NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering

Washington, D.C. 20594

July 29, 2020

Aircraft Performance ADS-B Study

by John O'Callaghan

Location:	Windsor Locks, Connecticut
Date:	October 2, 2019
Time:	09:53 Eastern Daylight Time (EDT) (13:53 Universal Coordinated Time (UTC))
Aircraft:	Boeing B-17G, registration N93012
NTSB#:	ERA20MA001

CONTENTS

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Washington, D.C. 20594

July 29, 2020

Aircraft Performance ADS-B Study

by John O'Callaghan

A. ACCIDENT

Location: Windsor Locks, Connecticut
Date: October 2, 2019
Time: 09:53 Eastern Daylight Time (EDT)
(13:53 Universal Coordinated Time (UTC))[1]
Aircraft: Boeing B-17G, registration N93012
NTSB#: ERA20MA001

B. GROUP

Not Applicable

C. HISTORY OF FLIGHT

On October 2, 2019, at 09:53 EDT, a Boeing B-17G, N93012, owned and operated by the Collings Foundation, was destroyed during a precautionary landing and subsequent runway excursion at Bradley International Airport (KBDL), Windsor Locks, Connecticut. The commercial pilot, airline transport pilot, and five passengers were fatally injured. The flight mechanic/loadmaster and four passengers were seriously injured, while one passenger and one person on the ground incurred minor injuries. The local commercial sightseeing flight was conducted under the provisions of Title 14 Code of Federal Regulations Part 91, in accordance with a Living History Flight Experience exemption granted by the Federal Aviation Administration (FAA). Visual meteorological conditions prevailed in the area and no flight plan was filed for the flight, which departed KBDL at 09:47.

According to preliminary air traffic control (ATC) data provided by the FAA, shortly after takeoff, at 09:49, one of the pilots reported to ATC that he wanted to return to the airport. At that time, the airplane was about 600 ft. above the field elevation (AFE) on the right crosswind leg of the airport traffic pattern for runway 6. The approach controller verified the request and asked if the pilot required any assistance, to which he replied no. The controller then asked for the reason for the return to the airport, and the pilot replied that the airplane had a "rough mag" on the No. 4 engine. The controller then instructed the pilot to fly a right downwind leg for runway 6 and confirmed that the flight needed an immediate landing. He subsequently cancelled the approach of another airplane and advised the pilot to proceed however necessary to runway 6. The approach controller instructed the pilot to contact the tower controller, which he did.

[1] Local time at Windsor Locks on the day of the accident was Eastern Daylight Time (EDT). EDT = UTC - 4 hours. Times in this *Study* are in EDT unless otherwise noted.

The tower controller reported that the wind was calm and cleared the flight to land on runway 6. The pilot acknowledged the landing clearance; at that time, the airplane was about 400 ft. AFE on a midfield right downwind leg for runway 6. The tower controller asked about the airplane's progress to the runway and the pilot replied that they were "getting there" and on the right downwind leg. No further communications were received from the accident airplane. Witness statements and airport surveillance video confirmed that the airplane struck approach lights about 1,000 ft. prior to the runway, then contacted the ground about 500 ft prior to the runway before reaching runway 6. It then veered right off the runway before colliding with vehicles and a deicing fluid tank about 1,100 ft. right of the center of the runway threshold.

This *Aircraft Performance ADS-B Study* presents the results of using Automatic Dependent Surveillance – Broadcast (ADS-B) Global Positioning System (GPS) position and speed data, video and crash site evidence, surface weather information, and available performance data in the 1944 B-17G "Flight Handbook" (Reference 1) to calculate N93012's position, orientation, speed, and other performance parameters during the airborne portion of the accident flight. The flaps-up power required throughout the flight, with the landing gear both up and down, is computed, as well as the expected power available from 1 to 4 engines at climb and emergency power settings. The flight path angle and rate of climb resulting from different combinations of power settings, number of engines operating, and airspeed are also presented.

The ATC communications and post-accident examinations of the airplane's engines (see Reference 5) indicate that power was lost completely on the #4 engine, and may have been substantially reduced on the #3 engine. Both these engines are on the right wing, and so the loss of thrust on these engines would have resulted in an asymmetric thrust condition which would have acted to yaw the nose of the airplane to the right. Left rudder would have been required to compensate for this thrust asymmetry. Compensating for the loss of right-wing thrust by increasing the thrust on the left-wing engines (#1 and #2) would have exacerbated the thrust asymmetry, and required additional rudder to prevent the airplane from yawing to the right. Consequently, the amount of additional thrust that could have been provided by the left-wing engines might have been limited not only by the maximum power output of those engines, but also by the amount of rudder available to compensate for the thrust asymmetry; once the maximum rudder is applied, any further increase in the thrust asymmetry will result in a right yaw.

To determine the maximum thrust asymmetry that can be balanced by the airplane's rudder, considerable knowledge about the airplane's aerodynamics is required, including the behavior of the airplane's side force and yawing moment coefficients as a function of sideslip angle and rudder deflection. It is not possible to deduce these characteristics from the information published in the B-17G Flight Handbook. No other sources of this information are available to the investigation,[2] and consequently this aspect of the airplane's performance cannot be addressed quantitatively in this *Study*. However, the Collings Foundation Chief Pilot, who is familiar with the flying qualities of the B-17, provided the NTSB with a qualitative assessment of the amount of rudder and airspeed required to trim an asymmetric thrust condition in comments to a draft version of this *Study*. These comments are addressed below and presented in full in Appendix A.

This *Study* presents calculations of the power required during the flight based on lift and drag characteristics deduced from engine power and rate of climb information presented in the Flight Handbook. These calculations correspond to a flaps-up and gear-up configuration. Additional calculations for a flaps-up, gear-down configuration are based on a landing gear drag increment

[2] Additional information about the B-17G's aerodynamics might be discovered through research into Boeing's historical archives, or by flight-testing an exemplar B-17G. These measures are beyond the scope of the investigation.

estimated using textbook methods. (Examination of the wreckage indicates that the flaps were up, and video evidence indicates that the landing gear was down during the downwind leg of the traffic pattern.) The effect of airspeed on power required, flight path angle, and rate of climb is also presented, and indicates that during most of the flight, the airspeed was below the airspeed that would maximize the flight path angle (the condition required for maximizing the distance flown for a given altitude loss), and suggests that the airplane might have been able to clear the runway approach lights and reach the runway 6 threshold if the airspeed during the return to the airport had been higher (and/or if the landing gear had been kept raised until landing was assured).

Nonetheless, the airplane did reach the flat runway safety area (RSA) in front of the runway 6 threshold, and presumably could have rolled to a safe stop along the runway heading (taking some damage from impacts with the frangible runway approach lights) had it not yawed right, accelerated, and crashed into vehicles and the deicing fluid tank. One witness to the accident stated that the right yaw occurred after the right wing contacted the ground, and that the increase in power occurred after the right wing "leveled out" again (see Reference 12):

- He emerged from the tree line and made a right hand turn to final on runway 6.
- He was less than 100 ft above the ground.
- My elevation level relative to the runway 6 threshold, I did not see the landing gear hit the lighting.
- It looked like he was 5 feet off the ground.
- He squared off the ground and was 5 ft off the ground of runway 6.
- The right-wing tip dropped, and I heard it scrap[e] the runway.
- The plane made a hard-sharp right turn.
- It made the sharp right almost pivoting on the wing.
- It leveled out again.
- After it leveled out again, the engines went to full throttle and the airplane accelerated into the tanks.
- Everything was slow motion but when he made that right turn, the engines went to full throttle and I saw the tail actually raise up from the prop wash and it started to accelerate toward the tank. At the last minute I saw him pull up like he was trying to clear the tank.

This sequence of events is generally consistent with video captured by another witness (still frames from this video are presented in Addendum 1 to this *Study* (Reference 14)). In this video, the airplane appears continuously rolled to the right, but the right wing does not perceptibly "drop" suddenly. Instead, it appears that the wings might never have leveled after the airplane was aligned on the runway centerline following the downwind-to-final turn, but simply maintained the right roll present during that turn (the video does not capture the turn itself). This possibility is consistent with the roll angle computed from GPS data, as described below. The reasons why the wings were not leveled once the airplane was aligned with the runway are not known, but might include:

- The right wing operating very close to its maximum lift coefficient, or perhaps a bit beyond it (resulting in flow separation and a loss of lift), and consequently being unable to generate additional lift to help roll the airplane left towards wings-level;
- A left sideslip angle (resulting from asymmetric thrust and perhaps higher drag on the right wing) that would generate a rolling moment to the right, countering control inputs to the left.

The sustained right roll before touchdown, the loss of directional control after touchdown, and the application of power on the ground (accelerating the airplane and likely exacerbating the directional control problem) were critical events affecting the outcome of the flight. However, the lack of information about the airplane's aerodynamics (noted above) and detailed data about the airplane's motion, power settings, and flight control positions (such as would be provided by a flight data recorder) preclude a quantitative evaluation of the controllability of the airplane during this time.

The data sources and performance calculations for the airborne portion of the flight are described in further detail in the sections that follow.

