWAY surface. Runways that are wet, or contaminated with slush or snow will adversely affect the runway coefficient of friction and subsequently increase the take-off, accelerate-stop and landing distance.

The Cessna 402C POH/AFM does not include a similar statement; it makes no reference at all to performance on wet or contaminated runways.

For Part 135 operators, the required landing distance provisions in §135.385 are usually reflected in their Operations Specifications (OpsSpecs) and General Operating Manuals, if they operate airplanes to which this regulation applies. As noted above, Section 2.14.2 of Cape Air’s GOM (“Preparation and Planning”) states that

Before each flight, the pilot shall become familiar with all available information concerning that flight. For all flights, this includes, but is not limited to:

- Runway lengths, and takeoff and landing distances
- ...

This content reflects the language of 14 CFR §91.103. However, the GOM does not provide any additional guidance or instructions for adjusting the POH/AFM landing distances to account for non-dry runway conditions. Similarly, while the PC-12 AFM cited above notes that a wet runway will increase the required landing distance, it does not offer any method for quantifying the increase. Thus, pilots of these small airplanes must rely on their own judgement and experience to select an appropriate safety margin for operations on wet or contaminated runways. In the absence of other guidance (such as Safety Alert for Operators (SAFO) 19001, discussed below), these pilots could consider using the dispatch requirements of §135.385 to help establish such margins.

D.8.2. Landing distance data in the Cessna 402C POH/AFM

According to the Type Certificate Data Sheet (TCDS) for the Cessna 402C (Reference 12), the airplane was certificated in 1978 in the “normal category” to Part 3 of the 1956

Civil Air Regulations (CAR), with various amendments and exclusions, and with various inclusions of and amendments to 14 CFR Part 23 dated from 1965.

CAR §3.780, "Performance Information," specifies the landing distance information that must be presented in the AFMs of airplanes certificated under CAR Part 3:¹⁴

Performance information. (a) Information relative to the following items of performance shall be included:

...

(4) The landing distance determined in accordance with §3.86, including the airplane configuration, if pertinent ...

The landing distance is defined in §3.86(a) as "the horizontal distance required to land and to come to a complete stop ... from a point at a height of 50 feet above the landing surface." Furthermore, §3.86(b) states that "the distance so obtained [and] the type of landing surface on which made ... shall be entered in the Airplane Flight Manual." 14 CFR §23.45(g), which is a successor to CAR §3.86(b), states explicitly that the landing distance of §23.75 "must be determined on a smooth, dry, hard-surfaced runway."

The regulations do not require the determination of landing distance on other than a dry runway (largely because of the difficulty of achieving a consistent "wet" or "contaminated" runway surface), though manufacturers may opt to include such information in AFMs as optional "advisory" data. The Cessna 402C POH/AFM only contains data for dry runways. (The POH/AFM states that the data is for a "level, hard surface runway," but doesn't explicitly state that the runway is dry. In response to an inquiry from the NTSB, Textron confirmed the data assumes a dry runway.)

Figure 14 duplicates part of Figure 5-25 of the POH/AFM, which depicts a table of the required landing distance (at flaps 45°) as a function of airplane weight, pressure altitude, and air temperature.¹⁵ The table provides both the ground roll distance (the distance required to stop once the airplane has touched down), and the total distance required starting from 50 ft. above the runway threshold (specified as the "total distance required to clear 50 feet"). A note in the table states, "for operations with tailwinds up to 10 knots, increase total distances by 14% for each 5 knots wind."

Interpolating the table in Figure 14 for sea level altitude, 20° C, and 6,215 lb. weight yields a speed at 50 ft. of 90 KIAS, and a total landing distance of 2,305 ft., including a

¹⁴ The parallel requirement for 14 CFR Part 25 (transport category) airplanes is §25.1587, and refers to landing distances determined under §25.125.

¹⁵ STC SA01763SE (Aircraft Payload Extender System) modifies Figure 5-25 of the AFM to account for a maximum gross weight of 7,200 lb. The STC does not affect the table at 6,215 lb. (the accident weight).

ground roll distance of 875 ft.¹⁶ The corresponding air distance (the distance from a point 50 ft. above the runway to touchdown) is 2,305 ft. - 875 ft. = 1,430 ft.

At the time of the accident, the tailwind component on the runway was about 11 knots; with this tailwind, Figure 14 specifies an on-speed landing distance of $[1 + (11/5) \times (0.14)] \times (2,305 \text{ ft.}) = 3,015 \text{ ft.}$ The required distance at the 5-kt. tailwind limit allowed by the Cape Air GOM would be $[1 + (5/5) \times (0.14)] \times (2,305 \text{ ft.}) = 2,628 \text{ ft.}$ Consequently, without any adjustment for wet runway conditions, the 3,502 ft. runway was long enough to accommodate the landing (with an 11-knot tailwind) within 86% of its length. However, the reduction in braking friction resulting from a wet runway increases the required landing distance significantly.

The average deceleration implied by the POH/AFM ground roll distance can be determined from the distance itself and the initial ground speed during the ground roll. For constant acceleration,

$$a = \frac{V_1^2 - V_0^2}{2(x_1 - x_0)} \quad [34]$$

Where:

a = acceleration (deceleration = negative acceleration)

V_0 = initial ground speed

V_1 = final ground speed

x_0 = initial position on runway

x_1 = final position on runway

As stated above, the Figure 14 ground roll distance, interpolated for the accident conditions, is 875 ft. The ground speed at the beginning of the ground roll can be estimated from the 90 KIAS airspeed interpolated from the table. The true airspeed (and ground speed, in calm wind) at this point is also 90 knots. Reference 13 indicates that the speed at touchdown can be estimated as approximately 96% of the speed at 50 ft.; in this case, the touchdown ground speed would be 90 knots $\times$ 0.96 = 86.4 knots.

Using $V_0 = 86.4 \text{ knots} = 145.8 \text{ ft/s}$, $V_1 = 0 \text{ ft/s}$, and $(x_1 - x_0) = 875 \text{ ft.}$ in Equation [34] gives a deceleration ($-a$) of $12.2 \text{ ft/s}^2 = 0.38 \text{ G}$. The actual deceleration of the airplane following touchdown, as estimated from surveillance video evidence, is about 5.15 ft/s^2 , or 0.16 G (see Table 1). This reduction in deceleration on a wet runway is not unexpected. Figure 15 compares the deceleration achieved during several wet-runway overrun events investigated by the NTSB. All of the events plotted in Figure 15 involve

¹⁶ The actual pressure altitude at KPVC with an altimeter setting of 29.79 "Hg is about 130 ft., and the actual temperature at the time of the accident was 21°C. These values are close to the landing distance table entries of sea level altitude and 20°C temperature.

turbine powered airplanes; some are equipped with thrust reversers, and most have ground spoilers that deploy on touchdown to reduce lift and increase the downforce on the main gear, thereby increasing the effectiveness of the brakes. All have anti-skid braking systems that modulate the brake pressure so as to maximize the braking force on the tires without skidding. The Cessna 402C does not have reverse thrust, spoilers, or an anti-skid braking system, yet the 0.16 G deceleration achieved in the KPVC accident is comparable to that achieved in several of these other events, most of which show deceleration significantly below 0.38 G.

D.8.3. 14 CFR Part 135 landing distance dispatch requirements

The accident flight was conducted under the provisions of Part 135. However, since the Cessna 402C is a small, normal category airplane with reciprocating engines and fewer than 10 passenger seats, the corresponding regulation regarding the runway lengths required at a destination airports is §91.103, "Preflight Action:"

Each pilot in command shall, before beginning a flight, become familiar with all available information concerning that flight. This information must include—

- (a) ...
- (b) For any flight, runway lengths at airports of intended use, and the following takeoff and landing distance information:
 - (1) For civil aircraft for which an approved Airplane or Rotorcraft Flight Manual containing takeoff and landing distance data is required, the takeoff and landing distance data contained therein; ...

Note that the regulation only specifies that the pilot in command shall "become familiar" with the available runway lengths and AFM takeoff and landing distances requirement; by implication, the runway lengths available should be at least as long as the AFM required lengths, but no safety factor on the available length is specified.

In contrast, for Part 135 operations with commuter or transport category airplanes, the use of the AFM landing distances required by §23.1587 is mandated by §135.385,¹⁷ which states, in part,

- (b) Except as provided in paragraph (c), (d), (e), or (f) of this section, no person operating a turbine engine powered large transport category airplane may take off that airplane unless its weight on arrival, allowing for normal consumption of fuel and oil in flight (in accordance with the landing distance in the Airplane Flight Manual for the elevation of the destination airport and the wind conditions expected there at the time of landing), would allow a full stop landing at the intended destination airport within 60 percent of the effective length of each runway ... from a point 50 feet above the intersection of the obstruction clearance plane and the runway.

¹⁷ The parallel requirement for Part 121 operations is in §121.195.

The AFMs for commuter and transport category airplanes typically include “factored” dry runway landing distances that are based on the actual (unfactored) landing distances for a dry runway, multiplied by a mandated safety factor of $1/0.6 \cong 1.67$; this guarantees that the actual demonstrated dry runway landing distance is at most 60% of the factored dry distance. For Part 135 operations, these factored dry distances are used by the crew during pre-flight planning to determine the dry-runway field length required and / or maximum allowable landing weight.

If, prior to takeoff, the destination runway is not forecast to be dry, then §135.385(d) applies:

(d) Unless, based on a showing of actual operating landing techniques on wet runways, a shorter landing distance (but never less than that required by paragraph (b) of this section) has been approved for a specific type and model airplane and included in the Airplane Flight Manual, no person may take off a turbojet airplane when the appropriate weather reports or forecasts, or any combination of them, indicate that the runways at the destination airport may be wet or slippery at the estimated time of arrival unless the effective runway length at the destination airport is at least 115 percent of the runway length required under paragraph (b) of this section.

Hence, when the destination runway is forecast to be wet, the wet factored landing distance is the dry factored distance multiplied by an additional safety factor of 1.15. This results in a required landing distance of about 1.92 times the actual, unfactored demonstrated dry runway distance $((\text{unfactored distance} / 0.6) \times 1.15 \cong \text{unfactored distance} \times 1.92)$. Note that this wet-runway landing distance is obtained by applying safety factors to demonstrated dry runway performance, not on actual demonstrated wet-runway landing performance.

The dispatch requirements of §135.385, if applicable, would have precluded dispatching the accident flight to KPVC at the planned arrival weight of 6,215 lb. As noted above, the zero-wind, dry runway landing distance for the arrival conditions from Figure 14 is 2,305 ft.; §135.385(b) would therefore require an arrival runway length of $2,305 \text{ ft.} / 0.60 = 3,842 \text{ ft.}$, 340 ft. longer than KPVC runway 7. To dispatch to KPVC with the expected wet (rain) arrival conditions, §135.385(d) would require an additional 15% of runway, for a total of $3,842 \text{ ft.} \times 1.15 = 4,418 \text{ ft.}$, 916 ft. longer than runway 7. The reduction in deceleration resulting from the wet runway conditions apparent in this accident, which is comparable to that seen in other wet-runway landing accidents, illustrates why the conservatism built into the 14 CFR Part 135 dispatch requirements is prudent. Though these regulations are intended primarily for turbine-powered airplanes that typically land at higher airspeeds than the Cessna 402C, this accident indicates that there is merit in applying their provisions to smaller, piston-powered airplanes as well. In the absence of other guidance, the 14 CFR Part 135 dispatch requirements can help the pilots of these other aircraft to fulfill their obligation under §91.103 to “become familiar with all available information concerning [their] flight” and evaluate the “runway lengths at airports of intended use” prudently.

D.8.4. FAA SAFO 19001

In March 2019, the FAA published Safety Alert for Operators (SAFO) 19001, titled *Landing Performance Assessments at Time of Arrival* (Reference 21). The SAFO states that it

... replaces cancelled SAFO 06012 and provides recommendations for airplane operators at airports reporting runway conditions following the procedures in AC 150/5200-30 (Airport Field Condition Assessments and Winter Operations Safety). This information is provided to assist operators in developing methods to ensure sufficient landing distance exists to safely make a full stop landing.

Runway conditions are reported “following the procedures in AC 150/5200-30” using the Runway Condition Assessment Matrix (RCAM), which defines six “runway condition codes” corresponding to different runway contamination conditions and friction levels (see Figure 22). Per AC 150/5200-30, the RCAM is

... the basis for performing runway condition assessments by airport operators and for interpreting the reported runway conditions by pilots in a standardized format based on airplane performance data supplied by airplane manufacturers for each of the stated contaminant types and depths. The concept attempts, to the maximum extent feasible, to replace subjective judgments of runway conditions with objective assessments which are tied directly to contaminant type and depth categories, which have been determined by airplane manufacturers to cause specific changes in the airplane braking performance.

SAFO 19001 notes that

14 CFR part 139 certificated and/or federally obligated airports use the procedures in AC 150/5200-30D to report runway surface conditions when they are not dry. These conditions may be reported using the RCAM in AC 150/5200-30D, when airport operators receive pilot braking action reports, or when surface conditions are other than dry.

KPVC is not a 14 CFR part 139 certificated airport, and does not have the means to report runway conditions per the RCAM as envisioned by SAFO 19001 and AC 150/5200-30D. Consequently, operators have to assess the runway condition at KPVC by other means, such as from AWOS reports of active or recent precipitation, or by communication with personnel on the ground (for example, the pilot of N88833 communicated with another Cape Air pilot who was holding short of runway 25, who informed him about the status of the runway lights and the visibility and rainfall trends).

SAFO 19001 recognizes that, for some airplane models (such as the Cessna 402C), manufacturers or third-party performance providers might not provide data for computing landing distances on runways that are not dry. The SAFO states:

If performance-provider data is not available, the landing distance factors (LDF) from Table 1 [of the SAFO], Landing Distance Factors, may be used. To find the Landing Distance Required

(LDR), multiply the certificated (i.e., AFM dry, unfactored) Landing Distance by the applicable LDF in Table 1 for the runway conditions existing at the time of arrival.

For a wet, smooth runway with good braking (an RCAM runway condition code 5, which could describe KPVC runway 7 at the time of the accident), Table 1 of the SAFO suggests a landing distance factor of 2.6 for airplanes with reciprocating engines (those likely to have neither reverse thrust nor anti-skid braking systems). This factor is even greater than the 1.92 wet-runway dispatch factor specified in 14 CFR §135.385(d) (discussed above).

In light of their experience, some operators of small, reciprocating-engine airplanes might consider the wet-runway safety factors specified in 14 CFR §135.385(d) and SAFO 19001 to be overly conservative and needlessly restrictive to operations. This is a legitimate concern, and underscores the need to establish reliable, deterministic methods that pilots can use to calculate actual landing distances that will be required on other than dry runways, and to which reasonable safety margins can be applied. The FAA has proposed such methods, using the RCAM, in AC 25-32, *Landing Performance Data for Time-of-Arrival Landing Performance Assessments*:

This advisory circular (AC) provides guidance and standardized methods that data providers, such as type certificate (TC) holders, supplemental type certificate (STC) holders, applicants, and airplane operators, can use when developing landing performance data for time-of-arrival landing performance assessments for transport category airplanes.

AC 25-32 is specific to transport category airplanes, but this accident suggests that the data envisioned by the AC would be beneficial to operators of all airplane types.

D.8.5. Operational guidance to pilots provided by Cape Air

The certification of air carriers and commercial operators in the USA is governed by 14 CFR §119.33(b)(3), which states that “a person other than a direct air carrier may not conduct any commercial passenger or cargo aircraft operation for compensation or hire under part 121 or part 135 of this chapter unless that person ... obtains operations specifications that prescribe the authorizations, limitations, and procedures under which each kind of operation must be conducted.” The content of operations specifications is defined in §119.49.

Hyannis Air Service Inc. (dba Cape Air) holds operations specifications (OpsSpecs) for its operations conducted under Parts 91 and 135. Cape Air’s *General Operations Manual* (GOM, Reference 3), Section 1.1, “General,” states that

This manual has been prepared in accordance with Federal Aviation Regulations Part 135. The procedures and policies contained herein supplement the regulations and are considered essential to good operating practices and safety. The contents of this manual shall not be construed to be contrary to any Federal Aviation Regulation or any applicable State or Foreign

Regulation. All operations shall be conducted in compliance with all applicable aircraft operating rules and as required by the Federal Aviation Regulations and in States in whose airspace the operations are conducted.

This manual shall be used for guidance of management, flight, ground and maintenance personnel of the company in the conduct of its operations of aircraft in compliance with FAR Part 135 and the Operations Specifications.

Within this manual are specific instructions, information and facts necessary for all personnel to carry out their duties and responsibilities with the utmost safety and continuity.

Section 2.14.2 of Cape Air's GOM ("Preparation and Planning") states that

Before each flight, the pilot shall become familiar with all available information concerning that flight. For all flights, this includes, but is not limited to:

- Runway lengths, and takeoff and landing distances
- ...

This content reflects the language of 14 CFR §91.103. However, the GOM does not provide any additional guidance or instructions for adjusting the POH/AFM landing distances to account for non-dry runway conditions.

To address non-dry runway conditions, Cape Air provides pilots with training regarding "Adverse Weather Practices" (Reference 22), which includes a module on "Operations from Contaminated Runways." This module notes that:

- Normal landing distance calculations for the [Cessna] 402C ... are predicated on Level, Hard Surface Runway and don't take into account contamination.
- The FAA recommends pilots follow the recommendations of The Safety Alert For Operators (SAFO 19001) for operating on wet or contaminated runways.
- The SAFO recommends adding a safety margin of *at least* 15% be added to the actual airplane landing distance. [Emphasis in original]

The training addresses the RCAM and gives examples of RCAM-driven Notices to Airmen (NOTAMs), and discusses the effects of hydroplaning. The training material also notes that the FAA recommends that pilots follow the recommendations of SAFO 19001 for operations on wet or contaminated runways. In correspondence with the NTSB, Cape Air indicated that the 15% safety margin recommended by the SAFO is applied to the dry-runway landing distances to account for reduced performance on wet runways, and that in their experience this margin is sufficient. (The 2.6 factor from Table 1 of the SAFO, described above, is not used.)

Regarding the conduct of landings, the Cessna 402C POH/AFM states:

Landings are conventional in every respect. A power approach is used down to 50 feet above ground level using power as required to stabilize the approach speed and attitude with wing flaps fully extended, landing gear extended and airspeed of 95 KIAS.

This POH/AFM landing procedure calls for stabilizing the “approach speed and attitude” in the landing configuration. Similarly, the Cape Air GOM requires adherence to the “Stabilized Approach” concept:

2.19.7 Stabilized Approach

All approaches are to be flown in adherence with the Stabilized Approach concept. An approach is stabilized when all of the following criteria are met:

- The aircraft is on the correct flight path.
- Only small changes in heading/pitch are required to maintain the correct flight path.
- The aircraft speed is not more than 149 KIAS (C402), $V_{app} + 20$ (P2012) or 114 KIAS (BN2) and not less than landing speed (VLDNG) or V_{ref} (P2012 threshold crossing speed).
- The aircraft is in the correct landing configuration (flaps as required).
- Sink rate is not greater than 1000 feet per minute; if an approach requires a sink rate greater than 1000 feet per minute, a special briefing should be conducted. A rate of descent in excess of 1500 feet per minute is never permitted.
- Power setting is appropriate for the aircraft configuration and is not below the minimum power for the approach as defined in the Normal Procedures Handbook (NPH) or Flight Crew Operating Manual (FCOM).
- All briefings and checklists have been conducted.
- Specific approach criteria:
 - ILS approaches must be flown within one dot of the glideslope and localizer.^[18]
 - During a circling approach, wings should be level on final when the aircraft reaches 300 feet above airport elevation.
- Unique approach procedures or abnormal conditions requiring a deviation from the above elements of a stabilized approach require a special briefing. An approach that becomes unstabilized below 1000 feet above airport elevation in IMC [Instrument Meteorological Conditions] or below 500 feet above airport elevation in VMC [Visual Meteorological Conditions] requires an immediate go-around. Go-Around maneuvers are a no jeopardy event and should be executed anytime a pilot determines the continuance of an approach is unsafe.