D. DETAILS OF THE INVESTIGATION

I. The Boeing B-17G "Flying Fortress"

Reference 2 is a "Historical Snapshot" published on Boeing's website that describes the B-17:

> On July 28, 1935, a four-engine plane took off from Boeing Field in south Seattle on its first flight. Rolling out of the Boeing hangar, it was simply known as the Model 299. Seattle Times reporter Richard Smith dubbed the new plane, with its many machine-gun mounts, the "Flying Fortress," a name that Boeing quickly adopted and trademarked. The U.S. Army Air Corps designated the plane as the B-17.
>
> In response to the Army's request for a large, multiengine bomber, the prototype, financed entirely by Boeing, went from design board to flight test in less than 12 months.
>
> The B-17 was a low-wing monoplane that combined aerodynamic features of the XB-15 giant bomber, still in the design stage, and the Model 247 transport. The B-17 was the first Boeing military aircraft with a flight deck instead of an open cockpit and was armed with bombs and five .30-caliber machine guns mounted in clear "blisters."
>
> The first B-17s saw combat in 1941, when the British Royal Air Force took delivery of several B-17s for high-altitude missions. As World War II intensified, the bombers needed additional armament and armor.
>
> The B-17E, the first mass-produced model of the Flying Fortress, carried nine machine guns and a 4,000-pound bomb load. It was several tons heavier than the prototypes and bristled with armament. It was the first Boeing airplane with the distinctive — and enormous — tail for improved control and stability during high-altitude bombing. Each version was more heavily armed.

According to Reference 3 (Wikipedia), the B-17G variant first flew on August 16, 1943, and is the final version of the airplane:

> By the time the definitive B-17G appeared, the number of guns had been increased from 7 to 13, the designs of the gun stations were finalized, and other adjustments were completed. The B-17G was the final version of the Flying Fortress, incorporating all changes made to its predecessor, the B-17F, and in total, 8,680 were built, the last (by Lockheed) on 28 July 1945. Many B-17Gs were converted for other missions such as cargo hauling, engine testing, and reconnaissance. Initially designated SB-17G, a number of B-17Gs were also converted for search-and-rescue duties, later to be redesignated B-17H.

The airplane is powered by four Wright R-1820-97 radial engines equipped with turbosuperchargers to boost manifold pressure for takeoff and high-altitude flight. Each engine produces 1,380 shaft horsepower (SHP) in the "war emergency" condition (with a carburetor modification that N93012 did not have), 1,200 SHP in the takeoff condition, 1,000 SHP in the maximum continuous power condition, and 650 SHP in the maximum cruise condition. Operation at 1,200 SHP and higher is limited to 5 minutes duration (see Figure 1, from Reference 1).

The Flight Handbook states that the airplane "can be safely flown with a gross weight of 64,500 pounds" if certain restrictions are observed. The performance charts contained in the Flight Handbook present data for gross weights as high as 70,000 lb. The B-17F Flight Handbook states that "B-17F airplanes … can be flown up to and including a gross eight of 64,500 pounds" with restrictions. Reference 3 cites the B-17G maximum takeoff weight as 65,500 lb.

The Collings Foundation operated N93012 as part of its "Wings of Freedom" tour. Figure 2 presents a pre-accident photograph and two video stills of N93012, from the Collings Foundation website.[3] Figure 3 presents three-view diagrams of the B-17G, taken from the B-17G Field Service Manual (Reference 4). Table 1 provides some dimensions of the airplane, as well as the estimated weight of N93012 at the time of the accident. The weight items summing to the ramp weight were provided by the NTSB Operations Group Chairman. The fuel used is estimated at about the middle of the flight based on the takeoff power fuel consumption rate. A weight of 46,360 lb. is used for the performance analyses described in this *Study*.

Item	Value
Reference dimensions (from Reference 2):	
Wing area	1,420 ft.^{2} (from Reference 3)
Wing span	103.78 ft.
Propeller diameter	11.58 ft.
Mass properties for N93012:	
Basic Airplane	37,655 lb.
Oil 120 Gal.	1080 lb.
Pilot Weights (3 crew)	600 lb.
Passenger Weights (10 passengers)	2,000 lb.
Baggage/Cargo Weight	0
Operating Weight	41,335 lb.
Fuel Weight (takeoff) 800 gallons @ 6.5 lb./gal.	5,200 lb.
Ramp Weight	**46,535 lb.**
Fuel used: 3 minutes @ 552 gal./hr. = 27.6 gal. @ 6.5 lb./gal.	-179 lb.
Accident weight	**46,356 lb. (rounded to 46,360 lb. for *Study*)**

Table 1. Relevant geometry and mass properties for N93012.

Information about the airplane's aerodynamic characteristics, such as the lift coefficient (C_L) as a function of angle of attack (α), are needed to estimate the airplane's Euler angles (pitch, roll, and heading) throughout the flight. The drag coefficient (C_D) as a function of C_L is needed to compute the thrust and engine power required. As described in Section D-IV, the flaps-up and gear-up C_L and C_D are estimated based on information published in the Flight Handbook, and a C_D increment due to the landing gear is estimated based on textbook methods. As noted above, the asymmetric thrust condition resulting from reduced power on engines #3 and #4 would have had required left rudder to maintain heading, and the maximum rudder available might have limited the possible power increase to engines #1 and #2 to compensate for the loss of thrust. Determining the maximum amount of asymmetric thrust that could be trimmed with the rudder requires knowledge of the airplane's side force and yawing moment characteristics as a function of sideslip angle and rudder, which are unknown and cannot be deduced from information published in the Flight Handbook. Further, while it is certain that at some point engine #4 was not producing thrust, the amount of thrust produced by engine #3 is also unknown. These unknowns preclude a quantitative analysis of the directional controllability and maximum power that could be applied to engines #1 and #2. However, the comments submitted by the Collings Foundation Chief Pilot in Appendix A provide a qualitative assessment of the controllability of the airplane based on testing and experience, and state that under the accident conditions "maintaining directional control and any sort of performance would've been nearly impossible."

[3] See https://www.collingsfoundation.org/aircrafts/boeing-b-17g-flying-fortress/, accessed 05/07/2020.

As discussed below in Section D-IV, the airplane's C_L and C_D are computed from flaps-up, gear-up rate of climb and engine power data published in the Flight Handbook. This data corresponds to an all-engines operating, coordinated flight (zero sideslip angle) condition. On the accident flight, engine #4 was shut down, engine #3 was likely not producing full power, and the resulting asymmetric thrust would have required rudder to trim. Consequently, additional sources of drag were likely present on the accident flight that are not accounted for in the C_D computed using the Flight Handbook rate of climb data, such as drag due to rudder deflection, sideslip angle (if non-zero), and a stopped and feathered propeller on engine #4 (see Reference 5). These additional sources of drag would increase the power required during the flight, and hence the power required presented in this *Study* might underestimate the actual power that was applied to the airplane. These uncertainties must be borne in mind when considering the results of the *Study.*

N93012 was ADS-B Out equipped, and ADS-B data from the airplane was recorded by the FAA and provided to the NTSB. This data is used to compute the additional airplane performance parameters presented in this *Study.* The ADS-B system, and the ADS-B data for N93012, are described in Section D-III.

II. Crash site information

The crash site was surveyed in detail with aerial imagery obtained using an Unmanned Aircraft System (UAS), as documented in Reference 6. An annotated plan-view image of the site from Reference 6 is shown here as Figure 4. The initial structure to be struck by the airplane was a runway approach light fixture located about 1,000 ft. away from the runway 6 threshold, along the extended runway centerline. Damage to additional light fixtures between the initial impact point and the runway threshold indicate that the airplane generally tracked the runway heading before yawing to the right, with the right main gear and right wing leaving scrapes on the ground as shown in Figure 4. The right main gear mark was continuous to the final resting point of the airplane, about 730 ft. from the runway threshold and 940 ft. to the right of the runway centerline. The left main landing gear also left a tire mark 581 ft. long leading to the final resting point.

For performance work, it is convenient to express the position of the airplane in a Cartesian coordinate system centered on a relevant reference point. This *Study* uses a north vs. east coordinate system centered on the centerline of the KBDL runway 6 threshold.

III. Automatic Dependent Surveillance – Broadcast (ADS-B) data

The ADS-B data from N93012 is described and presented in this section, beginning with a brief description of the ADS-B system.

Introduction to the ADS-B system

According to a 2007 "Fact Sheet" published by the FAA,[4] the "Next Generation Air Transportation System" (NextGen) program "is a wide ranging transformation of the entire national air transportation system - not just certain pieces of it - to meet future demands and avoid gridlock in the sky and in the airports. It moves away from legacy ground based technologies [such as radar] to a new and more dynamic satellite based technology." A key component of NextGen is the surveillance of aircraft through the Global Positioning System (GPS) satellite constellation instead

[4] See: http://web.archive.org/web/20150403151639/http://www.faa.gov/news/fact_sheets/news_story.cfm?newsid=8145

of by ground radar. This GPS-based surveillance is enabled through the “Automatic Dependent Surveillance – Broadcast” (ADS-B) system. As described in the FAA fact sheet,

> Automatic Dependent Surveillance Broadcast (ADS-B) is, quite simply, the future of air traffic control. As the backbone of the NextGen system, it uses GPS satellite signals to provide air traffic controllers and pilots with much more accurate information that will help keep aircraft safely separated in the sky and on runways. Aircraft transponders receive GPS signals and use them to determine the aircraft’s precise position in the sky, which is combined with other data and broadcast out to other aircraft and air traffic control facilities. When properly equipped with ADS-B, both pilots and controllers will, for the first time, see the same real-time displays of air traffic, substantially improving safety.

Since January 1, 2020, ADS-B Out equipment (that broadcasts the airplane’s position to ATC and other aircraft) is required to be installed on all aircraft in the National Airspace System (NAS) operating above 10,000 ft. and within or above Class B and C airspace, with certain exceptions (see 14 CFR 91.225).

Presentation of the ADS-B data

To calculate performance parameters from the ADS-B data (such as ground speed, track angle, pitch and roll angles, etc.), it is convenient to express the position of the airplane in rectangular Cartesian coordinates. As stated in Section D-II, the Cartesian coordinate system used in this *Study* is centered at the KBDL runway 6 threshold and its axes extend east, north, and up from the center of the Earth. The ADS-B latitude and longitude data are converted into this coordinate system using the WGS84 ellipsoid model of the Earth for plotting and performance calculations. The latitude, longitude and elevation of the KBDL runway 6 threshold are:

Latitude: 41° 55’ 55.25” N
Longitude: 72° 41’ 47.6885” W
Elevation: 173 ft. above mean sea level (MSL)

Figures 5 & 6 show plan views of the ADS-B data plotted in terms of nautical miles north and east of the runway 6 threshold. Figure 5a shows the entire flight over a simple grid background, and Figure 5b shows the same data over a *Google Earth* satellite image background. Figure 6 shows an expanded view of the portion of the flight near the runway 6 threshold over a *Google Earth* background. The labels in Figures 5 and 6 indicate the time and airplane altitude corresponding to the location of the labels along the flight path. Additional labels indicate the airplane location at the time of selected radio communications between N93012 and Air Traffic Control (ATC), as documented in the transcripts provided by the FAA (References 7 and 8). Each communication is identified by a code – for example, “N93012.1,” “BR.2,” etc. – that identifies the originator of the transmission (source) and the transmission number from that source. The source and content of the communication corresponding to each code are presented in Table 2.

Note that as depicted in Figure 5b, at 09:51:10, N93012 was essentially on a right base leg for runway 33, and had more than enough energy for an approach and landing on that runway. Runway 33 was closed except for taxi operations, per Notice to Airmen (NOTAM) BDL 09/166. However, the pilot did not ask ATC if runway 33 was available for emergency use.

In addition to the latitude, longitude, and GPS altitude of the airplane, the ADS-B data also recorded the airplane’s pressure altitude, and GPS-based rate of climb, ground speed, and ground track angle.[5] The position of the airplane was also computed by integrating this velocity and rate of climb data over time, per the theorems of Calculus. The resulting position and altitude are depicted by the lines labeled "Integrated ADS-B speeds" in Figures 5 and 6, and "Integrated ADS-B rate of climb" in Figure 8.

The north and east positions of the ADS-B data are shown as a function of time in Figure 7, along with the "Integrated ADS-B speeds" positions. The altitude of the airplane, as determined from the ADS-B data, is shown as a function of time in Figure 8, along with the integrated altitude. The time parameter recorded in the ADS-B data is in UTC time, and is converted to EDT for presentation in this *Study.*

Time (EDT)	Source / Code	Content
09:48:16	LC.1	N93012 contact departure
09:48:49	N93012.1	departure N93012 is with you stand by one please
09:48:55	BR.1	... 93012 bradley departure radar contact you can resume own navigation and just verify you are going to be working twenty miles east of the field
09:49:03	N93012.2	that's affirm
09:49:19	N93012.3	departure ah boeing 93012 we would like to return to the field
09:49:24	BR.2	N93012 sorry say again
09:49:26	N93012.4	yeah we are returning to the field immediately
09:49:30	BR.3	N93012 do you need any assistance
09:49:34	N93012.5	negative
09:49:35	BR.4	and what's the reason for coming back
09:49:38	N93012.6	we have a rough mag on number four engine we would like to return for it out
09:49:42	BR.5	N93012 roger you can proceed ah onto the downwind for runway six and you said you need an immediate landing
09:49:50	N93012.7	(unintelligible)
09:49:51	BR.6	N93012 so i just want to make sure because we have jet traffic coming in can you go behind them or do need to be on the ground right now
09:50:00	N93012.8	i kinda would like to be on the ground as soon as possible
09:50:11	BR.7	N93012 you can proceed however necessary for runway six
09:50:16	N93012.9	okay entering a downwind for runway six 93012
09:50:50	BR.8	N93012 contact tower 120.3
09:50:54	N93012.10	1203 so long
09:51:00	N93012.11	bradley tower boeing 93012 is entering a downwind for 06
09:51:07	LC.2	N93012 wind calm runway six cleared to land
09:51:08	N93012.12	93012 cleared to land on six
09:51:28	LC.3	N93012 how's your progress for runway six
09:51:34	N93012.13	we'll get there midfield downwind now

Table 2. Selected radio communications between ATC and N93012, from References 7 and 8. Sources: LC = Bradley Airport Air Traffic Control Tower; BR = Yankee TRACON,[6] Bristol Radar; N93012 = B-17G N93012.

[5] The ADS-B data recorded the airplane's north-south and east-west velocities, which combine to define the total ground speed and ground track angle.
[6] TRACON = Terminal Radar Approach Control facility.

IV. Estimated Boeing B-17G lift, drag, and power based on Flight Handbook data

Engine power and propeller efficiency

Figure 1 is the "Specific Engine Flight Chart" from the B-17G Flight Handbook. It lists the power output of an individual engine under various conditions. The maximum possible power output is 1,380 SHP in the "war emergency" condition, corresponding to 2,500 RPM and 54" Hg manifold pressure (MP), but this condition can only be achieved with a carburetor modification that N93012 did not have. Normal takeoff power is 1,200 SHP at 2,500 RPM and 47.5" Hg MP.

The power for normal climb can be gleaned from Figures 9 and 10, which show the rate of climb vs. airspeed at sea level, and engine power vs. altitude, respectively. The rate of climb chart (Figure 9) is for a power setting of 2,300 RPM and 38" Hg MP, which per Figure 10 produces about 925 SHP per engine at sea level.

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

$$\eta_P = \frac{HP}{SHP} = \frac{(T)(V_T)}{SHP} \qquad [1]$$

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,

$$\eta_P = \eta_i \eta_0 \qquad [2]$$

η_0 is assumed to be 0.9 in this *Study*, following the practice observed at a manufacturer of propeller-driven airplanes. 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 11 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 11.

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

$$T = \frac{d}{dt}(mv) = v\frac{dm}{dt} + m\frac{dv}{dt} \qquad [3]$$

Since mass is constant,

$$\frac{dm}{dt} = 0 \quad [4]$$

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

$$m = \rho A dx \quad [5]$$

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

$$\frac{dx}{dt} = V_1 \quad [6]$$

Consequently

$$m\frac{dv}{dt} = \frac{\rho A dx dv}{dt} = \rho A V_1 dv \quad [7]$$

The total change in air velocity dv is

$$dv = V_2 - V_T \quad [8]$$

Combing Equations [3], [4], [7], and [8] gives

$$T = \rho A V_1 (V_2 - V_T) \quad [9]$$

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,

$$T dx = \frac{1}{2}\rho A dx V_2^2 - \frac{1}{2}\rho A dx V_T^2 \quad [10]$$

$$T = \frac{1}{2}\rho A (V_2^2 - V_T^2) \quad [11]$$

The right-hand side of Equation [10] is the change in the kinetic energy of the air. Combining Equations [9] and [11] gives, after some algebraic manipulation,

$$V_1^2 = V_T V_1 + \frac{T}{2\rho A} \quad [12]$$

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 trust of the propeller multiplied by the speed of the air passing through the propeller disk:

$$(SHP)\eta_0 = T V_1 \quad [13]$$

Substituting Equation [13] into Equation [12] and rearranging terms results in the following cubic polynomial for the propeller thrust T, in terms of the known quantities $\rho, A, V_T, SHP,$ and η_0:

$$T^3 + [2\rho A V_T (SHP)\eta_0]T - 2\rho A[(SHP)\eta_0]^2 = 0 \quad [14]$$

Equation [14] can be solved numerically for T. The propeller efficiency η_P can then be computed using Equation [1].

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 as a function of airspeed at the climb power setting indicated by Figures 9 and 10 can be computed using Equation [14]. The resulting thrust can be used with the weight and rate of climb information in Figure 9 to compute the airplane's flaps-up and gear-up drag coefficient C_D as a function of its lift coefficient C_L (the drag polar), as described below.

Flaps and gear up drag polar from Flight Handbook rate of climb data

For small flight path angles (γ), such that $\sin\gamma \cong \gamma$ and $\cos\gamma \cong 1$ (γ in radians),

$$\gamma \cong \frac{T-D}{W} \cong \frac{T-D}{L} \qquad [15]$$

Where:
T = total thrust
D = drag
W = airplane gross weight
L = lift

The thrust, drag, and lift coefficients C_T, C_D, and C_L are defined as

$$C_T = \frac{T}{\bar{q}S} \qquad [16]$$

$$C_D = \frac{D}{\bar{q}S} \qquad [17]$$

$$C_L = \frac{L}{\bar{q}S} \qquad [18]$$

Where S is the airplane's reference wing area (1,420 ft.^{2} for the B-17G), and $\bar{q}$ is the dynamic pressure of the air meeting the airplane, defined as

$$\bar{q} = \frac{1}{2}\rho V_T^2 \qquad [19]$$

Substituting Equations [16]-[18] into Equation [15] gives

$$\gamma \cong \frac{C_T - C_D}{C_L} \qquad [20]$$

For small γ in radians, γ is related to the rate of climb (RC) and the true airspeed (V_T) by

$$RC \cong \gamma V_T \qquad [21]$$

Combining Equations [20] and [21] and solving for C_D gives

$$C_D = C_T - \left(\frac{RC}{V_T}\right) C_L \qquad [22]$$

Figure 9 plots RC as a function of indicated airspeed (equal to V_T at standard sea level) for different weights, and at the specified climb power. As noted above, T (and C_T) can be computed from Equation [14], and C_L can be computed from the given weight and V_T using Equation [18]. Hence, the B-17G flaps-up, gear-up drag polar (plot of C_D vs. C_L) can be constructed from the information presented in Figure 9. The resulting drag polar is plotted in the top plot of Figure 12.