NOTE:

Flying a stabilized approach that meets the above criteria does not preclude flying a delayed flaps approach to comply with air traffic (ATC) instructions.

While the GOM states that for the Cessna 402 the airspeed should not be “more than 149 KIAS ... and not less than landing speed,” Cape Air provides additional ILS approach performance standards in their Normal Procedures Handbook (NPH). For the final approach segment of an ILS approach, the NPH states that the airspeed should be 120 +5/-0 KIAS. Further, Cape Air’s “Adverse Weather Practices” training emphasizes the importance of a stabilized approach, which “requires the pilot to maintain a constant rate of decent and airspeed.” The NPH states that the speed should

¹⁸ On the King KCS-55A instrument used in Cape Air’s Cessna 402C airplanes, full-scale glide slope deviation is 2 dots (as shown in Figure 18), and full-scale localizer deviation is 5 dots.

be stabilized at 120 KIAS by 1,000 ft. AGL in Instrument Meteorological Conditions (IMC), and by 500 ft. AGL in Visual Meteorological Conditions (VMC).

In discussions with the NTSB, Cape Air explained that the approach speed of 120 knots (vs. the 95 KIAS noted in the POH/AFM) keeps the airplane above the single-engine best rate-of-climb speed ($V_{y,se}$), as recommended in the FAA Airplane Flying Handbook (Reference 23):

The final approach should be made with power and at a speed recommended by the manufacturer; if a recommended speed is not furnished, the speed should be no slower than the single-engine best rate-of-climb speed (VYSE) until short final with the landing assured, but in no case less than critical engine-out minimum control speed (VMC). Some multiengine pilots prefer to delay full flap extension to short final with the landing assured. This is an acceptable technique with appropriate experience and familiarity with the airplane.

Cape Air also notes that approaching at 120 KIAS with a reduced flap setting reduces drag and the power required on approach, and eases mixing with faster traffic at larger airports. Although the POH/AFM does provide a recommended approach speed of 95 KIAS at flaps 45°, Textron indicated in correspondence with the NTSB that Cape Air's approach method was reasonable, as long as the airplane is transitioned from the approach phase to the landing phase in time to be at flaps 45° and at the POH/AFM recommended speed when 50 ft. above the runway. Consistent with this requirement, the NPH calls for flaps 45° by 200 ft. AGL, and instructs pilots to

maintain a glide path that will result in a landing in the touchdown zone at touchdown speed. Airspeed of 95 KIAS is desired when crossing the threshold at an altitude of 50' AGL. Normally, throttles are continuously retarded throughout the landing flare allowing the airplane to touchdown, main wheels first, slightly above stall speed.

As shown in Figure 21, during the accident approach the airspeed remained above 125 KCAS until about 15:26:16, as the airplane was descending through 650 ft. MSL. Consequently, above 650 ft. MSL the airspeed exceeded the 120 +5/-0 KIAS final approach segment target prescribed in the NPH. Figure 21 indicates that the ground speed from 15:25:00 to 15:25:40 (between 1,560 and 1,000 ft. MSL) was relatively constant at about 144 knots; for the indicated airspeed to be no more than 125 knots during this time would require a tailwind of 16 knots (accounting for a 3 knot difference between true and indicated airspeeds at altitude). This magnitude of tailwind is not consistent with the winds indicated by the HRRR model in Table 4.

Figure 17 indicates that N88833 was at 58 ft. MSL (50 ft. above the runway) at about 15:27:00; at that time, the airspeed was 107 KCAS (and 110 KIAS at flaps 45°, per the airspeed calibration table in the POH/AFM). Consequently, the airplane was 15 KIAS above the 95 KIAS target at 50 ft. AGL recommended by the POH/AFM and the NPH. Considering that at the accident weight (6,215 lb.) the target speed at 50 ft. is 89 KCAS / 90 KIAS, at 110 KIAS the airplane was 20 KIAS faster than this target.

Cape Air's GOM states that for a stabilized approach, "sink rate is not greater than 1,000 feet per minute," and "ILS approaches must be flown within one dot of the glideslope and localizer." As shown in Figures 18 and 21, the ADS-B data indicates that the airplane deviated above the ILS glideslope one-dot "fly down" beam as it descended through an altitude of about 600 ft. MSL,¹⁹ and that the sink rate exceeded 1,000 ft./min. briefly as the airplane descended through an altitude of about 400 ft. MSL. The Captain reported breaking out of the clouds at 500 ft. above ground level (AGL);²⁰ if so, the airplane was in IMC when it was over 1-dot high on the glideslope, and in VMC when the sink rate exceeded 1,000 ft./min. According to the GOM, "an approach that becomes unstabilized below 1,000 feet above airport elevation in IMC or below 500 feet above airport elevation in VMC requires an immediate go-around." Although the glideslope deviation exceeded the GOM stabilized approach criteria in IMC below 1,000 ft. AGL and the sink rate exceeded the criteria in VMC below 500 ft. AGL, a go-around was not executed.

In their comments on a draft version of this *Study*, Cape Air noted that an explanation for the deviation above the glideslope one-dot "fly down" beam might be the "ballooning" effect of extending the flaps to 45° once the airplane was below the clouds and the runway was in sight:

[The *Study*] mentions the aircraft deviating one-dot high on the glideslope followed by sink rate "briefly" exceeding 1000 ft/min at around 600 ft MSL:

- Though the pilot indicated breaking out at 500 feet, these two data points are indicators that the crew may have broken out of IMC closer to 600 ft.
- Once the crew breaks out, the flaps are dropped to 45, this causes a slight "balloon" effect followed by increased sink rate as drag is increased.

If the airplane indeed deviated above the 1-dot "fly down" indication as a result of this ballooning effect as the flaps were lowered in VMC, then the glideslope exceedance did not occur in IMC conditions and the "immediate go-around" called for by the GOM did not apply. Nonetheless, the excessive airspeed (above 125 KIAS) until 650 ft. MSL, the sink rate exceedance at 400 ft. MSL, and the excessive airspeed at 50 ft. AGL are indicators that the approach was not stabilized and that a go-around was warranted.

¹⁹ The ILS glideslope centerline and deviation beams depicted in Figure 18 (and the localizer centerline deviation beams depicted in Figure 16) are based on the KPVC runway 7 ILS inspection report dated 12/02/2021 (Reference 14).

²⁰ See Reference 15.

D.9. Sequence of events during the approach, landing, and attempted takeoff

This *Study* examines the performance of N88833 from the time it descended through about 1,100 ft. above mean sea level (MSL) on final approach, through its landing and deceleration on runway 7, to its attempted takeoff shortly after landing and its subsequent impact with trees 660 ft. past the departure end of runway 7. Preceding sections of the *Study* contain detailed presentations and analyses of the data used to evaluate N88833's performance during the different segments of its trajectory; the results of these analyses are summarized and presented in this section and its accompanying Figures as a timeline or sequence of events.

At 15:25:40, N88833 descended through 1,100 ft. MSL centered on the localizer for the ILS approach to KPVC runway 7 (see Figures 16 and 17). The airplane was slightly above the ILS glideslope centerline, at an airspeed of 129 KCAS and descending at about 760 ft./min. (see Figures 18 and 21). The airspeed was slowly decaying, at about 1 knot every 10 seconds. Since the airplane was not equipped with (or required to be equipped with) an FDR, it is not known when the flaps or gear were extended.

At 15:26:15, at about 660 ft. MSL, the deceleration increased to about 6 knots every 10 seconds. At about the same time, the airplane started to deviate further above the ILS glideslope centerline, and at 600 ft. MSL exceeded the ILS glideslope 1-dot "fly down" beam (see Figure 18). At 15:26:38, the sink rate exceeded 1,000 ft./min. briefly as the airplane descended through an altitude of about 400 ft. MSL. The Captain stated he did not break out of the clouds until 500 ft. AGL, but Cape Air points out that the glideslope exceedance might have been the result of the "ballooning" effect of extending the flaps to 45° after breaking out of the clouds closer to 600 ft. AGL. If the cloud base was at 500 ft. (as reported by the Captain), then the airplane was below 1,000 ft. MSL and still in IMC when the glideslope exceedance occurred. Per the GOM, this should have triggered "an immediate go-around." If the cloud base was closer to 600 ft. AGL, then the airplane was likely in VMC when the exceedance occurred, and the GOM would not have required a go-around. However, the GOM would still have required a go-around when the sink rate exceeded 1,000 ft./min. at 400 ft. AGL.

The last ADS-B data point was received at 15:27:04.5, 100 ft. past the runway threshold at an altitude of 16 ft. MSL (about 8 ft. above the runway), and a recorded ground speed of 109 knots. With an 11 knot tailwind, the true and calibrated airspeeds would have been 98 KTAS and 97 KCAS, respectively.²¹ Per the POH/AFM, at the airplane's planned landing weight of 6,215 lb., the calibrated airspeed 50 ft. above the runway should

²¹ The final airspeeds shown in Figure 21 are about 3 knots higher than those cited here as a result of numerical artifacts associated with integrating the recorded ADS-B ground speed to get position, and then taking the derivative of the resulting position to get a ground speed from which the airspeeds are computed using the assumed wind. This effect is only notable for the last ADS-B data point.

have been 89 KCAS / 90 KTAS. N88833 was at 58 ft. MSL (50 ft. above the runway) at about 15:27:00; at that time, the airspeed was 107 KCAS / 108 KTAS, or 18 knots above the POH/AFM airspeed.

As described in the NTSB *Video Study*, three video cameras recorded N88833's movements at KPVC. The *Video Study*'s analysis of the recordings from Cameras 1 and 2 indicates that N88833 touched down about 500 ft. from the threshold at a ground speed of 104 knots, and then decelerated at an average rate of 5.15 ft/s^2 (0.16 G) to 57 knots before passing out of the field of view of Camera 2 (see Table 1). Although Camera 3 recorded N88833's lift-off and subsequent impact with trees, the speed and position of the airplane could not be determined from the recording because Camera 3 could not be calibrated accurately. However, Camera 3 did provide the time of the tree impact, and together with the speed and position data from Camera 2 and the known tree impact location, the average acceleration of N88833 between the end of the Camera 2 recording and the tree impact was determined to be 5.0 ft/s^2 (0.155 G).

The precise time and location at which the pilot decided to abort the landing and attempt to take off, and the minimum speed of the airplane during the landing roll, is not known. Nor is it known when the pilot raised the flaps, though it would be reasonable to assume he did so shortly after deciding to abort the landing.

The climb performance analysis presented in Section D.7 indicates that it is unlikely that N88833 could have climbed out of ground effect while simultaneously accelerating at 5.0 ft/s^2 . The analysis suggests that if the airspeed had been kept constant after liftoff, even though below V_x , the airplane would likely have achieved a climb angle high enough to clear the trees. However, it is understandable that a pilot might think that his best chance of clearing obstacles is to first accelerate to V_x , and then to climb while holding V_x . Unfortunately, in this case there was insufficient space to clear the trees by first accelerating to V_x before climbing.

The *Video Study* estimates that if N88833 had continued decelerating from 57 knots at 5.15 ft/s^2 , instead of accelerating and lifting off again, it would have stopped "between about 68 feet before the end of the runway and 88 feet beyond the end of the runway." Given the outcome of the attempted takeoff, in hindsight the better option would have been to accept an overrun into the open area beyond the end of runway 7.

D.10. The Owatonna BAe-800A accident and FAA InFO 17009

A 2008 accident involving a Hawker Beechcraft BAE 125-800A business jet has some similarities to the N88833 accident. On July 31, 2008, a BAE 125-800A was destroyed when it impacted terrain during an attempted go-around from runway 30 at the Owatonna Degner Regional Airport (KOWA), Owatonna, Minnesota. The non-scheduled domestic passenger flight was operating under the provisions of Title 14

CFR Part 135. The pilot, co-pilot, and six passengers sustained fatal injuries. The airplane landed in VMC conditions, and the runway was wet.

The NTSB determined that the probable cause of the Owatonna accident was

the captain's decision to attempt a go-around late in the landing roll with insufficient runway remaining. Contributing to the accident were (1) the pilots' poor crew coordination and lack of cockpit discipline; (2) fatigue, which likely impaired both pilots' performance; and (3) the failure of the Federal Aviation Administration to require crew resource management training and standard operating procedures for Part 135 operators.

In response to NTSB recommendations resulting from the Owatonna accident, in July 2017 the FAA issued "Information for Operators" (InFO) 17009 (Reference 16) "to inform operators of turbine-powered aircraft about the importance of establishing a point during landing where a go-around or rejected landing procedure will not be initiated and the only option will be bringing the aircraft to a stop."

Specifically, the InFO states that

The FAA has investigated the potential benefits and risks associated with incorporating a committed-to-stop point in the Aircraft Flight Manual [as originally recommended by the NTSB in Safety Recommendation A-11-18, now classified "Closed - Reconsidered"]. However, operational factors are too numerous and varied to establish a single committed-to-stop point. The FAA believes operators are in the best position to make this determination for their operation and type aircraft. Operators who establish committed-to-stop points would eliminate ambiguity for pilots making decisions during time-critical events.

Operators of turbine-powered aircraft should establish SOPs [standard operating procedures] for flightcrews to determine a point after touchdown where a go-around will not be initiated and the only option would be to bring an aircraft to a stop. This could be accomplished by any single procedure or combination of procedures, such as committing to stop following deployment of reversers or lift-dump, spoilers, or speedbrakes (if equipped); committing to stop below a certain airspeed (e.g., less than 80 knots), and/or runway distance remaining. Committed-to-stop points should be included in the approach briefing and incorporated into the operator's SOP, the flight operations manual, initial and recurrent training, and the crew resource management training program.

Although the InFO is intended for operators of turbine-powered aircraft, the circumstances of the N88833 accident suggest that the advice provided in the InFO is relevant to operators of piston-powered aircraft as well.

E. CONCLUSIONS

The material in this *Study* supports a number of observations and conclusions regarding the performance of N88833 during its approach to, landing on, and attempted takeoff from KPVC runway 7. Section D.9 of this *Study* describes the sequence of events during the approach, landing, and attempted takeoff, and Section

C.3 summarizes the results of analyses of the airplane's performance during each segment. The following observations from these Sections are particularly noteworthy:

- N88833 touched down about 18 knots faster than the speed assumed in the landing distance tables published in the POH/AFM.
- The deceleration achieved on the wet runway was significantly less than the deceleration assumed in the landing distance tables published in the POH/AFM, but is comparable to the deceleration achieved in other wet-runway landing overruns investigated by the NTSB.
- The fast touchdown speed and reduced deceleration significantly increased the distance that would have been required to stop the airplane.
- In the absence of other guidance, pilots of normal category airplanes could consider using the 14 CFR Part 135 dispatch requirements for transport-category airplanes to help establish safety margins for landings on wet or contaminated runways. These requirements result in safety factor of 1.92 applied to the unfactored, dry runway landing distances. The equivalent safety factor for reciprocating-engine airplanes proposed by SAFO 19001 is 2.6.
- Operators of all airplane types, not just turbojet airplanes, would be well served by having data available with which to compute required landing distances on runways that are not dry. Such data could be produced per the methods proposed in AC 25-32, *Landing Performance Data for Time-of-Arrival Landing Performance Assessments*.
- N88833's airspeed remained above the 120 +5/-0 KIAS approach speed target specified in the Cape Air Normal Procedures Handbook (NPH) until the airplane descended below 650 ft. AGL.
- During the ILS approach, N88833 might have exceeded the stabilized approach glideslope deviation criteria contained in the GOM, and did exceed the GOM stabilized approach sink rate criteria. Either exceedance should have triggered "an immediate go-around," but did not.
- N88833's airspeed at 50 ft. AGL was 110 KIAS, 15 KIAS higher than the 95 KIAS specified in the Cessna 402C POH/AFM and Cape Air's NPH, and 20 KIAS higher than the 90 KIAS target corresponding to the accident weight of 6,215 lb.
- The climb performance analysis indicates that after lifting off from the runway, it is unlikely that N88833 could have simultaneously climbed out of ground effect and accelerated continuously at the average 5.0 ft/s² derived from the surveillance camera recordings.
- N88833 could have achieved a higher climb angle and likely cleared the trees if it had maintained a constant airspeed after liftoff, instead of accelerating, even

though the airspeed was below V_x . However, it is understandable that a pilot would attempt to accelerate to V_x before climbing to clear obstacles.

- Given the outcome of the attempted takeoff, the better option would have been to accept an overrun into the open area beyond the end of runway 7.
- The circumstances of this accident suggest that the advice in FAA InFO 17009 that operators establish a “committed-to-stop” point for landings, though intended for operators of turbine aircraft, is relevant to operators of piston-powered aircraft as well.

Submitted by:

John O’Callaghan
National Resource Specialist – Aircraft Performance

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G. GLOSSARY

Acronyms

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance – Broadcast
AFM	Airplane Flight Manual
AGL	Above ground level
AWOS	Automated Weather Observation Station
CFR	Code of Federal Regulations
CG	Center of Gravity
CVR	Cockpit Voice Recorder
dba	Doing business as
EDT	Eastern Daylight Time
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
GNSS	Global Navigation Satellite System
GOM	Cape Air General Operations Manual
GPS	Global Positioning System
“Hg	Inches of mercury
HP	Horsepower
HRRR	High Resolution Rapid Refresh winds-aloft model
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
InFO	FAA Information for Operators publication
KBOS	Boston-Logan International Airport, Boston, Massachusetts
KCAS	Knots calibrated airspeed
KIAS	Knots indicated airspeed
KOWA	Owatonna Degner Regional Airport, Owatonna, Minnesota
KPVC	Provincetown Municipal Airport, Provincetown, Massachusetts
KTAS	Knots true airspeed
METAR	Meteorological Terminal Air Report
MP	Manifold pressure
MSL	Mean Sea Level
NOAA	National Oceanic and Atmospheric Administration
NPH	Cape Air Normal Procedures Handbook
NTSB	National Transportation Safety Board
POH	Pilot’s Operating Handbook
RCAM	Runway Condition Assessment Matrix
SAFO	Safety Alert for Operators
SHP	Shaft horsepower
SPECI	Aviation Select Special Weather Reports
STC	Supplemental Type Certificate
UTC	Universal Coordinated Time
VMC	Visual Meteorological Conditions

Symbols

α	Angle of attack
γ	Flight path angle
θ	Pitch angle
η_0	Profile propeller efficiency

η_i	Ideal propeller efficiency
η_P	Total propeller efficiency
ρ	Air density
μ_B	Wheel braking friction coefficient
a	Acceleration
A	Propeller disk area
AR	Wing aspect ratio = span ² /area
C_D	Drag coefficient
C_{D0}	Drag coefficient at $C_L = 0$
C_{DC}	Drag coefficient at best rate of climb
C_L	Lift coefficient
C_{LC}	Lift coefficient at best rate of climb
C_T	Thrust coefficient
d	Propeller diameter
D	Drag
e	Oswald's wing efficiency factor (see Equation [1])
F_x	Force along x axis
g	Acceleration due to gravity
h	Altitude
$\dot{h}$	Rate of climb (time derivative of $h = dh/dt$)
HP	Power delivered to the airplane to increase its energy state (less than the <i>SHP</i> of the engines because of losses due to propeller efficiency)
k	Induced drag coefficient constant (see Equation [1])
L	Lift
m	Mass
Q	Pitch rate (angular velocity about the y axis)
$\bar{q}$	Dynamic pressure
R	Yaw rate (angular velocity about the z axis)
RC	Rate of climb
S	Wing area
SHP	Shaft horsepower produced by the engine(s)
Δt	Time increment between data samples
t	Time
T	Thrust
u	Airplane velocity along x axis
$\dot{u}$	Time derivative of $u = du/dt$
v	Airplane velocity along y axis, or velocity of air in propeller's stream tube
V_0	Initial ground speed
V_1	Air velocity at the propeller disk or final ground speed
V_2	Final velocity of air accelerated through propeller disk
V_T	True airspeed
W	Weight
w	Airplane velocity along z axis
x	Distance along stream tube flowing through propeller
x_0	Initial position on runway
x_1	Final position on runway

FIGURES

THREE-VIEW DRAWING

MAXIMUM HEIGHT OF AIRPLANE WITH
NOSE GEAR DEPRESSED IS 11.75'.

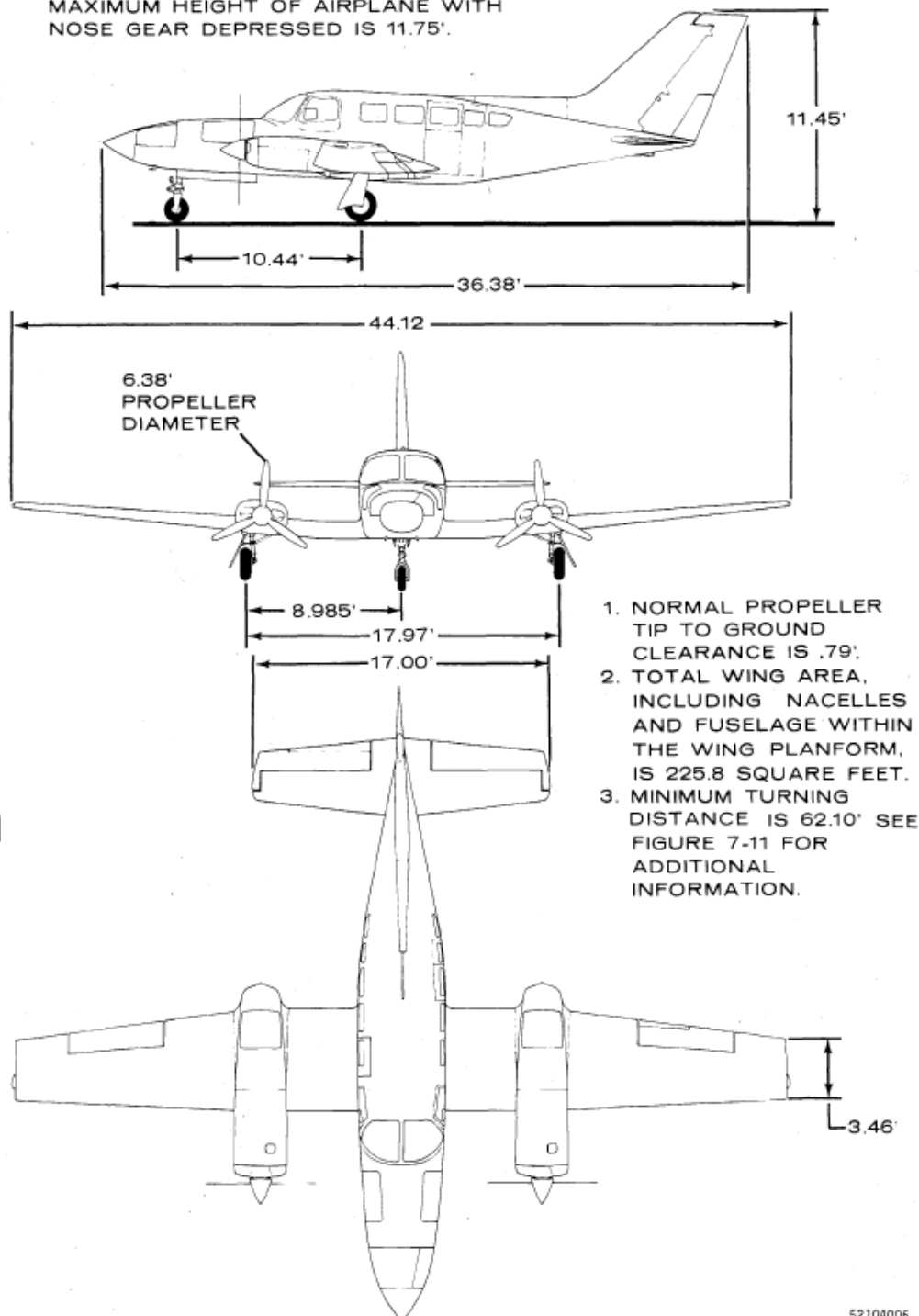


Figure 1-1

52104006
52104007

1 November 1979
Revision 2 - 3 Aug 1981

Figure 1. 3-view of the Cessna 402C airplane (from Reference 2).

Cessna 402C AutoWB™ 8.1.11

AC Master 07/12/21

Pilot

Aircraft N88833

Weigh Date: 03/24/20

Flight # 2072

Takeoff Fuel: 600 100 gal

Fuel Burn 90 15 gal

Route BOS-PVC

Co-Pilot None

Takeoff Wt 6305 7210 lbs max

Landing Wt 6215 7200 lbs max

Zero Fuel Wt 5705 6750 lbs max

Total available payload 779

	Takeoff CG(in)	Landing CG(in)	Max Lnd Wt (lbs)	Excess Alt A	Capacity Alt B
Heaviest Fwd	155.80	155.66	7200	293	0
Row5 Empty	158.87	158.78	7124	109	0

Seat#	Wt	Wing	Lap
Pilot	185	Bags	Infant
1	160		
2	165		
3	120		
4	130		
5	185		
6	167		
7			
8			
9			

Left Wing (200 lbs) 0

Right Wing (200 lbs)

Total Pax Wt: 987

Number of Pax: 6

	Baggage	Sand	Total
AV (244 lbs)	30		30
Nose (281 lbs)	72		72
Alt A (400 lbs)			
Alt B (100 lbs)			

Remarks:

Note! Row 5 must be empty.

Vlof 91

Vy 104

Vyse 100

Vrdg 85

Va 143

Flight 2072 Pax: 6

BOS-PVC

OUT

OFF

ETA

ON

IN

Captain:

09/09/21 15:54

Fwd CG Limit

Takeoff Landing Limit

150.30 150.09 160.7

Alt CG

Wt (lbs)

CG (Inches)

Max Takeoff Wt = 7210

Max Landing Wt = 7200 - 7004

Max Zero-Fuel Wt = 6515 - 6750

WEIGHT (lbs)

CG (Inches)

◆ Takeoff

● Landing

○ Zero Fuel

The Captain's CREW ID has been physically verified. The aircraft and flight assignment have been confirmed by the station agent. The GSC has communicated pertinent security information to the ISC.

The Captain acknowledges responsibility for completion of the aircraft search prior to departure.

Crew Search by:

Time of Aircraft Search: 1500 Ramp Agent Search by: 9K9K1513

2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2106 © Upside Aviation, LLC

Figure 2. Cape Air weight and balance form for the accident flight.



Time = 0.00 sec.



Time = 1.42 sec.



Time = 2.92 sec.



Time = 4.08 sec.



Time = 4.50 sec.



Time = 4.58 sec.



Time = 4.75 sec.



Time = 6.83 sec.



Time = 9.17 sec.

Figure 3. Selected frames from security camera video depicting departure from runway 7 and impact with trees. Note that the time intervals between the selected frames are not uniform.

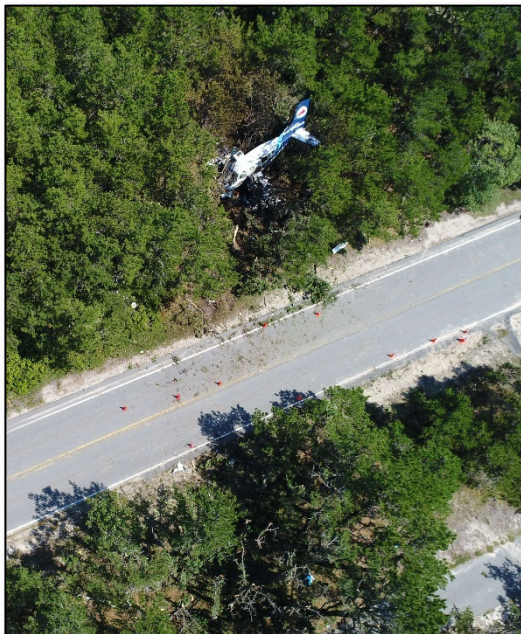
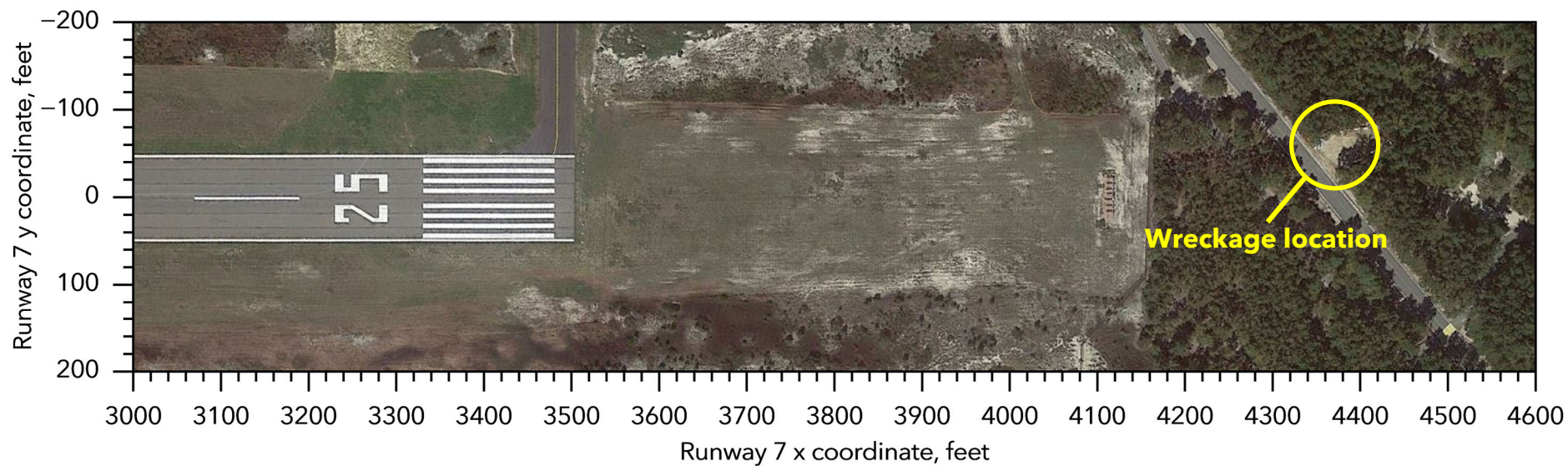


Figure 4. Google Earth image of runway end and tree line (top); photographs of accident site.

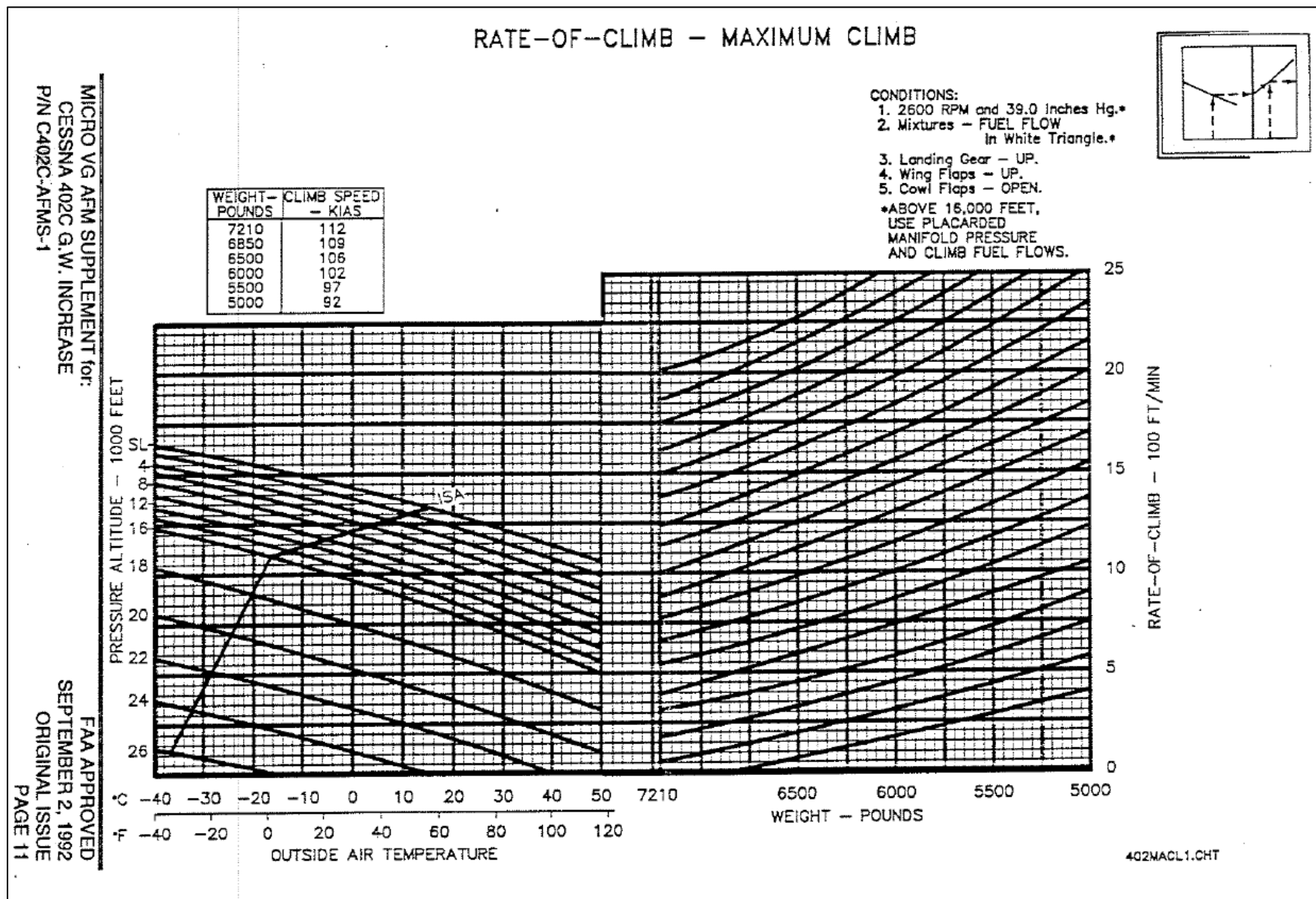
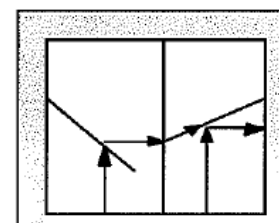


Figure 5. Maximum rate of climb chart for flaps up, gear up from the Cessna 402C Micro VG AFM supplement (Reference 18).

SECTION 5 – PERFORMANCE (CONTINUED)



CONDITIONS:

1. 2700 RPM and 39.0 Inches Hg.
2. Mixtures Check Fuel Flows In White Arc.
3. Landing Gear – DOWN.
4. Wing Flaps - 45°
5. Cowl Flaps – OPEN.
6. Climb Speed – Refer to Table

WEIGHT - POUNDS	CLIMB SPEED - KIAS
7200	95
6850	92
6500	89
6000	85
5500	84
5000	84

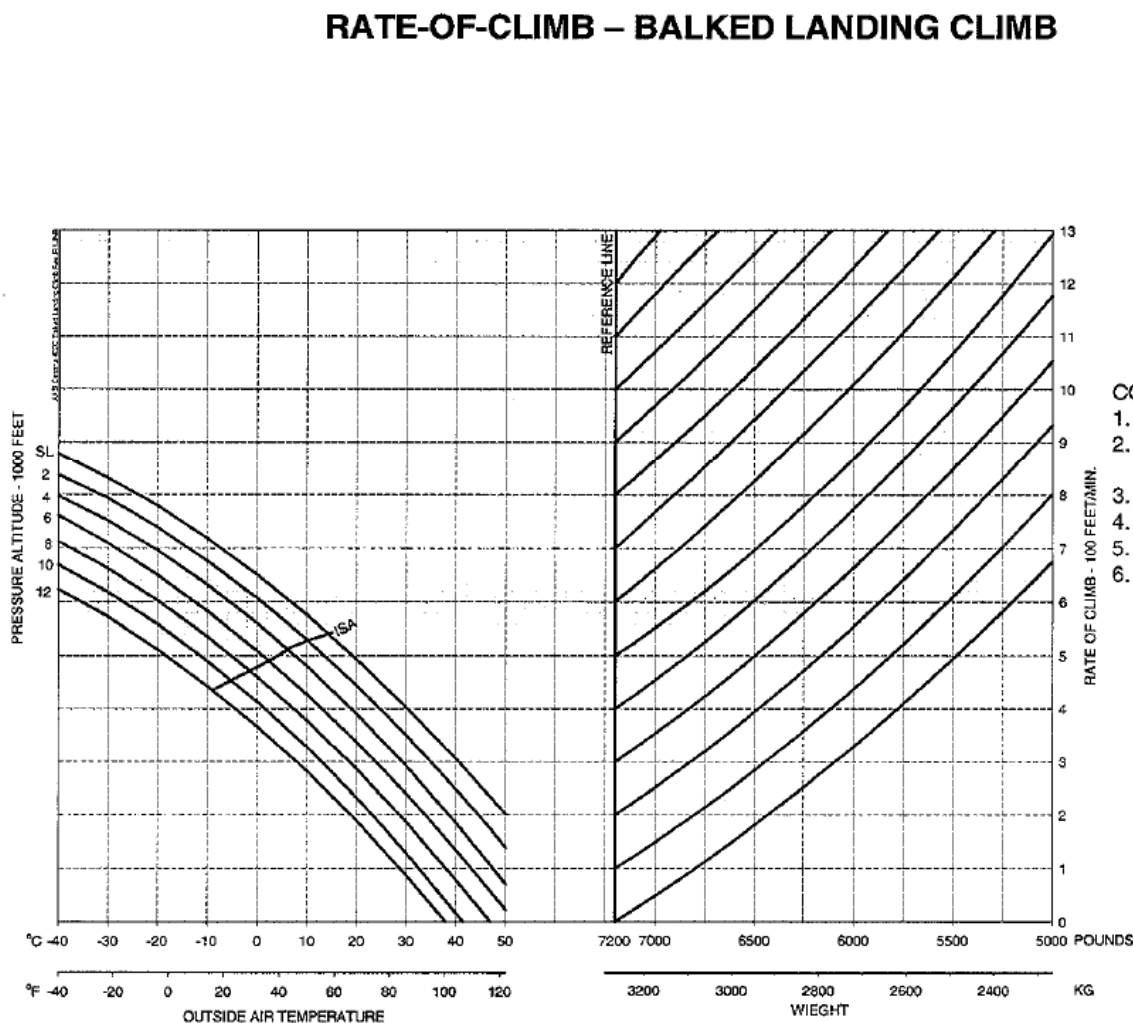


Figure 6. Maximum rate of climb chart for flaps 45°, gear down from the Cessna 402C AeroAcoustics Payload Extender POH supplement (Reference 19).