Video of the N93012's approach to runway 6 at KBDL shows the gear down during the downwind leg. To compute the power required during this portion of the flight, the C_D increment due to the landing gear in the extended position must be added to the drag polar computed from the data in Figure 9. For this *Study*, this C_D increment was estimated as 0.0084 based on the dimensions of the gear and a method described in Reference 9.[7] The resulting flaps-up, gear-down drag polar is shown in the top plot of Figure 12.

Lift curve and maximum lift coefficient

As described further in Section D-V, to estimate the pitch angle (θ) of the airplane throughout the flight, the lift curve (C_L as a function of angle of attack (α)) must be known. Furthermore, the proximity of the airplane to an aerodynamic stall is of interest. C_L increases with α until the stall. At the stall angle of attack (α_{stall}), C_L is a maximum (C_{Lmax}), and any further increase in α will result in large areas of flow separation from the wing, a dramatic increase in C_D, and a drop in C_L. If the stall is asymmetric (one wing stalling before the other), an uncontrollable roll can also result, though the Flight Handbook notes that "stalling characteristics are very satisfactory. There is never a sharp tendency to roll." However, this statement probably assumes that the power level on all the engines is equal, and that there is no asymmetric propwash blowing over the left and right wings.

The power-off (idling engines) C_{Lmax} can be computed from the stall speeds published in the Flight Handbook, and Equation [18]. The resulting flaps-up, power-off C_{Lmax} is about 1.39. However, the Flight Handbook notes that the stall speed can be reduced (C_{Lmax} increased) with engine power (this is likely the result of the propeller wash energizing the boundary layer over the wing):

> Full flap reduces the stalling speed about 15 MPH for gross weights 40,000 and 45,000 pounds, but full military power for the same loading conditions may reduce the stalling speed another 15 MPH.

The additional 15 MPH stall speed reduction due to power in this statement seems to be associated specifically with the full flaps configuration, but some reduction in the stall speed with power is likely also possible with the flaps up. Assuming that full power reduces the stall speed by 15 MPH even at flaps up, the resulting flaps-up, power-on C_{Lmax} is about 1.91.

The lift curve (relationship between α and C_L) cannot be determined solely from the data in the Flight Handbook. In this *Study*, a linear lift curve is assumed, and the lift curve slope is estimated based on the geometry of the wing and a method described in Reference 9 (Equation [8.22], p. 248). The zero-lift angle of attack (α_0) is estimated using the estimated lift curve slope and assuming that the pitch angle is 0° at a "representative" cruise condition. The Flight Handbook specifies a true airspeed of 217 MPH for weights between 45,000 lb. and 50,000 lb. at 15,000 ft. altitude, at 2,150 RPM and 31" Hg MP. Using this condition, α_0 is estimated as -4.9°. The lift curve slope is estimated as 0.0899 per degree. The true α_0 and lift curve slope could be different, and the lift curve itself may not be perfectly linear, but "curve over" at the higher α approaching α_{stall}.

[7] Specifically, the data and method presented in *Figure 4.59 – Gear Drag Increments: Retractable Gears* from Reference 9 (Chapter 4, p. 96) was used to estimate the C_D increment resulting from extending the main and tail gears.

V. Airplane performance calculations based on recorded ADS-B and EGPWS data

Horizontal trajectory (north and east positions, ground speed, and ground track)

The latitude and longitude coordinates in the ADS-B data are based on GPS positions, and are very accurate compared to radar data (range uncertainty in radar data alone is about ±1/16 nmi, or ±380 ft., and GPS positions are generally accurate to within 60 ft. (see Reference 11). Nonetheless, small uncertainties or inaccuracies in the positions result in unrealistic spikes or “noisiness” in ground speed and ground track computed from the first time-derivatives of the GPS data, which propagate into noisy heading and pitch angle calculations. To reduce this spurious noise in the ground speed and other calculated parameters presented in this *Study*, the GPS positions are smoothed by applying a running-average smoothing algorithm.

The north and east velocities recorded in ADS-B files are themselves filtered by aircraft avionics prior to broadcast over the ADS-B system, and so in general a very smooth ground speed can be obtained by combining these velocities. Interestingly, however, in this case the recorded ADS-B speeds are not as smooth as the speeds observed in other cases, and in fact contain obvious unrealistic “spikes” (see, for example, Figure 13 at 09:51:22). Consequently, in this *Study* the smoothed GPS positions are used to compute ground speed, ground track, and other performance parameters. The east and north positions obtained from integrating the recorded ADS-B north and east speeds are shown for comparison with the recorded positions in Figures 5 and 6.

Vertical trajectory (altitude and rate of climb)

The ADS-B data contains both barometric pressure altitude and GPS altitude and rate of climb parameters. The resolution of the pressure altitude data is to the nearest 100 ft., and the resolution of the GPS altitude data is to the nearest 25 ft.; hence, GPS altitude smoothed with a running-average algorithm is used in this study to compute rate of climb and other performance parameters. The recorded GPS-based rate of climb is not as smooth as the rate of climb computed from the smoothed GPS altitude data, and when integrated in time does not match the recorded GPS altitude data perfectly (see Figure 8).

The recorded GPS altitude is clearly offset from the true MSL altitude, since at the beginning and end of the flight it shows the airplane below the terrain elevation (see Figure 8). Consequently, the GPS altitude is shifted to match the terrain elevation at the times that the airplane was on the ground, and then smoothed as mentioned above for the rate of climb and additional performance calculations.

Airspeed, attitude, and flight angle calculations

The smoothed GPS position and altitude data are used to compute additional performance information, including airspeeds, flight path angle, angle of attack, Euler angles (heading, pitch, and roll), and power required. If the position (latitude, longitude, and altitude) of an airplane is known as a function of time, then its orientation (i.e., the Euler angles) can also be estimated as long as the following are true:

- The motion of the air mass relative to the Earth, i.e., the wind, is known;
- The lift coefficient of the airplane as a function of angle of attack is known;
- The gross weight of the airplane is known;
- The sideslip angle and lateral acceleration are negligible (i.e., coordinated flight).

Since the airplane remained within about 600 ft. of the field elevation and 4 miles of the runway, the surface winds at KBDL at the time of the accident were used for this *Study.* Relevant METAR observations from KBDL are presented in Table 3.

At the time of the accident (09:53 EDT), the METAR winds were calm, in agreement with the ATC tower report to N93012 at 09:51 shown in Table 2: "N93012 wind calm runway six cleared to land." A wind speed of zero is therefore assumed in this *Study*.

Parameter \ Report	KBDL METAR 08:51 EDT	KBDL METAR 09:51 EDT	KBDL METAR 10:51 EDT
Sky condition	Few 3,500 ft. Broken 18,000 ft. Broken 25,000 ft.	Few 11,000 ft. Few 14,000 ft. Broken 18,000 ft.	Few 4,000 ft. Broken 13,000 ft. Broken 18,000 ft.
Visibility	10 statute miles	10 statute miles	10 statute miles
Winds	210° @ 6 kt.	Wind calm	240° @ 4 kt.
Temperature / Dew Point	23°C / 19°C	23°C / 19°C	24°C / 20°C
Altimeter setting	29.81 "Hg	29.81 "Hg	29.79 "Hg

Table 3. Weather observations at KBDL surrounding the time of the accident.

The lift curve and drag polar of the B-17G are estimated as described in Section D-IV. A gross weight of 46,360 lb. (see Table 1) is assumed in the performance calculations. The flaps are normally up for takeoff, and the flaps were found up in the wreckage, so this *Study* assumes that the flaps were up throughout the flight. Video evidence indicates that the landing gear were down during the downwind leg of the traffic pattern. The power required for the flight, and the possible rate of climb and flight path angle values assuming both climb and takeoff power on different numbers of operating engines, are computed for both gear-up and gear-down configurations, as described below.

The position of an airplane as a function of time defines its velocity and acceleration components. In coordinated flight, these components lie almost entirely in the plane defined by the airplane's longitudinal and vertical axes. Furthermore, any change in the *direction* of the velocity vector is produced by a change in the lift vector, either by increasing the magnitude of the lift (as in a pull-up), or by changing the direction of the lift (as in a banked turn). The lift vector also acts entirely in the aircraft's longitudinal-vertical plane, and is a function of the angle between the aircraft longitudinal axis and the velocity vector (the angle of attack, α). These facts allow the equations of motion to be simplified to the point that a solution for the airplane orientation can be found given the additional information about wind and the airplane lift curve (C_L vs. α). The results of the performance calculations based on the smoothed position and altitude data described above are presented below.

Results: position and altitude

The north and east positions of N93012 are presented in a plan view in Figures 5 and 6, and as a function of time in Figure 7. These Figures present the recorded and smoothed ADS-B positions, and the positions obtained by integrating the ADS-B speed information, as described above.

GPS altitude is presented as a function of time in Figure 8. The shift in altitude to match the terrain elevation is shown, as well as the altitude resulting from the integration of the recorded GPS-based rate of climb. The smoothed curve through the shifted altitude is also shown. The density altitude at the time of the accident was about 1,000 ft. higher than the GPS altitude.

The maximum altitude attained was 770 ft. MSL, or about 600 ft. above the field elevation. The airplane started descending at about 09:49:57.