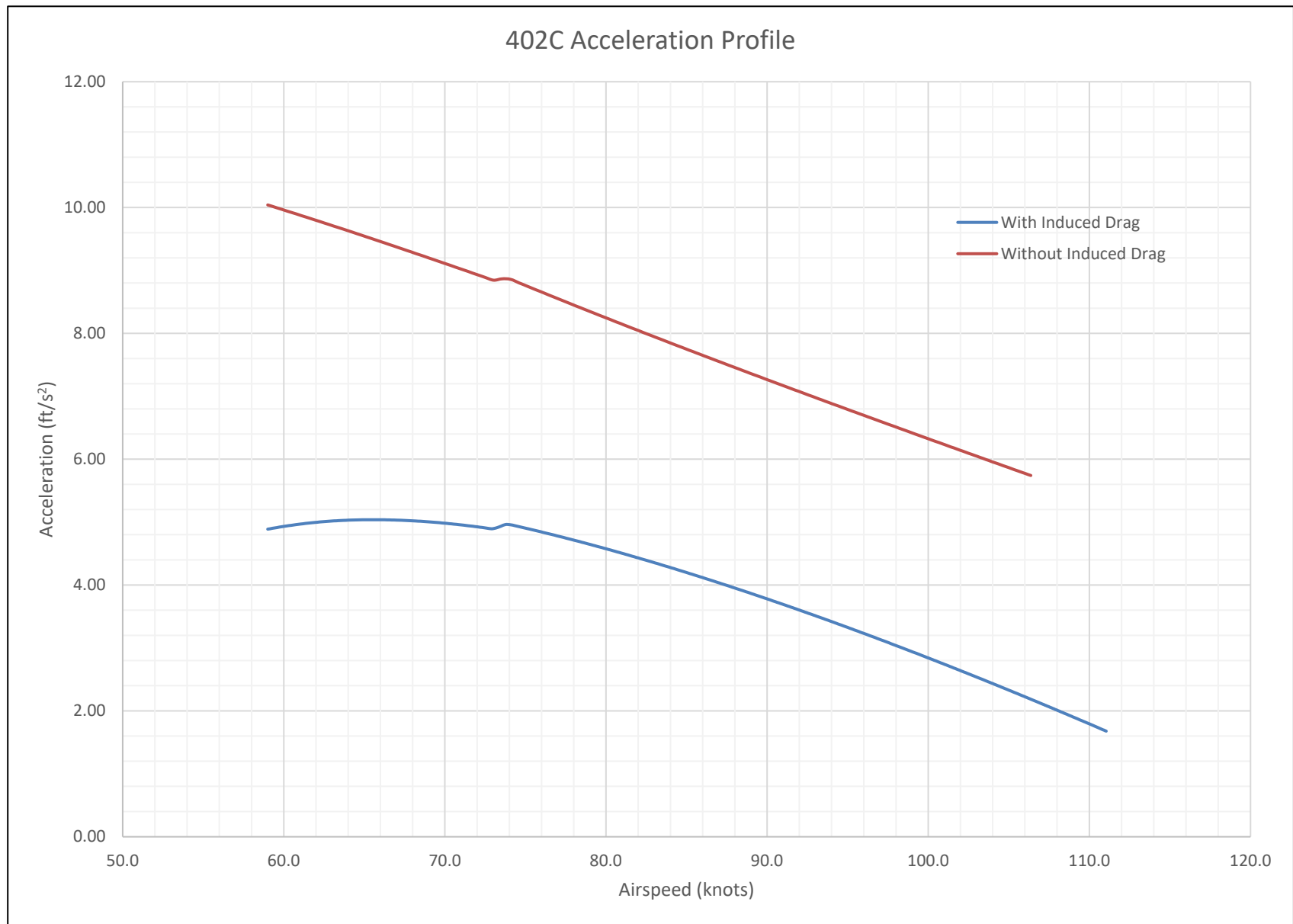


Figure 7. Cessna 402C level-flight acceleration capability at 6,215 lb. with flaps up and gear down (provided by Textron).

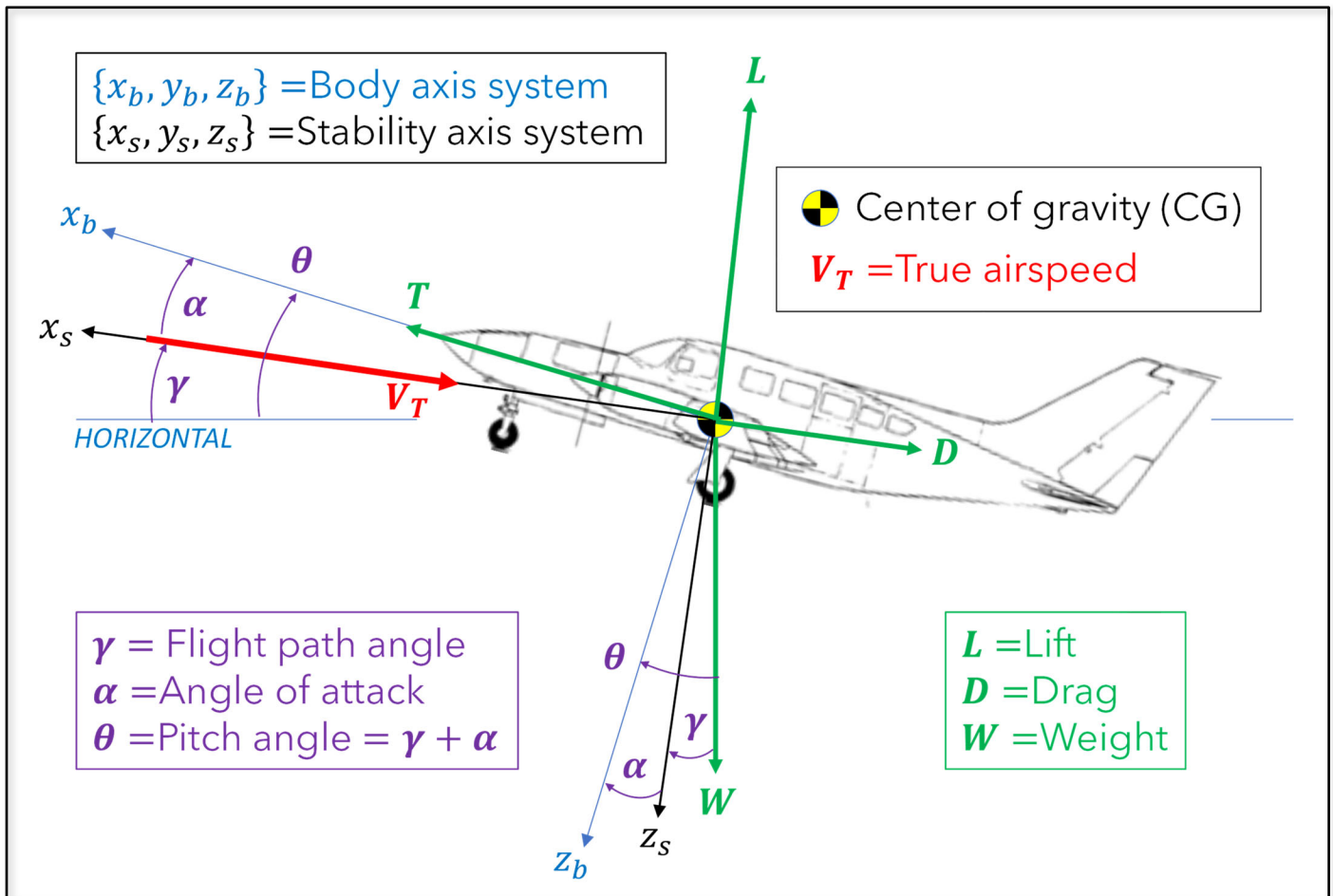


Figure 8. Forces on an airplane in a wings-level climb.

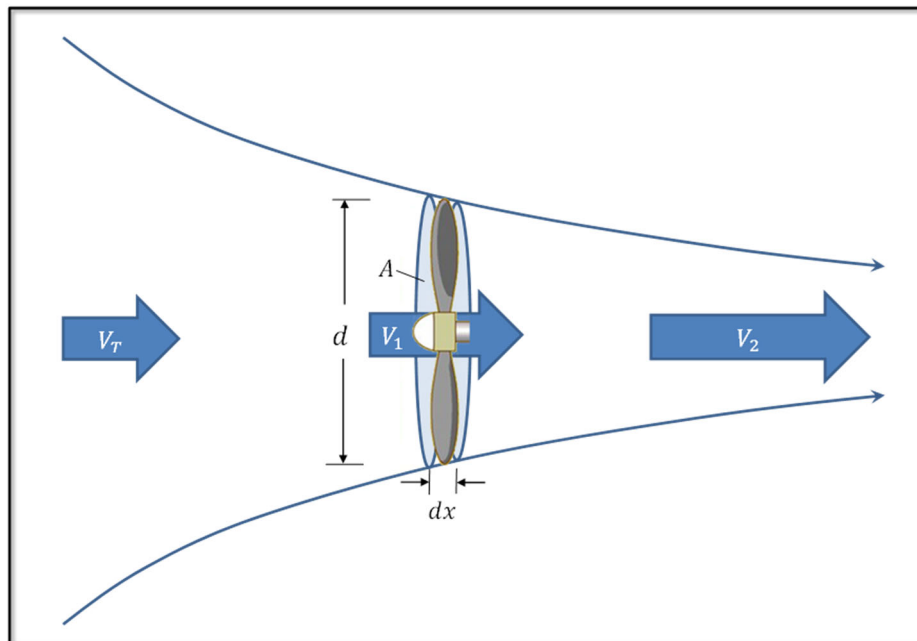


Figure 9. Diagram of a stream tube of air being accelerated through a propeller.

Rate of climb and flight path angle: zero acceleration

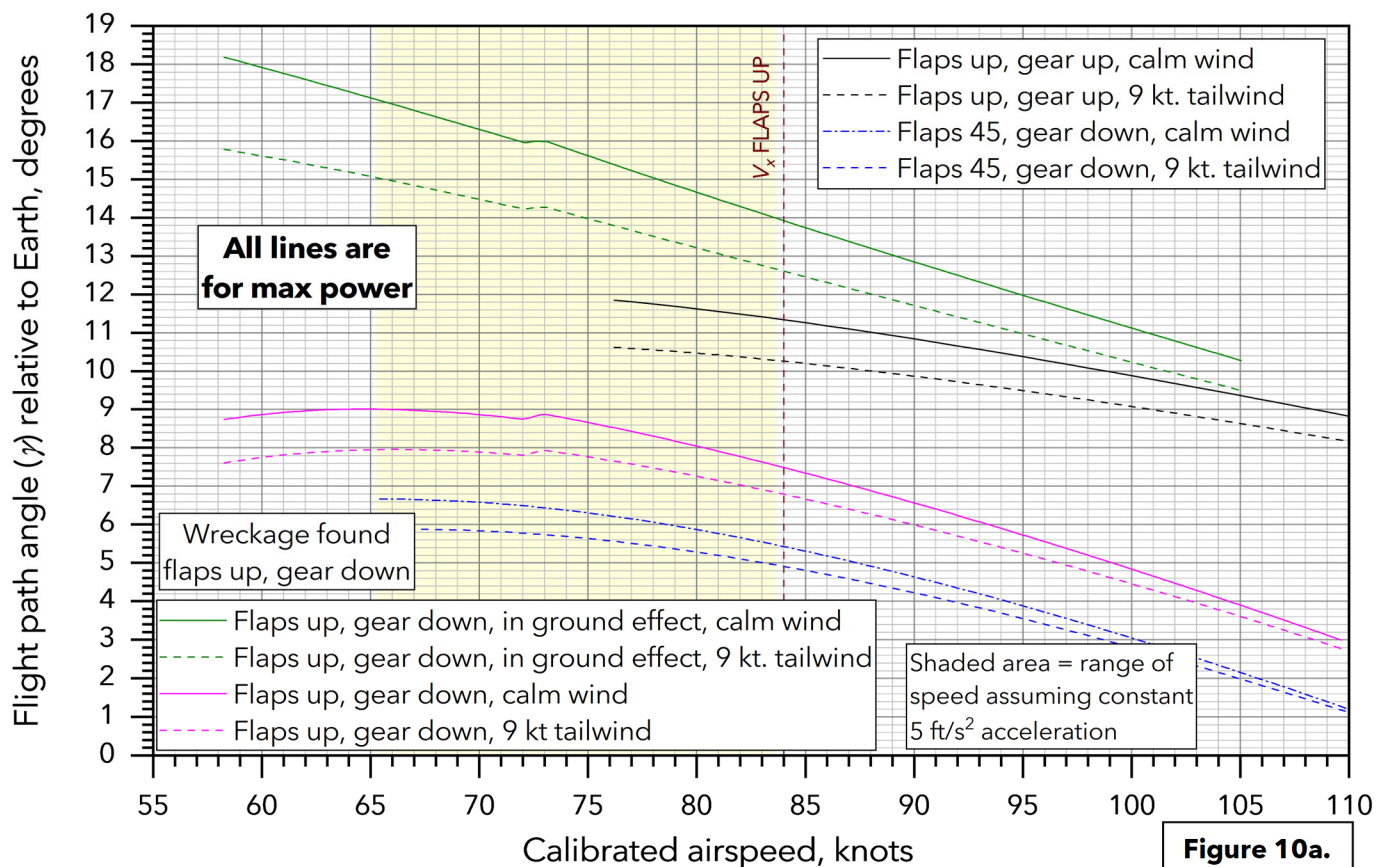
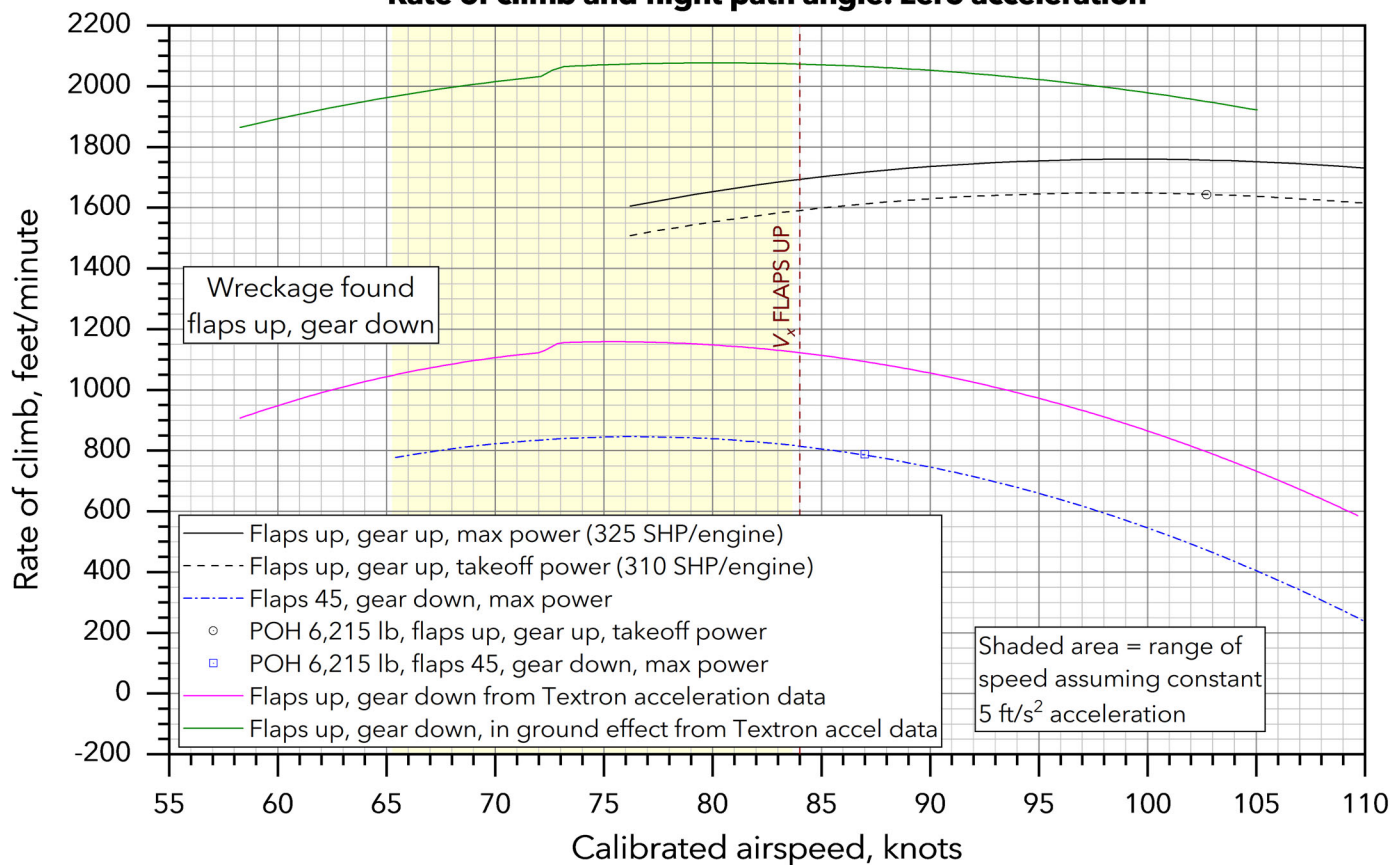


Figure 10a.