Results: speed and rate of climb

Figure 13 shows the results of the speed and rate of climb calculations. The ADS-B recorded ground speed is depicted by the black line and circle symbols; the ground speed computed by differentiating the “raw” (unsmoothed) GPS positions is shown by the light gray line; and the ground speed computed by differentiating the smoothed GPS positions is shown by the blue line. Because the wind is calm, the true airspeed (green line) is approximately identical to the ground speed. The calibrated airspeed is shown by the red line.

The peak calibrated airspeed in Figure 13 is 124 MPH at the start of the plotted data (09:47:53).[8] The airspeed progressively decays, with ups and downs, throughout the flight; a 14 MPH drop to 98 MPH occurs between 09:49:38 and 09:49:55, while the altitude increases from about 720 to 750 ft. The airspeed recovers to 114 MPH during the subsequent descent to about 530 ft. The speed decays again as altitude is increased to 600 ft., and stabilizes between 91 and 97 MPH between 09:51:00 and 09:53:00 as the airplane descends to 250 ft. MSL. The airspeed briefly increases to 99 MPH at 09:53:10 before sharply dropping to 86 MPH at the end of the data at 09:53:20 (a 13 MPH drop in 10 seconds, without an accompanying increase in altitude). It is likely that this sudden drop in airspeed (and ground speed) resulted from the airplane impacting the runway approach lights; Figure 6 indicates that the airplane was over the lights at this time.

The bottom graph in Figure 13 compares the ADS-B recorded rate of climb (black line and circle symbols) with the rate of climb computed by differentiating the “raw” GPS altitude (light gray line) and smoothed GPS altitude (blue line). The Figure indicates that N93012 initially climbed at a rate between 500 and 1,000 ft./min., but at 09:49:57 was descending at about 500 ft./min., and reached a maximum descent rate of 700 ft./min. at 09:50:00. Thereafter, the airplane descended at an average rate of about 160 ft./min.

Results: flight angles and lift coefficient

Figure 14 presents the following flight angles calculated from the trajectory obtained from the smoothed GPS position and altitude data, as described above:

- Flight path angle
- Pitch angle
- Angle of attack
- Roll angle (including an additional smoothing of the result to reduce noise)
- True ground track

The bottom plot of Figure 12 presents the airplane’s C_L as a function of time; the top plot presents the gear-up and gear-down flaps-up drag polar developed as described in Section D-IV. The flaps-up power-on and power-off C_{Lmax} values are also shown in Figure 12. Note that as the airplane’s speed decreased, the C_L (and α) increased to maintain lift, per Equation [18]. At about 09:51:06, the C_L exceeded 1.39, the power-off C_{Lmax}, suggesting that power on the engines increased the C_{Lmax} available and kept the airplane from stalling (the C_L remained below the power-on C_{Lmax} throughout the flight). However, the sudden decrease in speed between 09:53:10 and 09:53:20

[8] The ADS-B file includes data corresponding to the time that the airplane was on the ground before takeoff. The data presented in this *Study* is only for the airborne portion of the flight, starting shortly after liftoff.

(likely resulting from impacts with the runway approach lights) is reflected in a sudden jump in C_L at this time, and might indicate that the right wing was then operating very near its C_{Lmax} (or even a bit beyond C_{Lmax}, resulting in flow separation and a loss of lift) and unable to produce additional lift (through aileron deflection) to help roll the airplane left towards wings-level. This might be part of the reason the right wing remained low and eventually contacted the ground. Engine #4 was inoperative and engine #3 might not have been producing full power, and consequently the C_{Lmax} of the right wing might have been less than that of the left wing, if power was still applied on the left engines. Asymmetric power, and additional drag on the right wing due to flow separation, could have resulted in a left sideslip angle that would also have acted to roll the airplane to the right.
The top plot in Figure 14 shows the pitch angle and angle of attack increasing as speed decreases. It also shows the flight path angle reflecting the behavior of the rate of climb described earlier, and averaging about -1.5° from 09:51:20 onwards.

The middle plot of Figure 14 shows the computed roll angle. Even after smoothing the ADS-B position data, the computed roll angle is noisy (light gray line); this is the result of small oscillations in the ground track (plotted at the bottom of Figure 14) which result in oscillations in computed yaw rate and, consequently, roll angle. The solid black line in the middle plot is the result of smoothing the computed roll angle with a running-average algorithm, and indicates that the right turns that returned the airplane to the runway were executed with roll angles of about 25°. Note that the computed roll angle has the airplane in about a 20° right bank even past 09:53:10, when its ground track was aligned with the runway heading, consistent with the video evidence in Addendum 1.

Power required and climb performance vs. airspeed

The C_L throughout the flight (shown in the bottom plot of Figure 12) can be used along with the drag polar (shown in the top plot of Figure 12) to compute the C_D throughout the flight (for landing gear up and down). The C_L, C_D, and flight path angle γ (plotted in Figure 14) can be used with Equations [20] and [16] to compute the thrust coefficient C_T and total thrust T. The power required (i.e., the power delivered to the airplane) can then be computed as $HP = TV_T$ (see Equation [1]).

The resulting power required is plotted in Figure 15. The light gray line in both the top and bottom plots is the computed gear-down power required; the oscillations in the calculation correspond to oscillations in the computed ground speed (see Figure 13), which the calculation interprets as accelerations and associated variations in thrust and power. The solid black line is the computed gear-down power required smoothed with a running average algorithm, and is more realistic. The solid blue line is the smoothed gear-up power required. Note that the extended gear adds about 100 HP to the power required.

The green lines in the top plot of Figure 15 depict the power available from 1, 2, 3, and 4 engines operating at the climb power setting corresponding to the Flight Handbook rate of climb chart (925 SHP per engine; see Figures 9 and 10). The red lines in the bottom plot of Figure 15 depict the power available from 1, 2, 3, and 4 engines operating at the takeoff power setting defined in the Flight Handbook specific engine chart (1,200 SHP; see Figure 1). The power available is equal to the SHP from the engines multiplied by the propeller efficiency, computed as described in Section D-IV. The propeller efficiency as a function of airspeed, for both the climb and takeoff power settings, is shown as a function of airspeed in the top plot of Figure 16.

Figure 15 indicates that between 09:47:53 and 09:48:30, the engines were delivering about 2,700 HP to the airframe, which corresponds to about 3.5 engines operating at climb power (or 4 engines operating at 88% of climb power). At about 09:48:30, the delivered power dropped considerably, to about 1,500 HP, corresponding to 2 engines at climb power. Note, however, that if the drop in power was the result of the failure of engine #4 (as seems likely) and, possibly, a reduction of power on engine #3, then additional sources of drag might have been present that are not accounted for in the power required calculation, and that would act to increase the power required. These drag sources include propeller drag from the failed engine (which can be reduced, but not eliminated, by feathering the propeller), and trim drag due to rudder deflection and possibly sideslip required to compensate for the asymmetric thrust from the left and right side engines. Consequently, the actual power required in the period after 09:48:30 might be greater than that shown in Figure 15.

The bottom plot of Figure 16 shows the total thrust and drag on the airplane as a function of airspeed. The thrust for 1, 2, 3, and 4 engines at both climb and takeoff power is shown, and the drag is shown for the gear-up and gear-down configurations. Per Equations [15] and [21], the flight path angle γ and rate of climb RC are proportional to the difference between the thrust and the drag (the "excess thrust"). Figure 16 shows that the excess thrust is a function of airspeed.

Maximizing γ would have maximized the altitude at which the airplane would have arrived at the runway following the turn back to the airport. γ and RC are plotted as a function of airspeed in Figures 17 and 18, respectively. Note that the airspeeds for maximum γ and RC are different (consistent with the different "best angle of climb" and "best rate of climb" speeds found in pilot operating handbooks). Note also that the speeds for maximum γ and RC depend on the number of engines operating; this is the result of the different slopes of the thrust vs. airspeed lines shown in the bottom plot of Figure 16 for different numbers of operating engines. With 4 operating engines, maximum γ is obtained with the gear up at about 100 to 105 MPH, and maximum RC is obtained at about 120 MPH. With 3 operating engines, maximum γ is obtained with the gear up at about 105 to 113 MPH, and maximum RC is obtained at about 115 to 120 MPH. At lower speeds, the drag due to lift (induced drag) increases, and the airplane operates "on the back side of the power curve." At higher speeds, drag increases due to increased dynamic pressure.

The multi-colored lines in Figure 17 and 18 show the γ and RC achieved by N93012 as a function of airspeed. The color of the line indicates the time corresponding to each data point, per the color table in the plots. Figures 18 and 13 indicate that from about 09:51:00 onwards, the airplane was operating at or below 100 MPH, and below the airspeed for maximum γ, which would have been about 115 MPH for the 2 engines at climb power condition that most closely matches the computed power being delivered to the airplane. Figure 17 also indicates that with 2 engines at climb power, the airplane might just have been able to maintain level flight (γ=0) by flying with the gear up at about 115 to 120 MPH. The airplane would not be able to maintain level flight at that power level with the gear down, at any speed.

Figures 17 and 18 are constructed using the flaps up drag polar derived from the Flight Handbook rate of climb chart. Again, this data does not account for possible propeller drag due to an engine-out condition, or trim drag resulting from the rudder and sideslip angle required to compensate for asymmetric thrust. Accounting for these items would decrease the γ and RC values plotted in the Figures. As noted above, the aerodynamic characteristics of the B-17G required to estimate these quantities cannot be determined from information published in the Flight Handbook.