Rate of climb and flight path angle: 5 ft/s² (0.155 G) acceleration

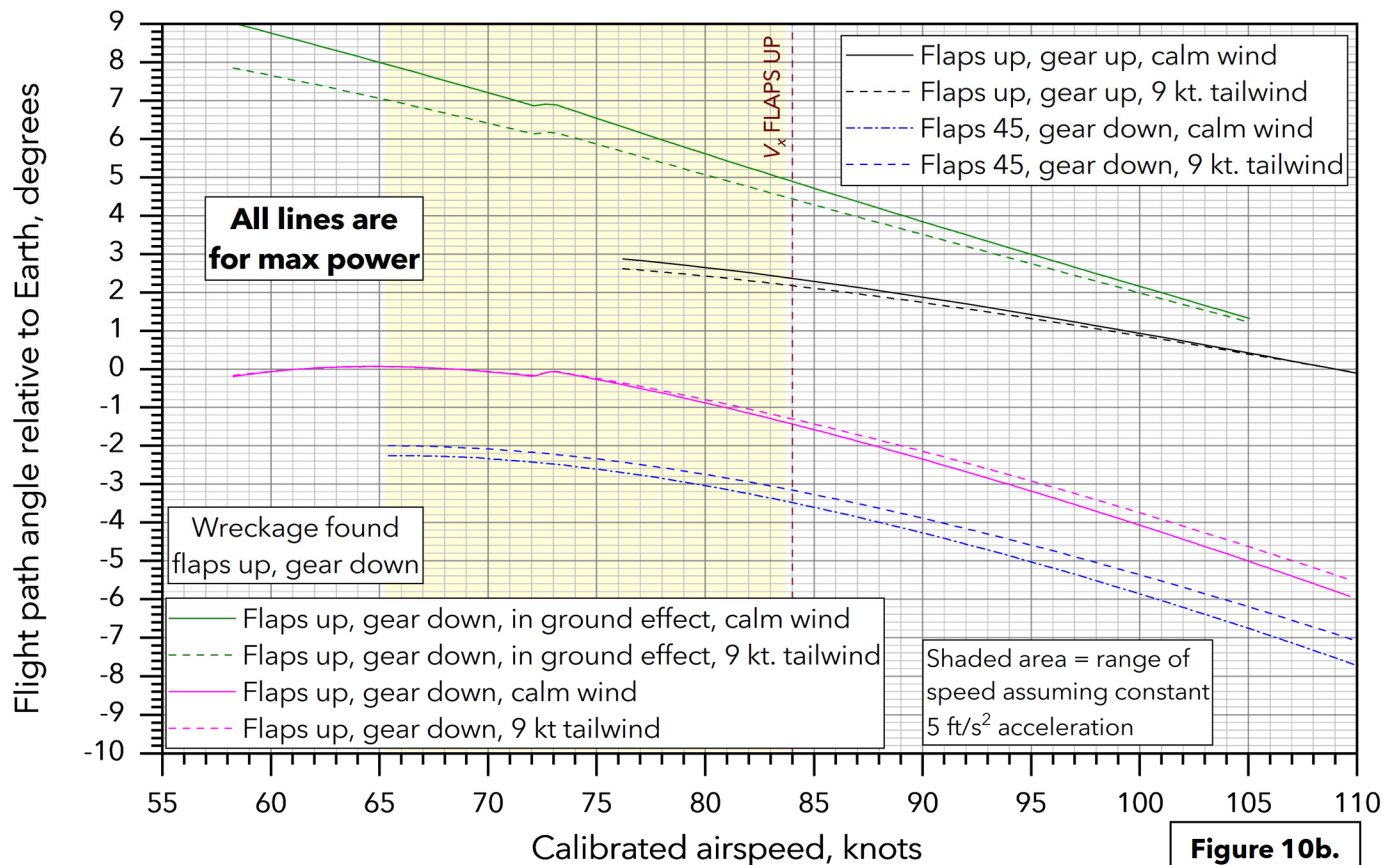
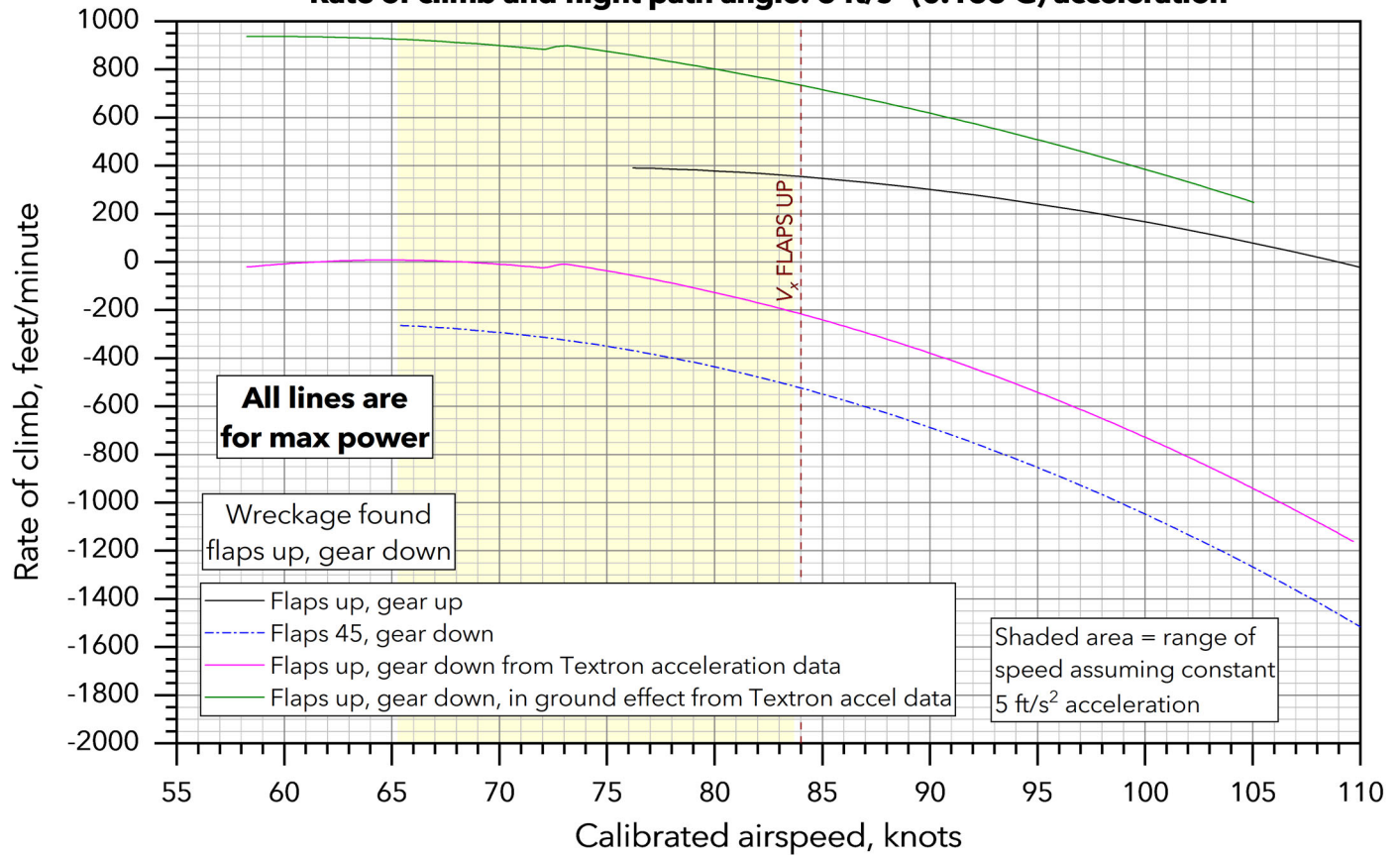


Figure 10b.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Speed & distance assuming constant acceleration from end of Camera 2 data

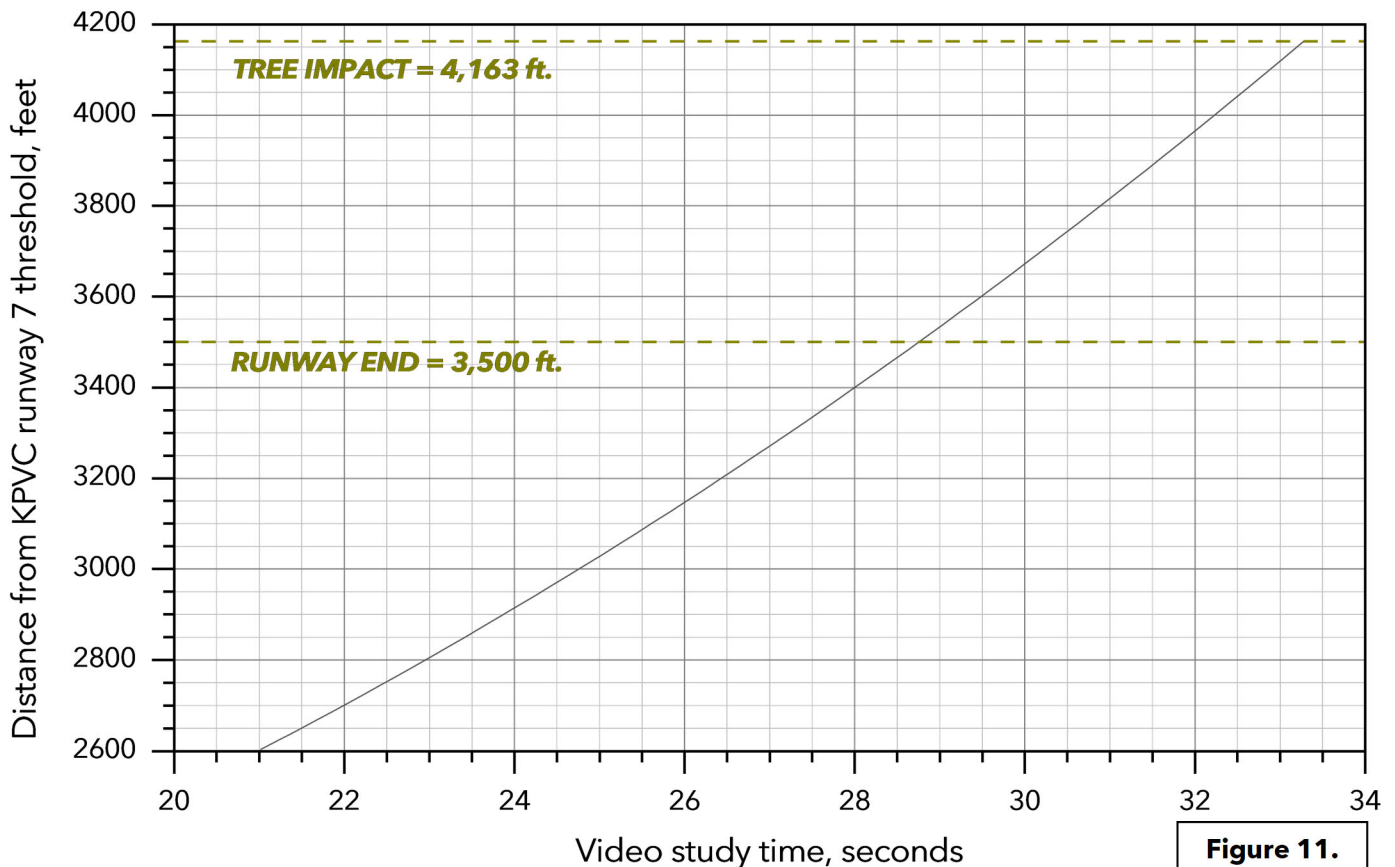
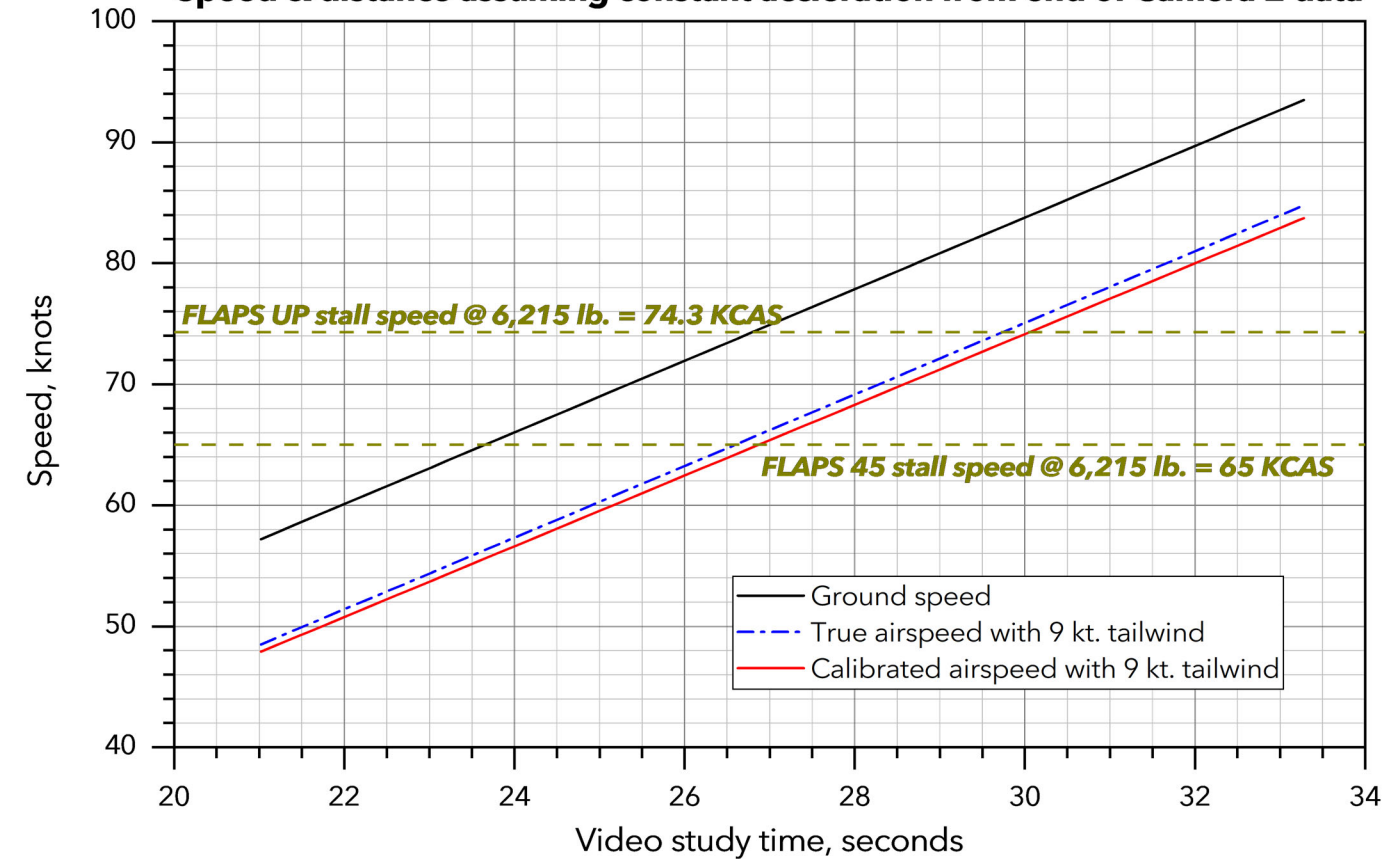


Figure 11.

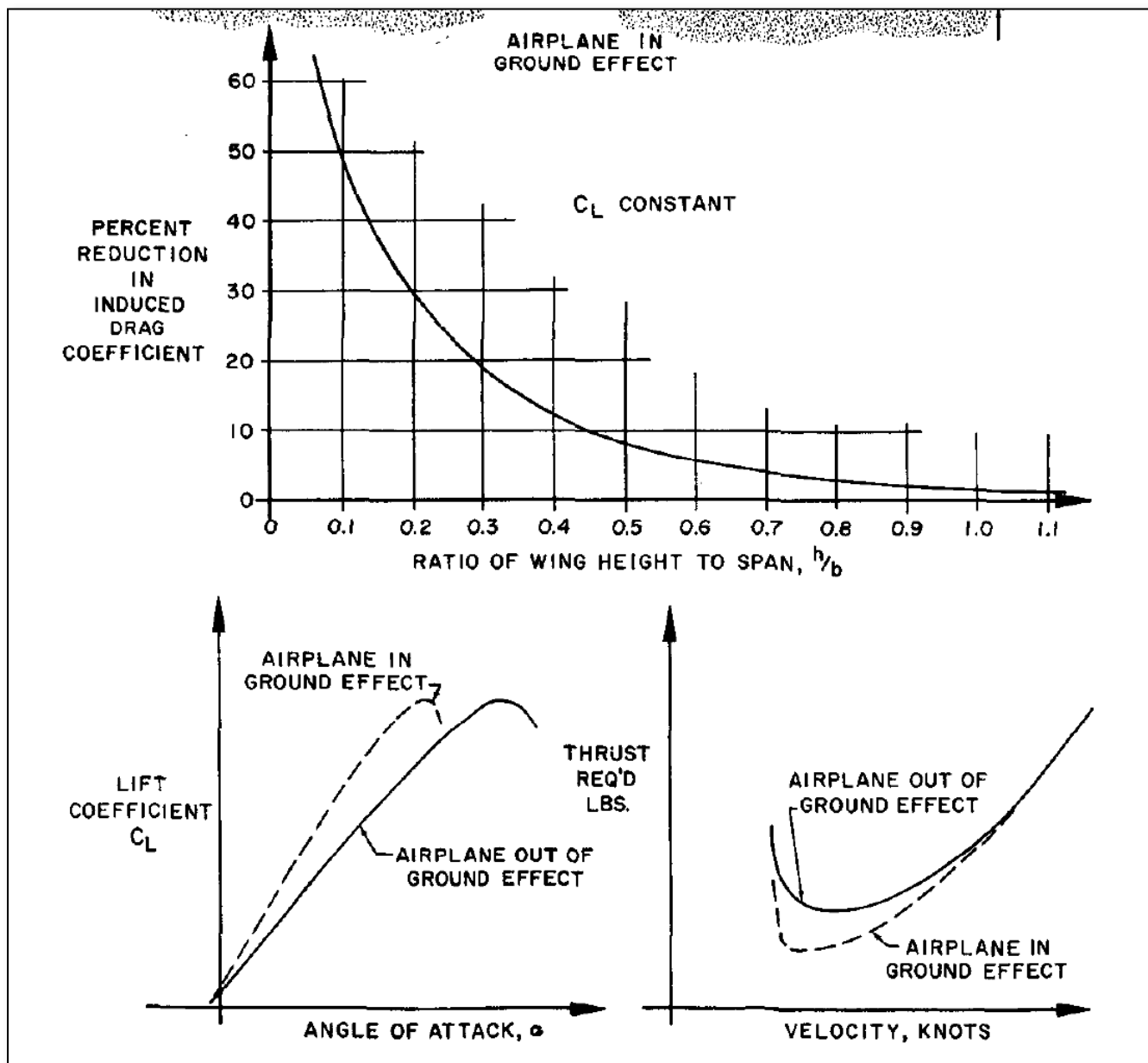


Figure 12. Ground effects on airplane aerodynamics (from Reference 7).

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Speed & distance assuming constant acceleration & earliest liftoff