Unknowns: control authority to trim asymmetric thrust and corresponding maximum thrust

Figure 17 also indicates that with two engines at full takeoff power, the airplane could climb (γ>0) at airspeeds between 90 and 140 MPH, even with the landing gear down. Even considering added drag due to the engine-out condition and trimming for asymmetric thrust, Figure 17 suggests that, if both left-wing engines had been operating at full takeoff power, the airplane should have had enough power and thrust to maintain level flight, and approach runway 6 along a normal glide path, rather than landing short into the approach lights as occurred during the accident.

However, it is unknown whether the airplane had enough rudder authority to trim the asymmetric thrust resulting from full thrust from both left wing engines, zero thrust (and probably some drag) from engine #4 on the right wing, and an unknown level of thrust from engine #3. Flying with some left sideslip in addition to full left rudder would help counter the yawing moment to the right from the asymmetric thrust; but depending on the amount of sideslip angle required, a considerable rolling moment to the right would have to be countered with the ailerons. Knowledge of the yawing moment characteristics of the airplane as a function of rudder and sideslip angle, and the rolling moment characteristics as a function of aileron and sideslip angle, would be required to evaluate the amount of asymmetric thrust that could be controlled, and hence the maximum power that could be applied to the left-wing engines. In addition, the drag due to sideslip and control surface deflections would be required to compute the resulting γ and RC. Figures 15 and 17 suggest that the power applied to the airframe was about that corresponding to two engines at climb power, or perhaps a bit more, accounting for propeller drag from engine #4 and trim drag from the rudder and sideslip. It seems possible that more power was available from the left wing engines, but it cannot be determined whether this power was not applied because of the pilot's deliberate choice, or because there was insufficient control authority to trim more asymmetric thrust from the left wing engines, or because of other reasons.

In comments on a draft version of this *Study*, the Collings Foundation Chief Pilot provided the NTSB with a qualitative assessment of the amount of asymmetric thrust that could be controlled at the airspeeds achieved during the accident flight (see Appendix A). The pilot's comments are based on B-17 operators' "experience and testing over the years," and state that "using full power at max gross with the bad engines windmilling, you would be looking at something more like 150 mph [airspeed] for one outboard out and 190+ for two out on one wing" to control the asymmetric thrust condition. On this basis, it is likely that the accident pilot did not have enough control authority, at the airspeeds flown, to apply more power to the left-side engines. The Chief Pilot's comments conclude that

> It appears that if #4 was failed and feathered, and that #3 lost some amount of power at some point, the airplane was likely flown right on the edge of being controllable with as much power as possible. Stories of B-17's making it back to base after losing 1-2 engines in WW2 are certainly true, when they lost those engines at 30,000 feet and over 150 mph in most cases. In this situation, at 700 feet and around 130 mph, maintaining directional control and any sort of performance would've been nearly impossible.

E. CONCLUSIONS

This *Aircraft Performance ADS-B Study* presents the results of using ADS-B position and speed data, video and crash site evidence, surface weather information, and performance data derived from information published in the B-17G Flight Handbook to calculate N93012's position, orientation, speed, and other performance parameters during the airborne portion of the flight. The results of these calculations are summarized in the "History of Flight" section above, and described in detail in the body of the *Study*.

The following observations can be drawn from the data and calculations presented in this *Study*:

- N93012 lifted off from runway 6 at about 09:47:53, and climbed at an average rate of about 750 ft./min. to an altitude of 730 ft. MSL (about 560 ft. AFE). During this climb, the power delivered to the airplane (power required) was equivalent to that of 3.5 engines at the nominal Flight Handbook climb power setting, or to that of 4 engines at 88% of the nominal climb power setting.
- At about 09:48:30, the delivered power dropped considerably, to that of about 2 engines at climb power. Additional sources of drag (such as propeller and trim drag) not accounted for in the power required calculation would act to increase the power required.
- During the return to the airport, from about 09:51:00 onwards, the airplane was operating at or below 100 MPH, below the airspeed for maximum γ (maximizing γ would have maximized the altitude at which the airplane would have arrived at the runway, and would likely have enabled the airplane to overfly the approach lights).
- Video evidence indicates that N93012's landing gear was extended on the downwind leg of the traffic pattern, which would have reduced γ at a given power setting, and increased the power required to maintain level flight.
- If both left-wing engines had been operating at full takeoff power, the airplane should have had enough thrust to maintain level flight, and approach runway 6 along a normal glide path, rather than landing short into the approach lights as occurred during the accident. However, it is unknown whether the airplane had enough control authority to trim the asymmetric thrust resulting from full thrust from both left wing engines, zero thrust (and probably some drag) from engine #4 on the right wing, and an unknown level of thrust from engine #3.
- As the airplane's speed decreased while returning to the runway, the C_L increased to maintain lift. At about 09:51:06 (about 2 minutes before the airplane touched down), the C_L exceeded the power-off C_{Lmax}, suggesting that power on the engines increased the C_{Lmax} available and kept the airplane from stalling (the C_L remained below the power-on C_{Lmax} throughout the flight).
- In a video of the touchdown (see Addendum 1), the airplane appears continuously rolled to the right, but the right wing does not perceptibly "drop." Instead, it appears that the wings might never have leveled after the airplane was aligned on the runway centerline following the downwind-to-final turn, but simply maintained the right roll present during that turn. This possibility is consistent with the roll angle computed from the ADS-B data. The reasons why the wings were not leveled once the airplane was aligned with the runway are not known, but might include the right wing operating very close to its maximum lift coefficient (see next bullet), and a left sideslip angle (resulting from asymmetric thrust and perhaps additional drag on the right wing).

- The sudden decrease in speed between 09:53:10 and 09:53:20 (likely resulting from impacts with the runway approach lights) is reflected in a sudden jump in C_L at this time, and might indicate that the right wing was then operating very near its C_{Lmax} (or perhaps a bit beyond, resulting in flow separation and a loss of lift), and unable to produce additional lift (through aileron deflection) to help roll the airplane left towards wings-level; consequently, the right wing remained low and eventually contacted the ground.
- One witness testified that the airplane yawed to the right after the right wing contacted the ground, and that engine power increased after the right wing "leveled out" again. The sustained right roll before touchdown, the loss of directional control after touchdown, and the application of power on the ground (accelerating the airplane and likely exacerbating the directional control problem) were critical events affecting the outcome of the flight.

This sequence of events is consistent with a loss of power on engine #4 at about 09:48:30, and is supported by witness evidence noting that the propeller on engine #4 was not turning,[9] and finding the propeller feathered in the wreckage. Evidence presented in Reference 5 indicates that engine #3 may not have been producing full power either.

This *Study* indicates that if the airspeed maintained during the return to the runway were closer to that required for maximum γ, and if the landing gear had been kept retracted until the final approach, the airplane would likely have overflown the runway approach lights and touched down past the runway threshold, and would have required a C_L comfortably below the power-off C_{Lmax} and thereby mitigated the risk of an asymmetric stall and/or a loss of roll control. Alternatively, an approach and landing on runway 33 (instead of runway 6) could likely have been accomplished more easily, at higher speeds and along a nominal glide path. The Collings Foundation Chief Pilot's comments in Appendix A note that at the airspeeds achieved during the accident flight, "maintaining directional control and any sort of performance would've been nearly impossible." This assessment underscores that an emergency landing on runway 33 would likely have been a better choice than the continued approach to runway 6.

Following the contact of the right wing with the ground and the sudden yaw to the right, the addition of power accelerated the airplane towards the deicing fluid tanks and likely contributed to the severity of the outcome. A safer course of action would have been to retard all engines to idle and use maximum braking to stop the airplane, and / or to use differential braking and rudder to yaw the airplane back to the left and parallel to the runway while rolling to a stop.

John O'Callaghan
National Resource Specialist – Aircraft Performance
Office of Research and Engineering

[9] As documented in Reference 13, a witness stated that "one of the motors was out, the propeller wasn't spinning."

F. REFERENCES

1. The Boeing Company, *USAF Series B-17G / Navy Series PB-1W Aircraft Flight Handbook,* T.O. 1B-17G-1, published under authority of the Secretary of the Air Force and the Chief of the Bureau of Aeronautics, 1 August 1944, revised 1 June 1953. Available online at: https://aviationshoppe.com/manuals/b-17_flight_handbook/b-17g_flight_handbook.html.
2. Boeing Historical Snapshot webpage: https://www.boeing.com/history/products/b-17-flying-fortress.page.
3. Wikipedia B-17 webpage: https://en.wikipedia.org/wiki/Boeing_B-17_Flying_Fortress.
4. The Boeing Company, *Boeing Model B-17G Flying Fortress Bombardment Airplane Field Service Manual*.
5. National Transportation Safety Board, Office of Aviation Safety, *Powerplants Group Chairman's Factual Report, Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019, NTSB #ERA20MA001*. (Contact NTSB at pubinq@ntsb.gov.)
6. National Transportation Safety Board, Office of Aviation Safety, *Unmanned Aircraft System (UAS) Aerial Imagery Report, Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019, NTSB #ERA20MA001* (Washington, D.C., March 4, 2020). (Contact NTSB at pubinq@ntsb.gov.)
7. Federal Aviation Administration, *Memorandum from Bradley Airport Traffic Control Tower to Aircraft Accident File 19-001-BDL: INFORMATION: Full Transcript, Aircraft Accident, N93012, Windsor Locks, CT, 10/02/2019,* October 30, 2019.
8. Federal Aviation Administration, *Memorandum from Yankee Terminal Radar Approach Control Facility to Aircraft Accident File 19-001-BDL: INFORMATION: Full Transcript, Aircraft Accident, N93012, Windsor Locks, CT, 10/02/2019,* October 31, 2019.
9. Roskam, Jan, Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics, Roskam Aviation and Engineering Corp., 1987.
10. [Not used]
11. International Civil Aviation Organization (ICAO), The Tenth Meeting of Automatic Dependent Surveillance – Broadcast (ADS-B) Study and Implementation Task Force (ADS-B SITF/10) Agenda Item 6: Review States' activities and interregional issues on trials and implementation of ADS-B and multilateration: ADS-B / GPS Accuracy (Presented by Australia). Singapore, 26-29 April 2011. Document available at: https://www.icao.int/APAC/Meetings/2011_ADS_B_SITF10/IP10_AUS%20AI.%206%20-%20GPS%20Accuracy.pdf
12. National Transportation Safety Board, *Memorandum for Record: Subject: ERA20MA001; Who: Jeff Dawson – Witness*, October 8, 2019. (Contact NTSB at pubinq@ntsb.gov.)
13. National Transportation Safety Board, *Memorandum for Record: Subject: ERA20MA001; Who: Chris Hagenow – Witness*, October 7, 2019. (Contact NTSB at pubinq@ntsb.gov.)
14. National Transportation Safety Board, Office of Research and Engineering, *Addendum 1 to the Aircraft Performance ADS-B Study, Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019, NTSB #ERA20MA001* (Washington, D.C., May 15, 2020). (Contact NTSB at pubinq@ntsb.gov.)

G. GLOSSARY

Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
AFE	Above field elevation
ATC	Air Traffic Control
CG	Center of Gravity
EDT	Eastern Daylight Time
FAA	Federal Aviation Administration
GPS	Global Positioning System
“Hg	Inches of mercury
HP	Horsepower
KBDL	Bradley International Airport, Windsor Locks, Connecticut
METAR	Meteorological Terminal Air Report
MP	Manifold pressure
MPH	Statute miles per hour
MSL	Mean Sea Level
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NTSB	National Transportation Safety Board
RSA	Runway safety area
SHP	Shaft horsepower
UAS	Unmanned Aircraft System
UTC	Universal Coordinated Time

Symbols

α	Angle of attack
α_0	Zero-lift angle of attack
α_{stall}	Stall 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
A	Propeller disk area
C_D	Drag coefficient
C_L	Lift coefficient
C_{Lmax}	Maximum lift coefficient (C_L at α_{stall})
C_T	Thrust coefficient
D	Drag
L	Lift
m	Mass
HP	Power delivered to the airplane to increase its energy state (less than the SHP of the engines because of losses due to propeller efficiency)
$\bar{q}$	Dynamic pressure
RC	Rate of climb
SHP	Shaft horsepower produced by the engine(s)
Δt	Time increment between data samples
t	Time
T	Thrust
v	Velocity of air in stream tube flowing through propeller
V_1	Air velocity at the propeller disk
V_2	Final velocity of air accelerated through propeller disk
V_T	True airspeed
W	Weight
x	Distance along stream tube flowing through propeller

H. FIGURES

FORM ASC-512A

AIRPLANE MODELS ....B-17G........

SPECIFIC ENGINE FLIGHT CHART

ENGINE MODELS ....R-1820-97........

CONDITION	FUEL PRESSURE (LB/SQ. IN.)	OIL PRESSURE (LB/SQ. IN.)	OIL TEMP. °C	OIL TEMP. °F	COOLANT TEMP. °C	COOLANT TEMP. °F		
DESIRED	17	70	70	158				
MAXIMUM	18	75	88	190				
MINIMUM	16	65						
IDLING	12	25						

MAX. PERMISSIBLE DIVING RPM: ....2760..........

CONDITION	ALLOWABLE OIL CONSUMPTION
NORMAL RATED (MAX. CONT.)	....14...U.S.QT/HR...23...IMP.PT/HR
MAX. CRUISE	....8...U.S.QT/HR...13...IMP.PT/HR
MIN. SPECIFIC	...•5...U.S.QT/HR....8...IMP.PT/HR

OIL GRADE: (S).... 1100 ....(W)... 1100 ....

SUPERCHARGER TYPE: GE TYPE B-22 TURBOSUPERCHARGER

FUEL GRADE: 100/130, Specification MIL-F-5572

OPERATING CONDITION	RPM	MANIFOLD PRESSURE (BOOST)	HORSE-POWER	CRITICAL ALTITUDE WITH RAM	CRITICAL ALTITUDE NO RAM	BLOWER	USE LOW BLOWER BELOW:	MIXTURE CONTROL POSITION	FUEL FLOW (GAL/HR/ENG.) U.S.	FUEL FLOW (GAL/HR/ENG.) IMP.	MAXIMUM CYL. TEMP. °C	MAXIMUM CYL. TEMP. °F	MAXIMUM DURATION (MINUTES)
TAKE-OFF	2500	47.5	1200	32,700				AUTO RICH	138*	115	260	500	5
WAR EMERGENCY	2500	54	1380	26,700				AUTO RICH	165*	140	260	500	5- (ONLY WITH CARBURETOR MODIFICATION)
MILITARY	2500	47.5	1200	32,700				AUTO RICH	138*	115	260	500	5
NORMAL RATED (MAX CONT.)	2300	41.5	1000	35,200				AUTO RICH	100	84	232 CLIMB 218	450 CLIMB 424	CONTINUOUS
MAXIMUM CRUISE	2100	31	650	OVER 35,000				AUTO LEAN	63	52	205	400	CONTINUOUS
MINIMUM SPECIFIC CONSUMPTION (HOVERING)	1400	24	370	11,000				AUTO LEAN	26	21	205	400	CONTINUOUS

REMARKS: 1. For detailed CRUISING DATA, see FLIGHT OPERATING INSTRUCTION CHARTS following. * Horsepower and Fuel Flow for 15,000 Feet Altitude
2. AIR INTAKE FILTERS MUST BE OFF ABOVE 15,000 FEET in order to obtain maximum power at altitude. NOTE: Critical Altitude is that at which Maximum Power is obtained with Full Throttle under conditions shown.
3. Do not manually lean. Auto lean gives maximum range.
4. Do use excessive part throttle above 25,000 feet because of power surge.

Figure 74—Specific Engine Flight Chart

Figure 1. Boeing B-17G Specific Engine Flight Chart, from Reference 1.

Figure 2. Pre-accident photograph (top) and video still images of N93012 from the Collings Foundation website.

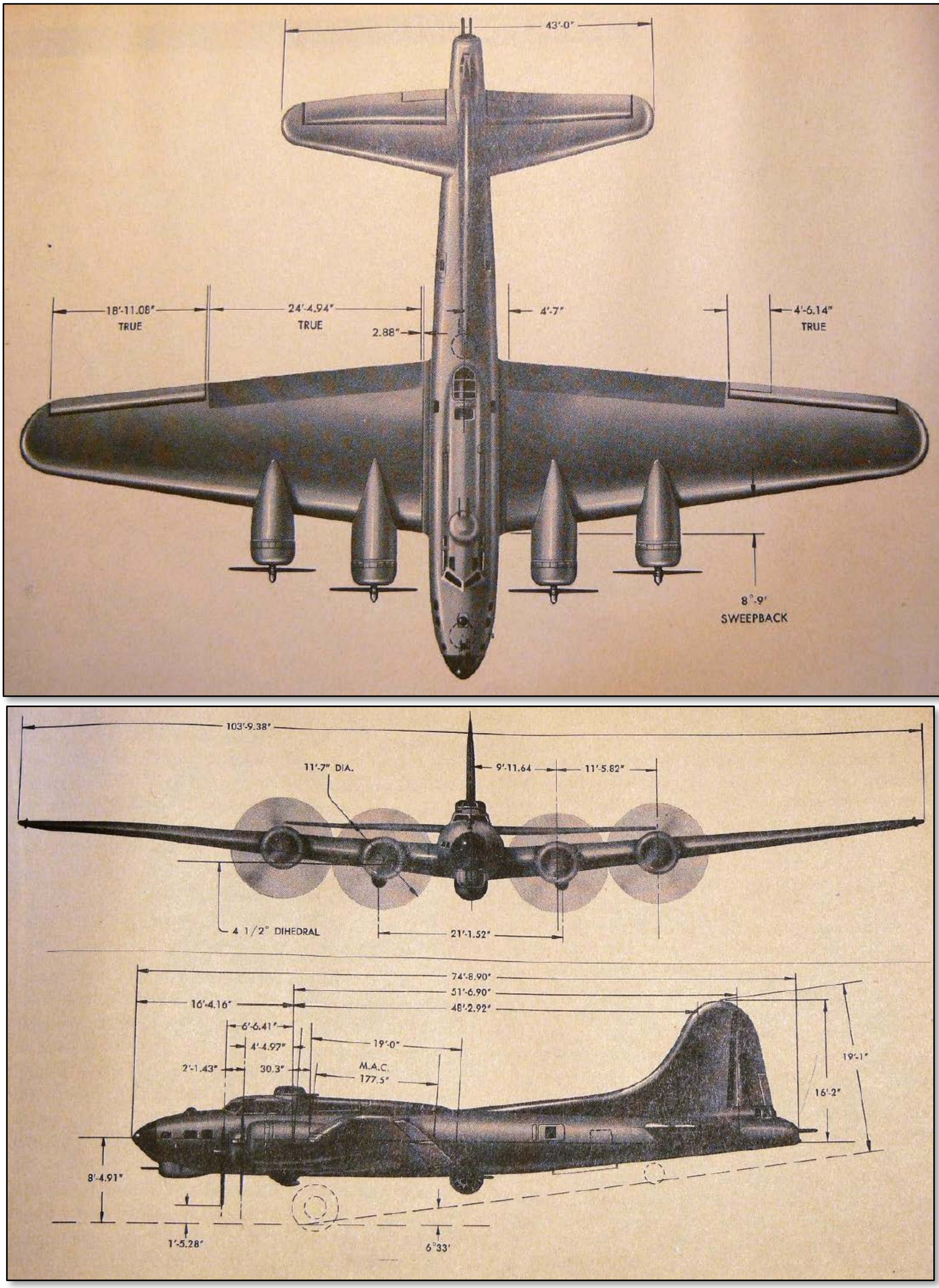


Figure 3. 3-view drawings of the Boeing B-17G, from Reference 4.