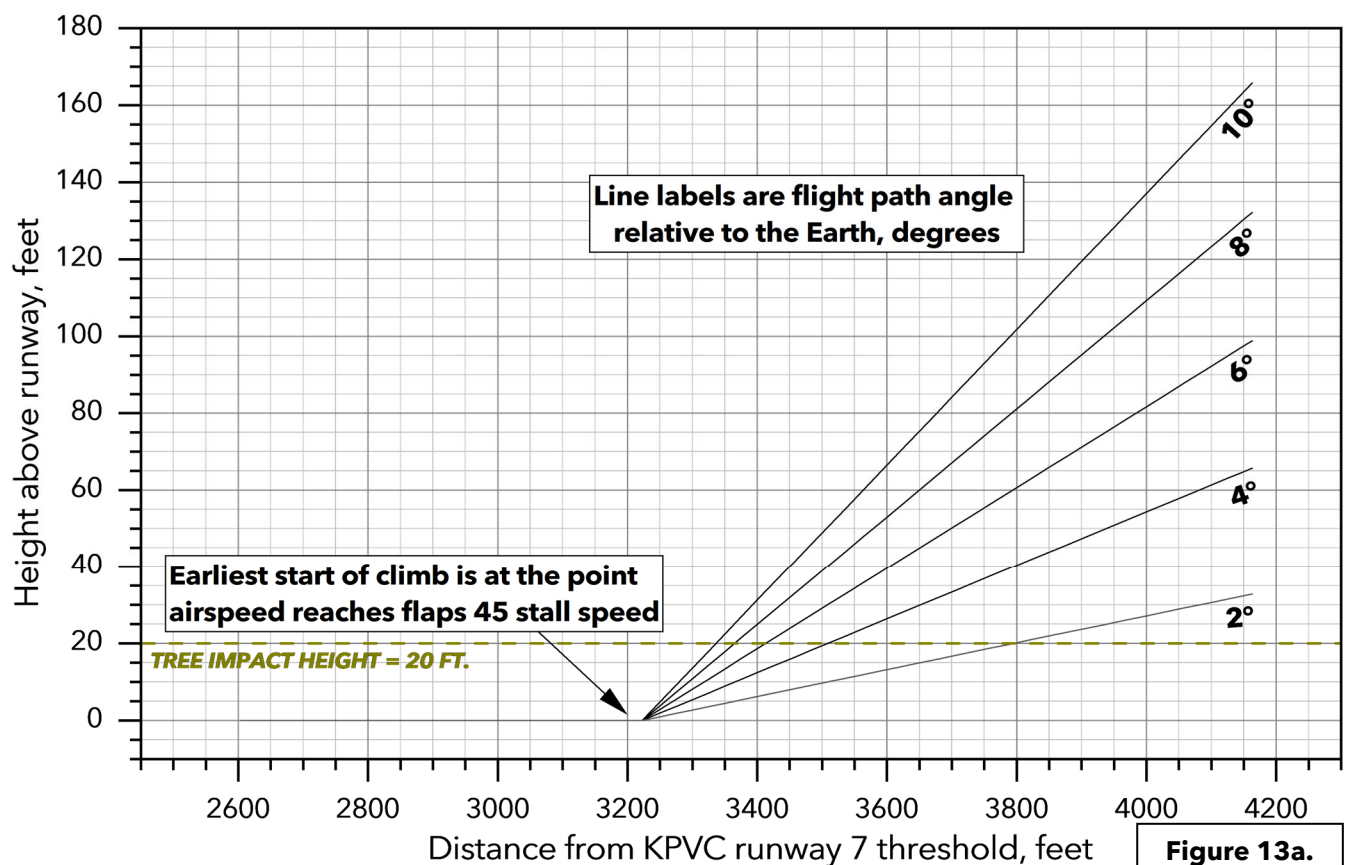
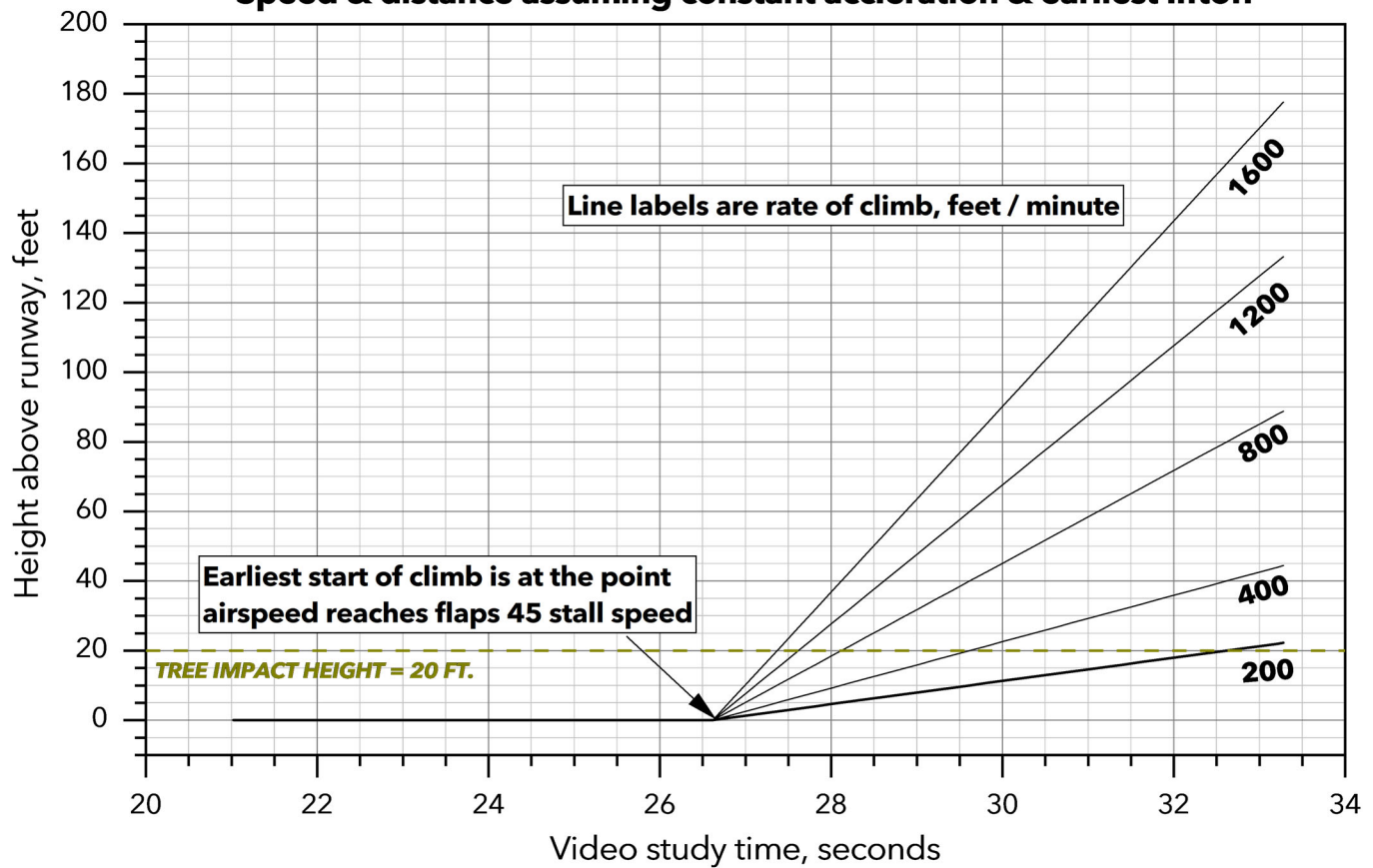


Figure 13a.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Speed & distance assuming constant acceleration & latest liftoff

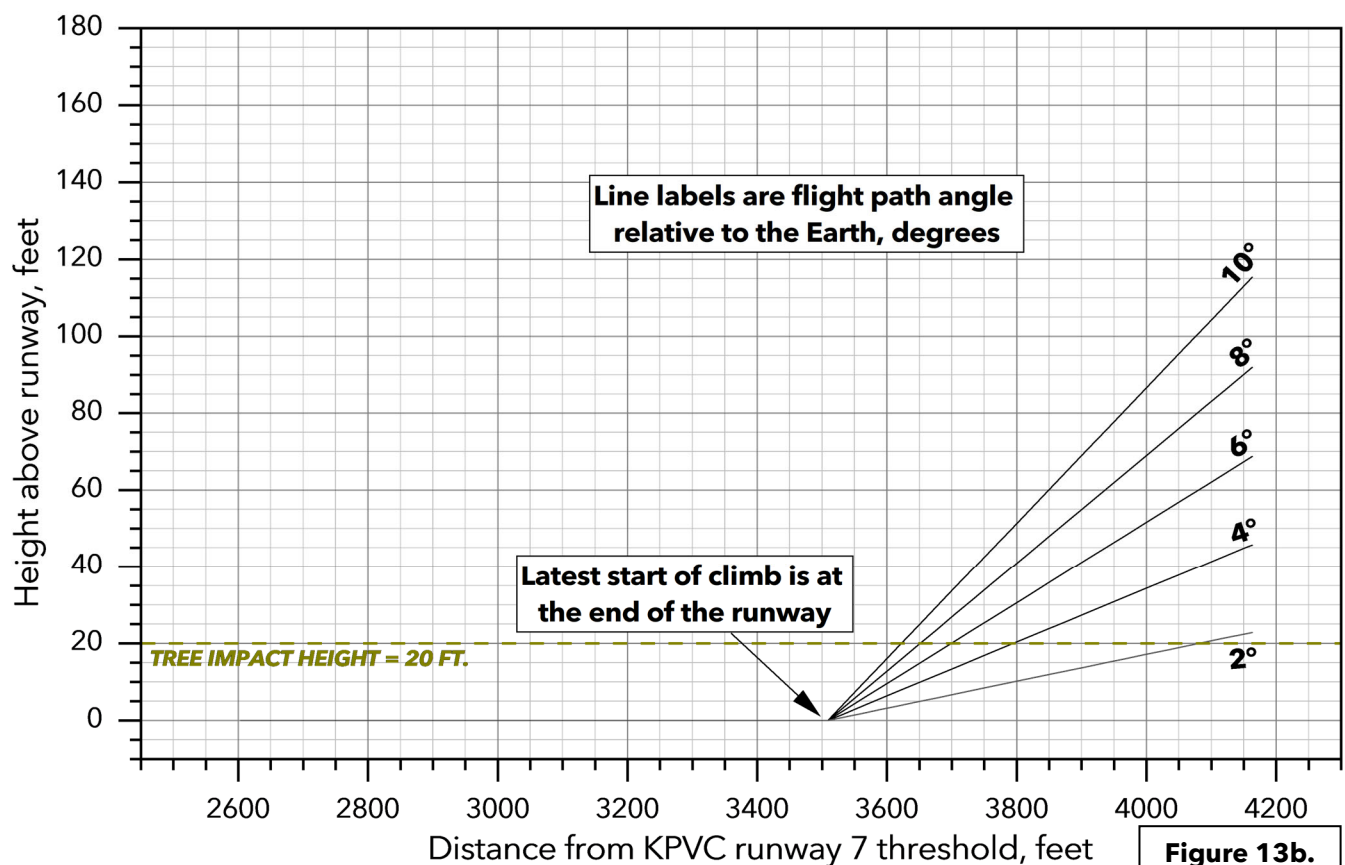
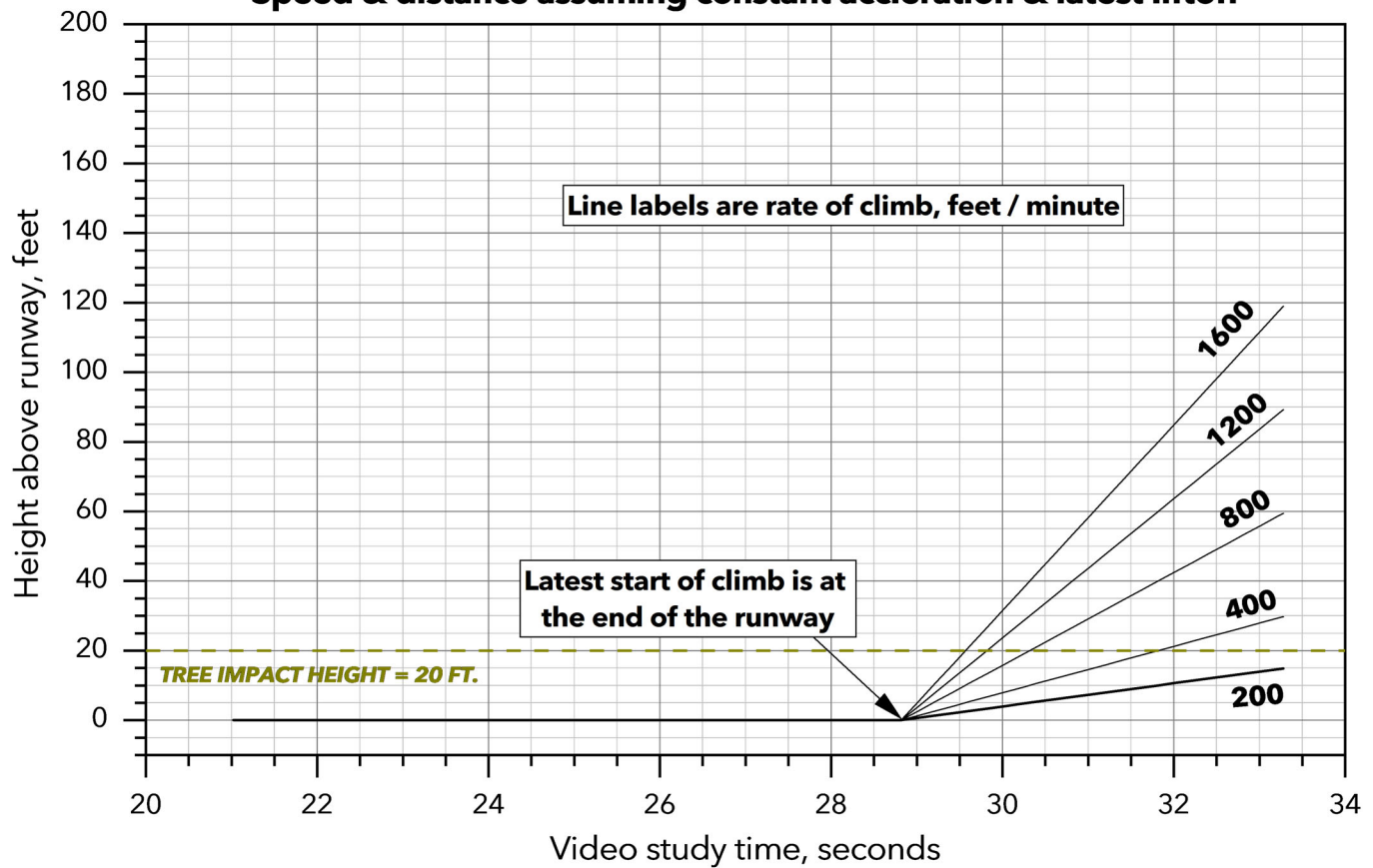


Figure 13b.

NORMAL LANDING DISTANCE

CONDITIONS:

1. Throttles - IDLE.
2. Landing Gear - DOWN.
3. Wing Flaps - 45°.
4. Cowl Flaps - CLOSE.
5. Level, Hard Surface Runway.
6. Maximum Effective Braking.

NOTE:

1. If necessary to land with wing flaps UP, the approach speed should be increased above the normal approach speed by 13 knots. Expect total landing distance to increase by 35%.
2. For altitudes of 10,000 feet or less, decrease distance by 3% for each 5 knots headwind. For altitudes above 10,000 feet, decrease the total landing distance by 1% for each 2 knots of headwind.
3. For operations with tailwinds up to 10 knots, increase total distances by 14% for each 5 knots wind.

WEIGHT- POUNDS	SPEED AT 50-FOOT OBSTACLE KIAS	PRESSURE ALTITUDE - FEET	20°C (68°F)		30°C (86°F)		40°C (104°F)	
			GROUND ROLL - FEET	TOTAL DISTANCE TO CLEAR 50 FEET	GROUND ROLL - FEET	TOTAL DISTANCE TO CLEAR 50 FEET	GROUND ROLL - FEET	TOTAL DISTANCE TO CLEAR 50 FEET
6850	95	Sea Level	1080	2510	1110	2540	1150	2580
		1000	1120	2550	1160	2590	1190	2620
		2000	1160	2590	1200	2630	1240	2670
		3000	1200	2630	1240	2670	1280	2710
		4000	1250	2680	1290	2720	1330	2760
		5000	1290	2720	1340	2770	1380	2810
		6000	1340	2770	1390	2820	1440	2870
		7000	1400	2830	1440	2870	1490	2920
		8000	1450	2880	1500	2930	1550	2980
		9000	1510	2940	1560	2990	1610	3040
		10,000	1570	3000	1620	3050	1670	3100
		11,000	1630	3060	1680	3110	1740	3170
		12,000	1690	3120	1750	3180	1810	3240
		13,000	1760	3190	1820	3250	1880	3310
		14,000	1830	3260	1890	3320	1960	3390
		15,000	1910	3340	1970	3400	2040	3470
6500	93	Sea Level	960	2390	990	2420	1030	2460
		1000	1000	2430	1030	2460	1060	2490
		2000	1030	2460	1070	2500	1100	2530
		3000	1070	2500	1110	2540	1140	2570
		4000	1110	2540	1150	2580	1190	2620
		5000	1150	2580	1190	2620	1230	2660
		6000	1200	2630	1240	2670	1280	2710
		7000	1240	2670	1290	2720	1330	2760
		8000	1290	2720	1340	2770	1380	2810
		9000	1340	2770	1390	2820	1430	2860
		10,000	1400	2830	1440	2870	1490	2920
		11,000	1450	2880	1500	2930	1550	2980
		12,000	1510	2940	1560	2990	1610	3040
		13,000	1570	3000	1620	3050	1680	3110
		14,000	1630	3060	1690	3120	1740	3170
		15,000	1700	3130	1760	3190	1820	3250
6000	88	Sea Level	810	2240	830	2260	860	2290
		1000	840	2270	860	2290	890	2320
		2000	870	2300	900	2330	930	2360
		3000	900	2330	930	2360	960	2390
		4000	930	2360	970	2400	1000	2430
		5000	970	2400	1000	2430	1030	2460
		6000	1010	2440	1040	2470	1070	2500
		7000	1040	2470	1080	2510	1120	2550
		8000	1080	2510	1120	2550	1160	2590
		9000	1130	2560	1170	2600	1200	2630
		10,000	1170	2600	1210	2640	1250	2680
		11,000	1220	2650	1260	2690	1300	2730
		12,000	1270	2700	1310	2740	1350	2780
		13,000	1320	2750	1360	2790	1410	2840
		14,000	1370	2800	1420	2850	1460	2890
		15,000	1430	2860	1470	2900	1520	2950

Figure 14. Cessna 402C landing distance table applicable to the accident conditions (from Figure 5-25 of Reference 2).

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Comparison of deceleration achieved in several wet-runway overruns

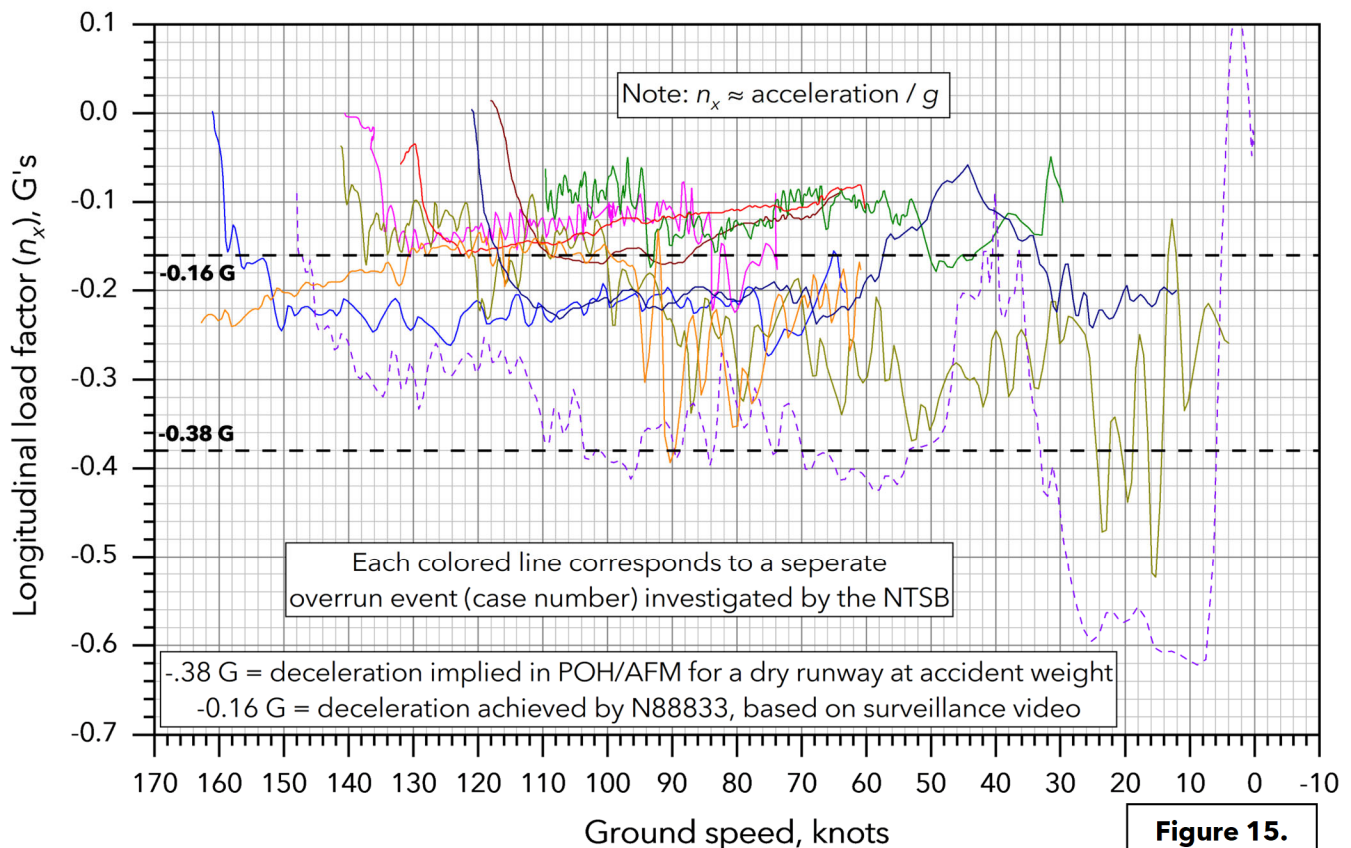
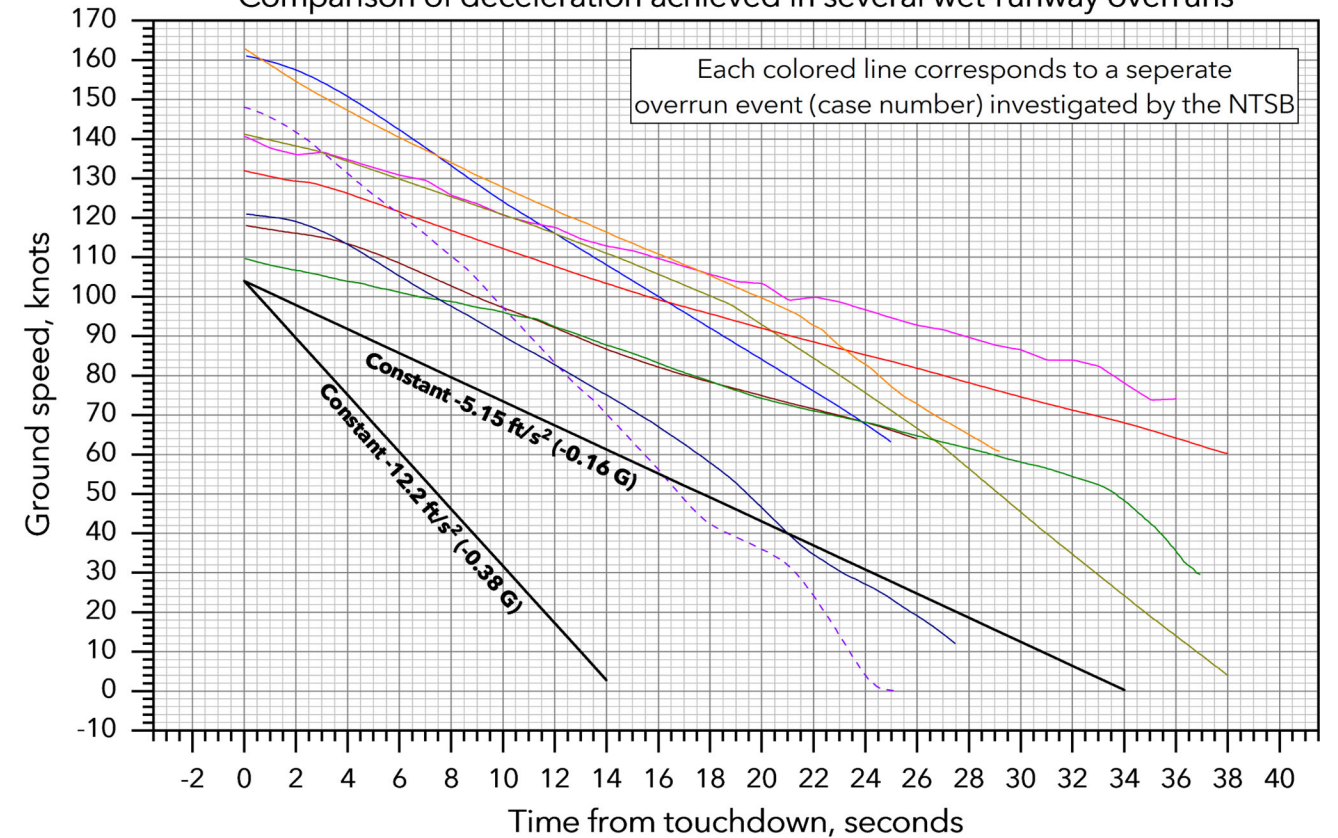


Figure 15.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Plan view of ADS-B data during final approach

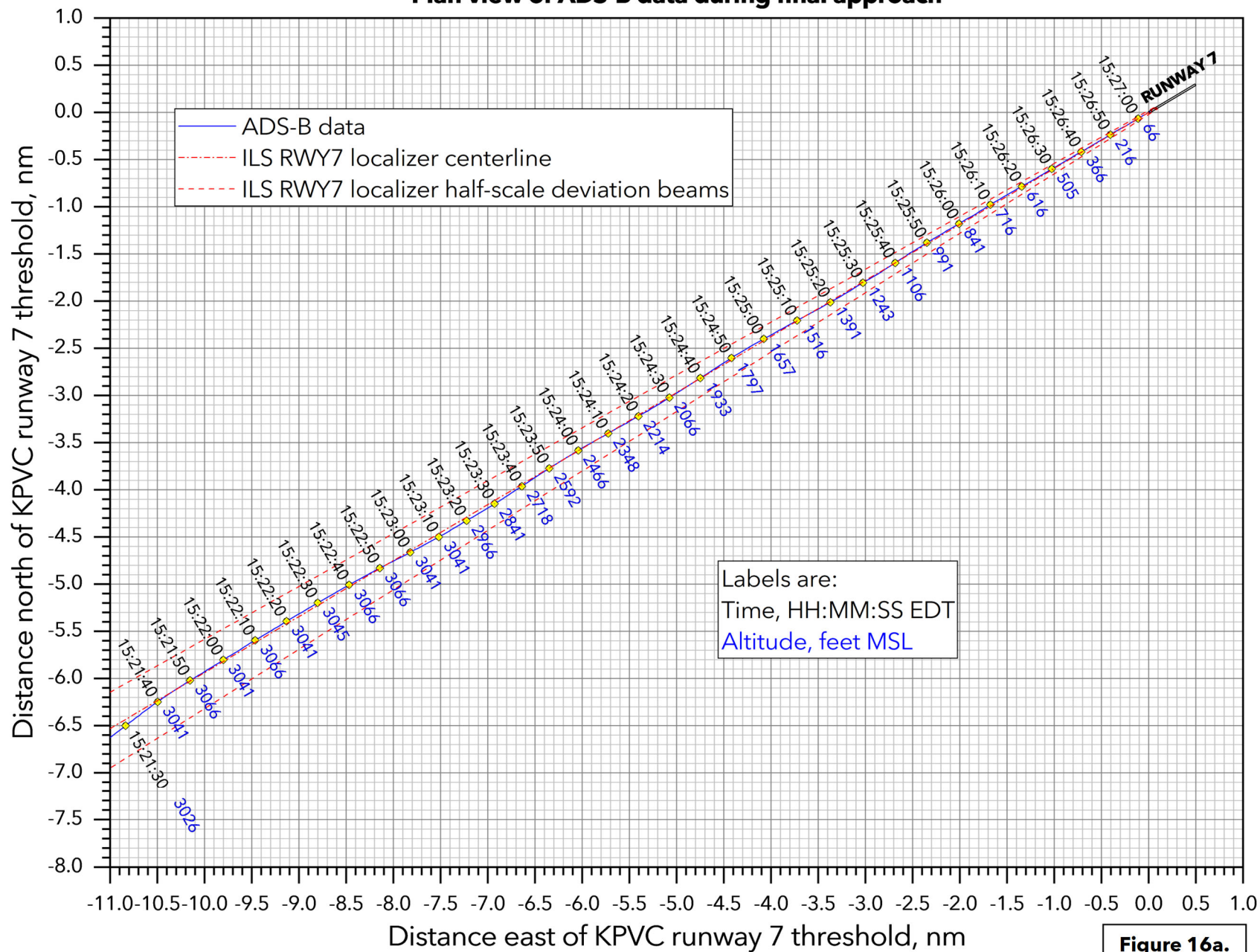


Figure 16a.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Plan view of ADS-B data during final approach

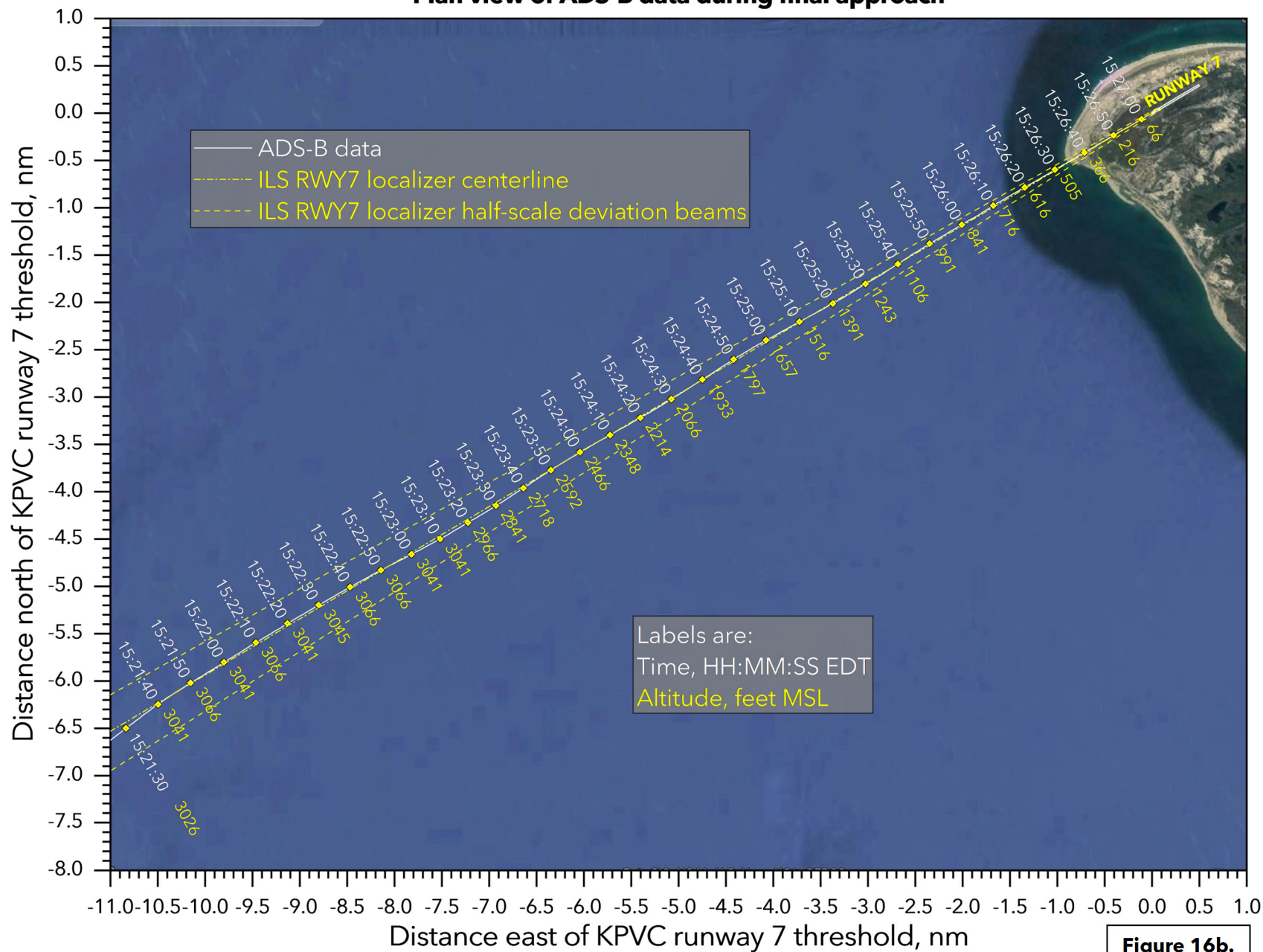


Figure 16b.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

ADS-B altitude data vs. time during final approach

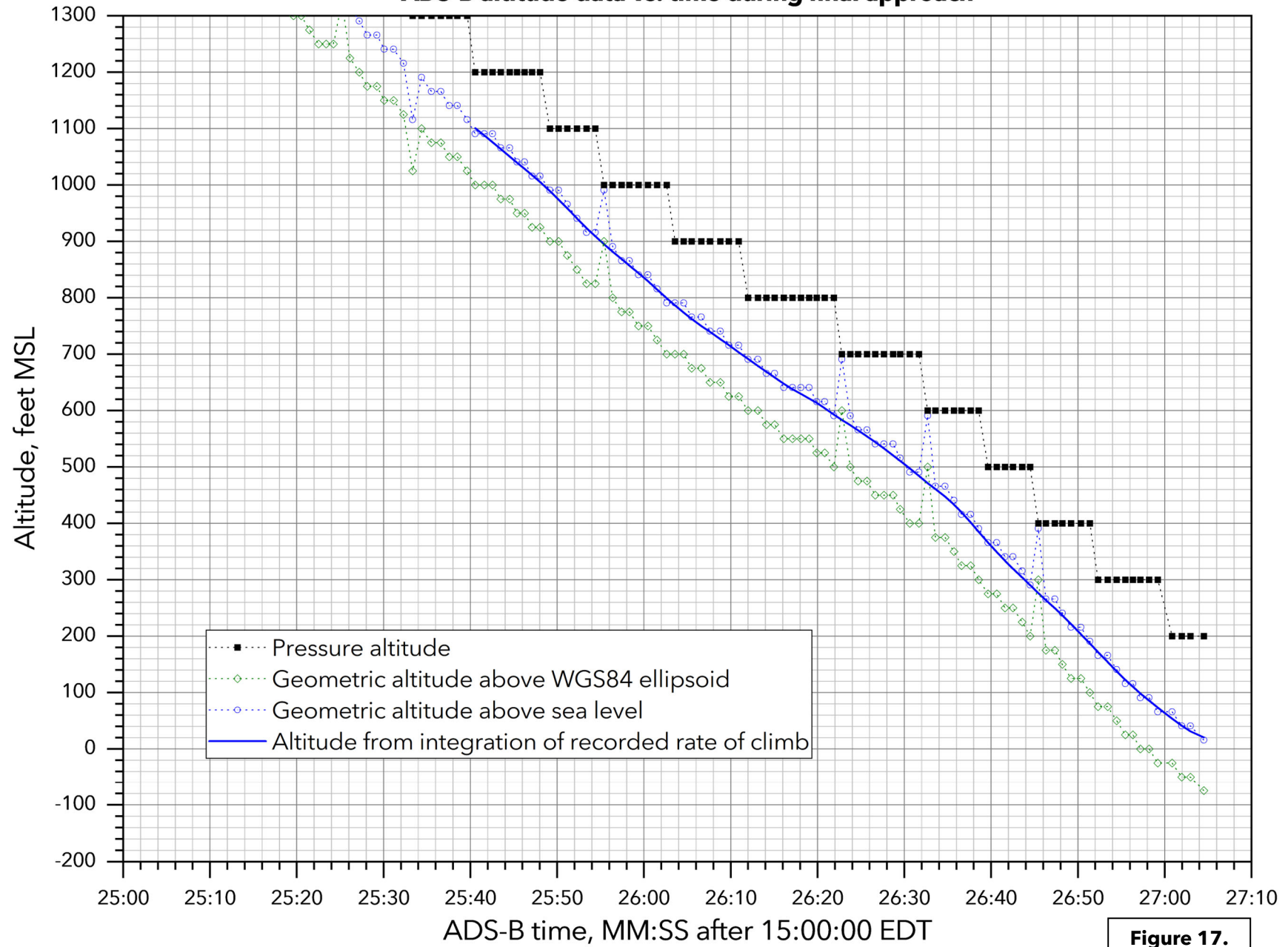
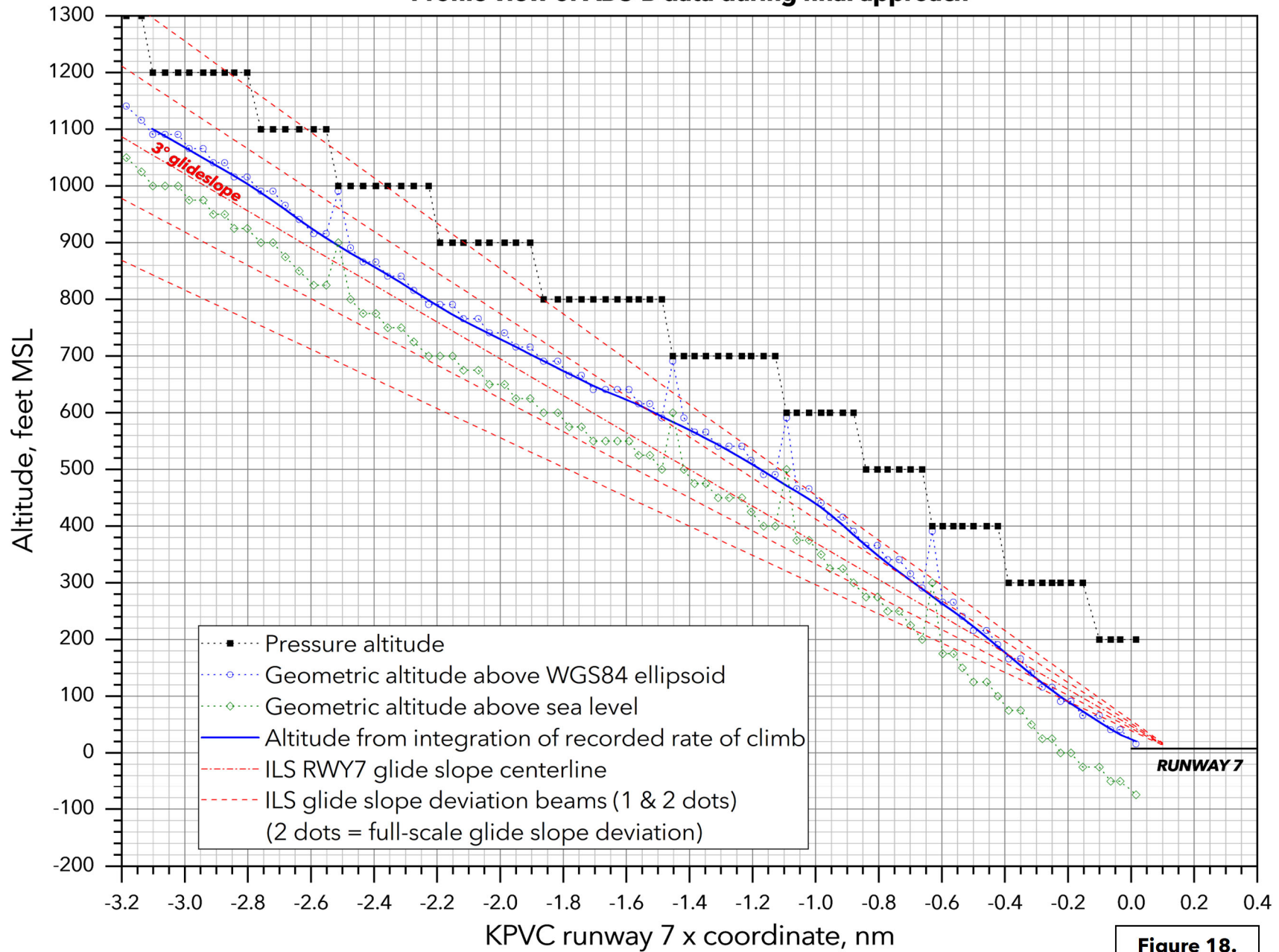


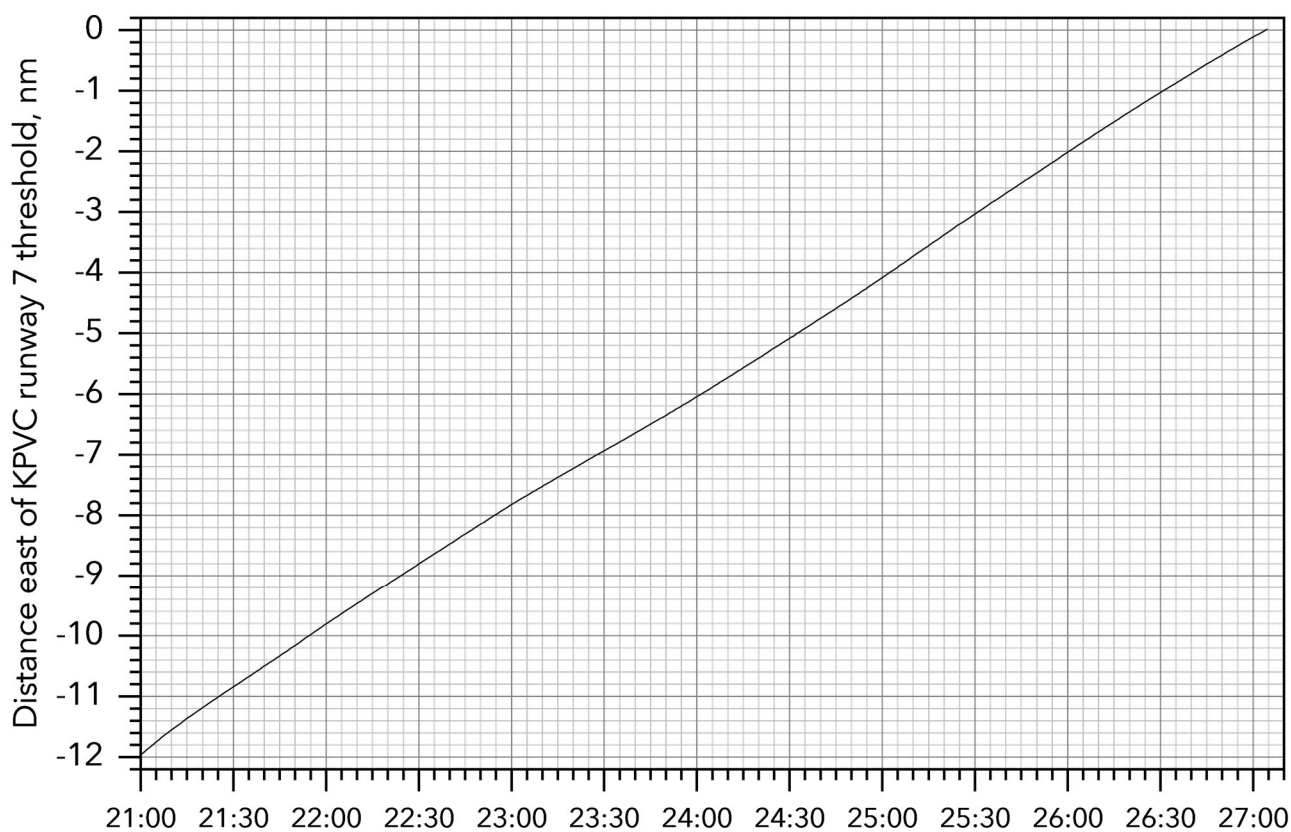
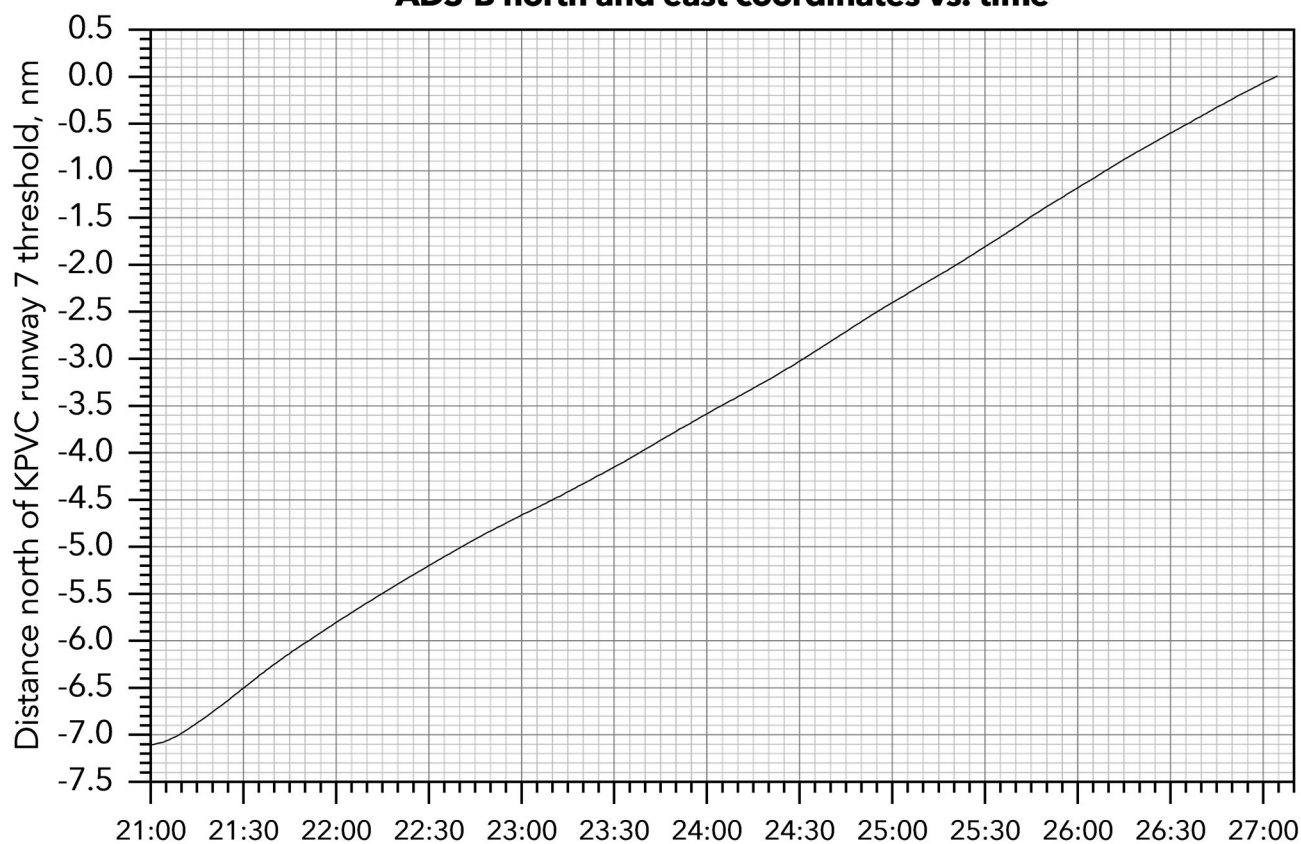
Figure 17.

Profile view of ADS-B data during final approach



ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

ADS-B north and east coordinates vs. time



ADS-B time, MM:SS after 15:00:00 EDT

Figure 19.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

ADS-B runway coordinates vs. time

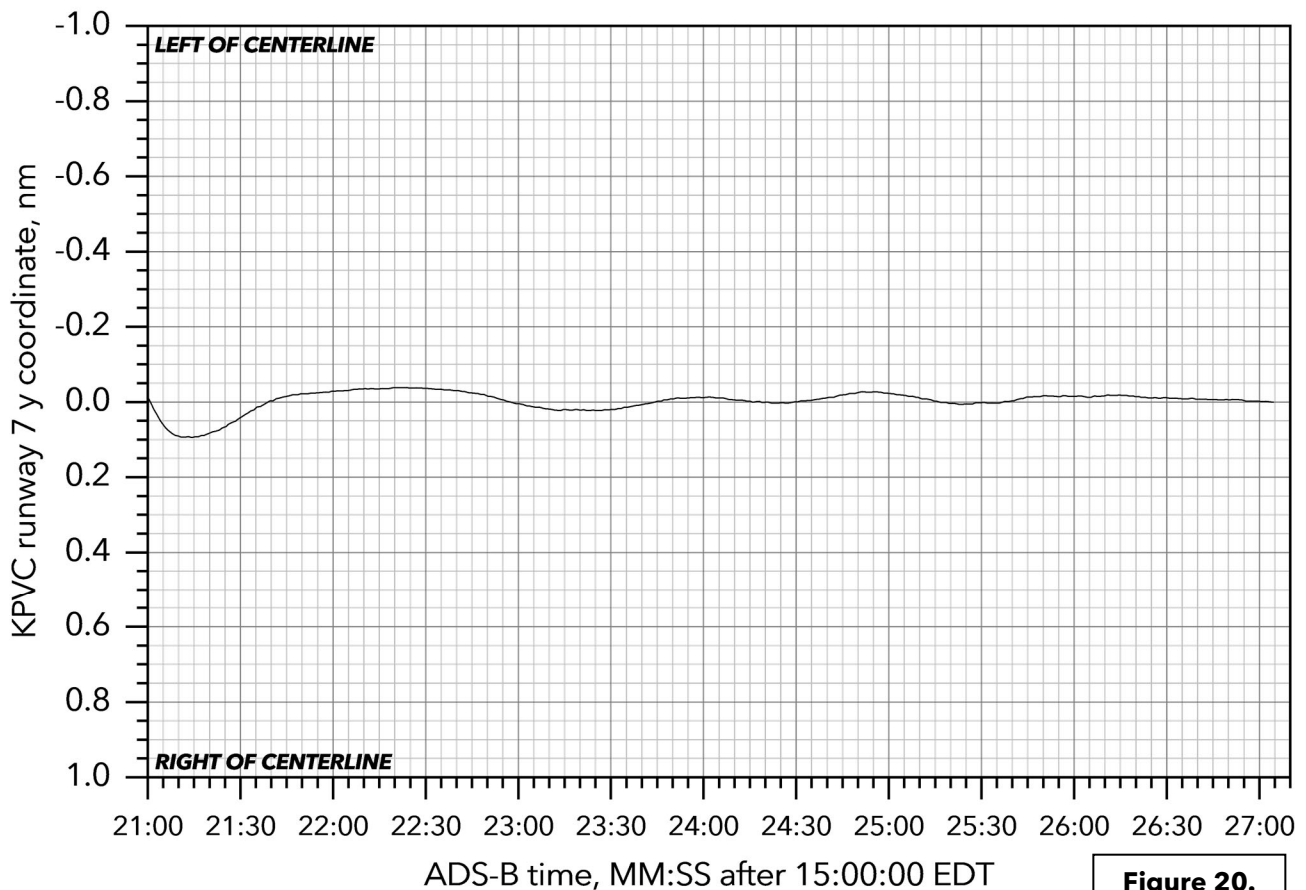
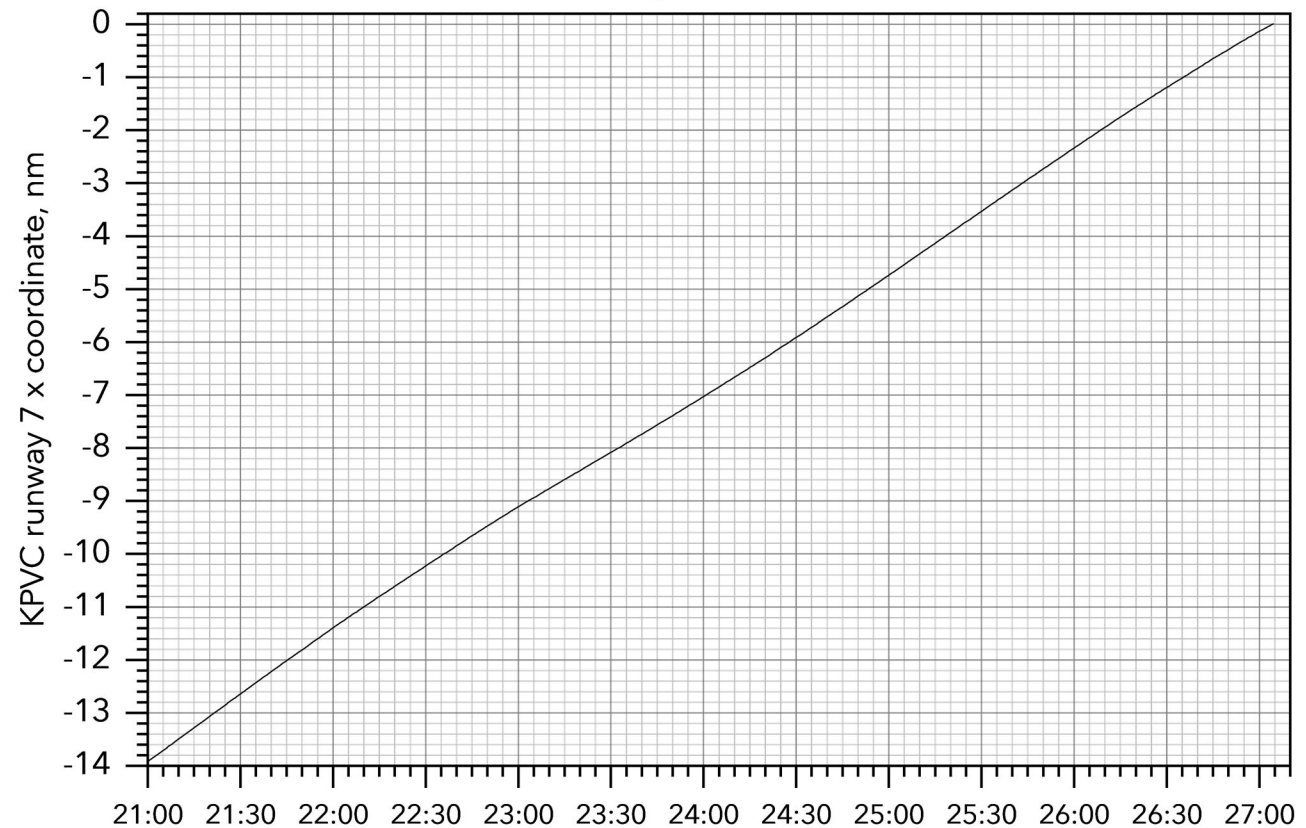


Figure 20.

ERA21LA354: Cessna 402C, N88833, Provincetown, MA, 09/09/2021

Speed and rate of climb vs. time during final approach

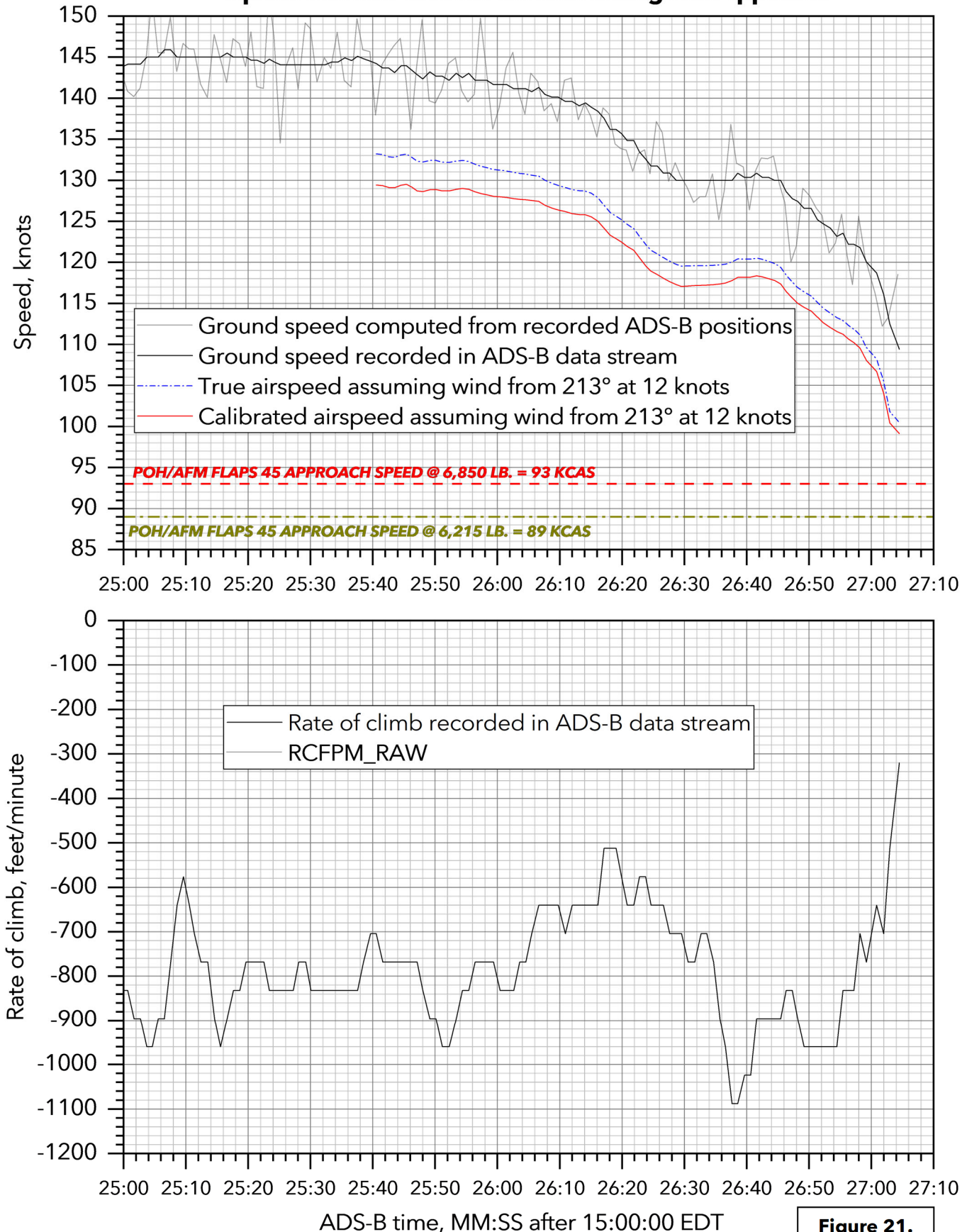


Figure 21.

Figure 22: Runway Surface Condition - Pilot Reported Braking Action - Wheel Braking Coefficient Correlation Matrix, from AC 25-32

Runway Condition Code	Runway Surface Condition Description	Pilot-Reported Braking Action	Wheel Braking Coefficient
6	Dry	–	90% of certified value used to comply with § 25.125 ¹ .
5	- Frost - Wet (includes damp and 1/8" (3 mm) depth or less of water) 1/8" (3 mm) depth or less of: - Slush - Dry snow - Wet snow	Good	Per method defined in § 25.109(c).
4	-15 °C and colder outside air temperature: Compacted snow	Good to Medium ²	0.20 ³
3	- Wet ("Slippery When Wet" runway) - Dry snow or wet snow (any depth) over compacted snow Greater than 1/8" (3 mm) depth of: - Dry snow - Wet snow Warmer than -15 °C outside air temperature: - Compacted snow	Medium ²	0.16 ³
2	Greater than 1/8" (3 mm) depth of: - Water - Slush	Medium ² to Poor	(1) For speeds below 85% of the hydroplaning speed ⁴ : 50% of the wheel braking coefficient determined in accordance with § 25.109(c), but no greater than 0.16 ³ ; and (2) For speeds at 85% of the hydroplaning speed ⁴ and above: 0.05 ³ .
1	Ice	Poor	0.08 ³
0	- Wet ice - Water on top of compacted snow - Dry snow or wet snow over ice	Nil	Not applicable. (No operations in Nil conditions.)

¹ 100% of the wheel braking coefficient used to comply with § 25.125 may be used if the testing from which that braking coefficient was derived was conducted on portions of runways containing operationally representative amounts of rubber contamination and paint stripes.

² The braking action term "FAIR" is in the process of being changed to "MEDIUM" throughout the FAA. Until an official change is published, the term "FAIR" may be used.

³ These wheel braking coefficients assume a fully modulating anti-skid system. For quasi-modulating systems, multiply the listed braking coefficient by 0.625. For on-off systems, multiply the listed braking coefficient by 0.375. (See AC 25-7C to determine the classification of an anti-skid system.) Airplanes without anti-skid systems will need to be addressed separately on a case-by-case basis.

⁴ The hydroplaning speed, V_P , may be estimated by the equation $V_P = 9\sqrt{P}$, where V_P is the ground speed in knots and P is the tire pressure in lb/in².