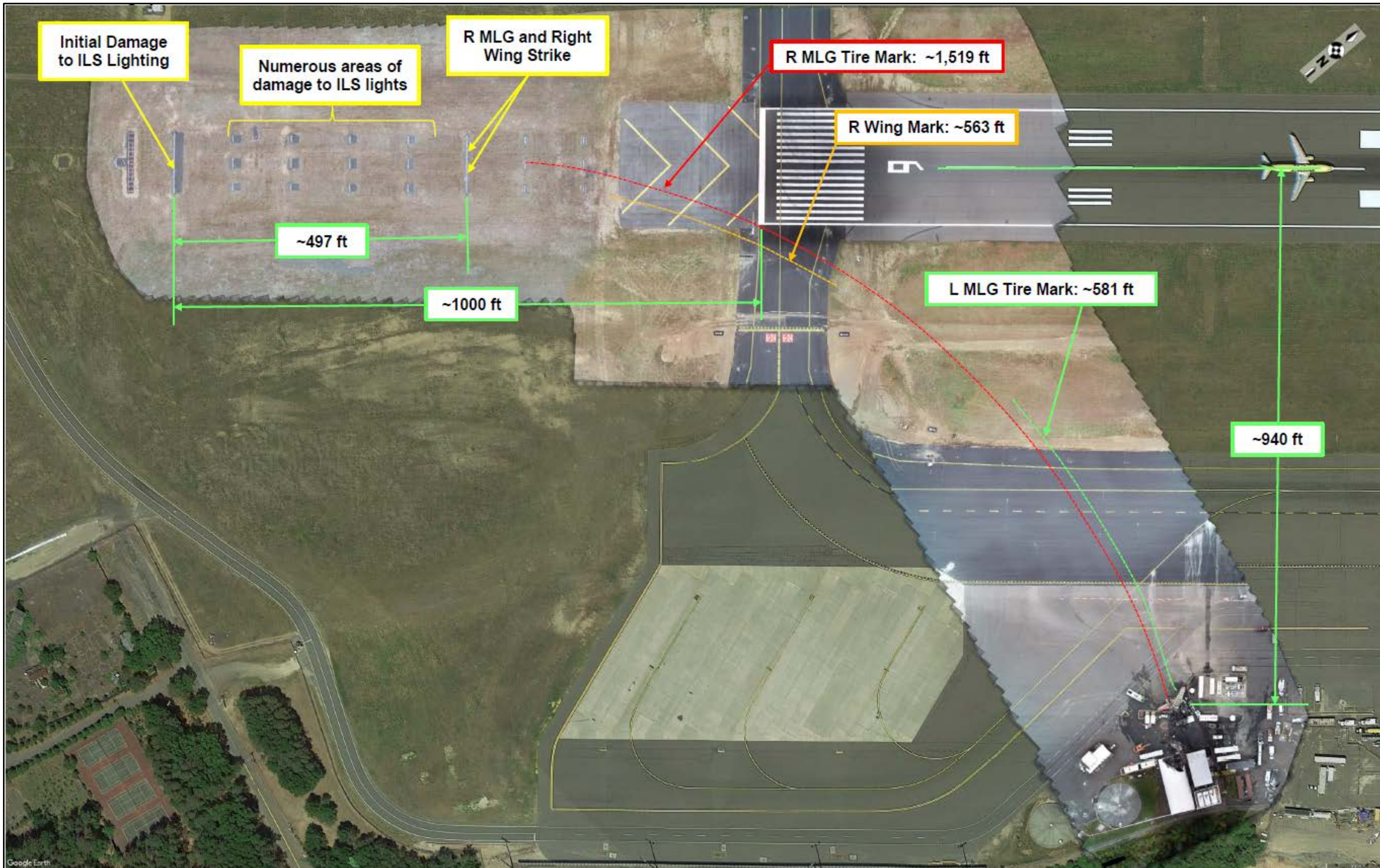
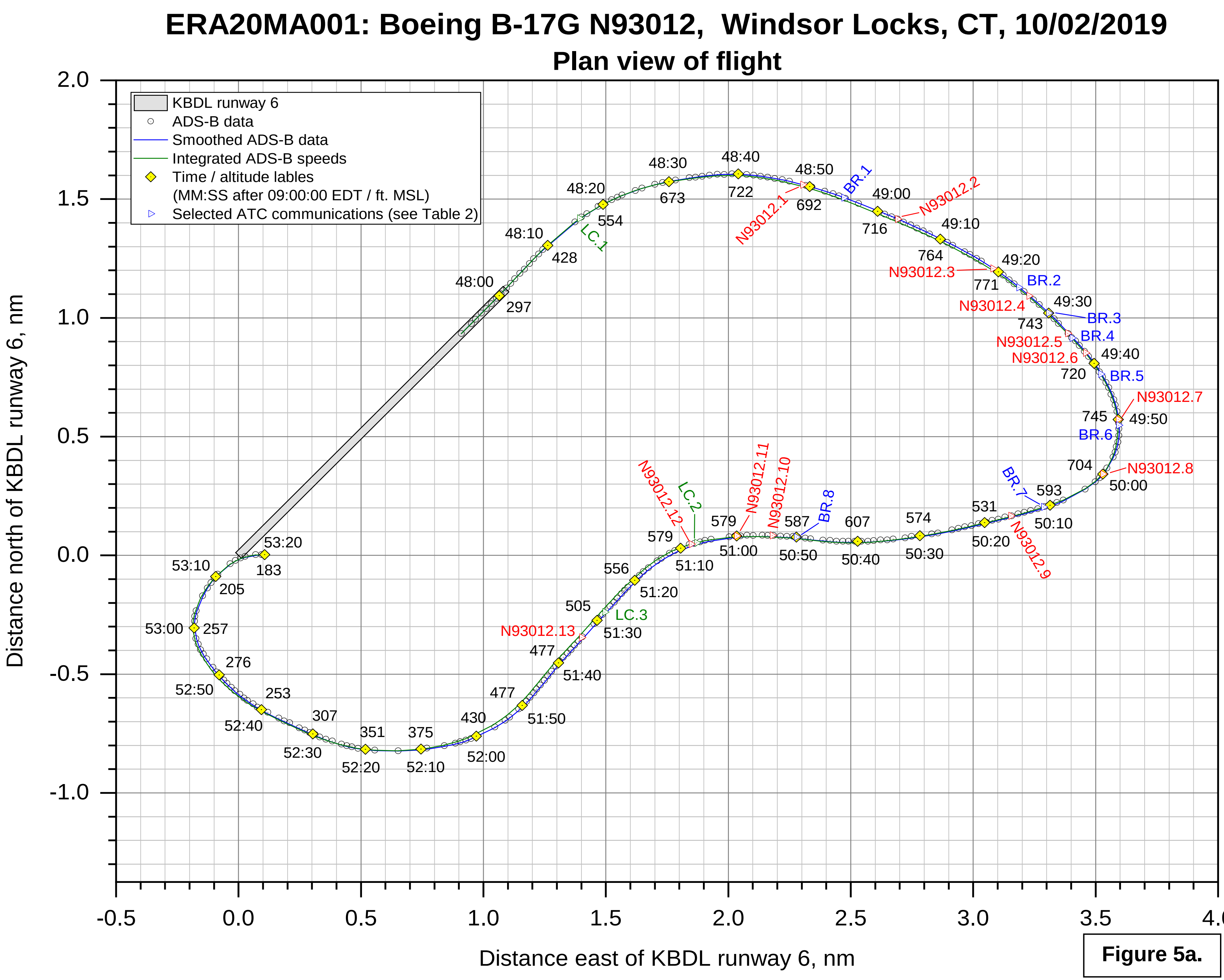


Figure 4. Annotated plan-view image of the accident site, from Reference 6.


ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019
Plan view of flight
KBDL runway 6
ADS-B data
Smoothed ADS-B data
Integrated ADS-B speeds
Time / altitude lables
(MM:SS after 09:00:00 EDT / ft. MSL)
Selected ATC communications (see Table 2)
Distance north of KBDL runway 6, nm
Distance east of KBDL runway 6, nm
LC.1
LC.2
LC.3
BR.1
BR.2
BR.3
BR.4
BR.5
BR.6
BR.7
BR.8
N93012.1
N93012.2
N93012.3
N93012.4
N93012.5
N93012.6
N93012.7
N93012.8
N93012.9
N93012.10
N93012.11
N93012.12
N93012.13
48:00
48:10
48:20
48:30
48:40
48:50
49:00
49:10
49:20
49:30
49:40
49:50
50:00
50:10
50:20
50:30
50:40
50:50
51:00
51:10
51:20
51:30
51:40
51:50
52:00
52:10
52:20
52:30
52:40
52:50
53:00
53:10
53:20
Figure 5a.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

Plan view of flight

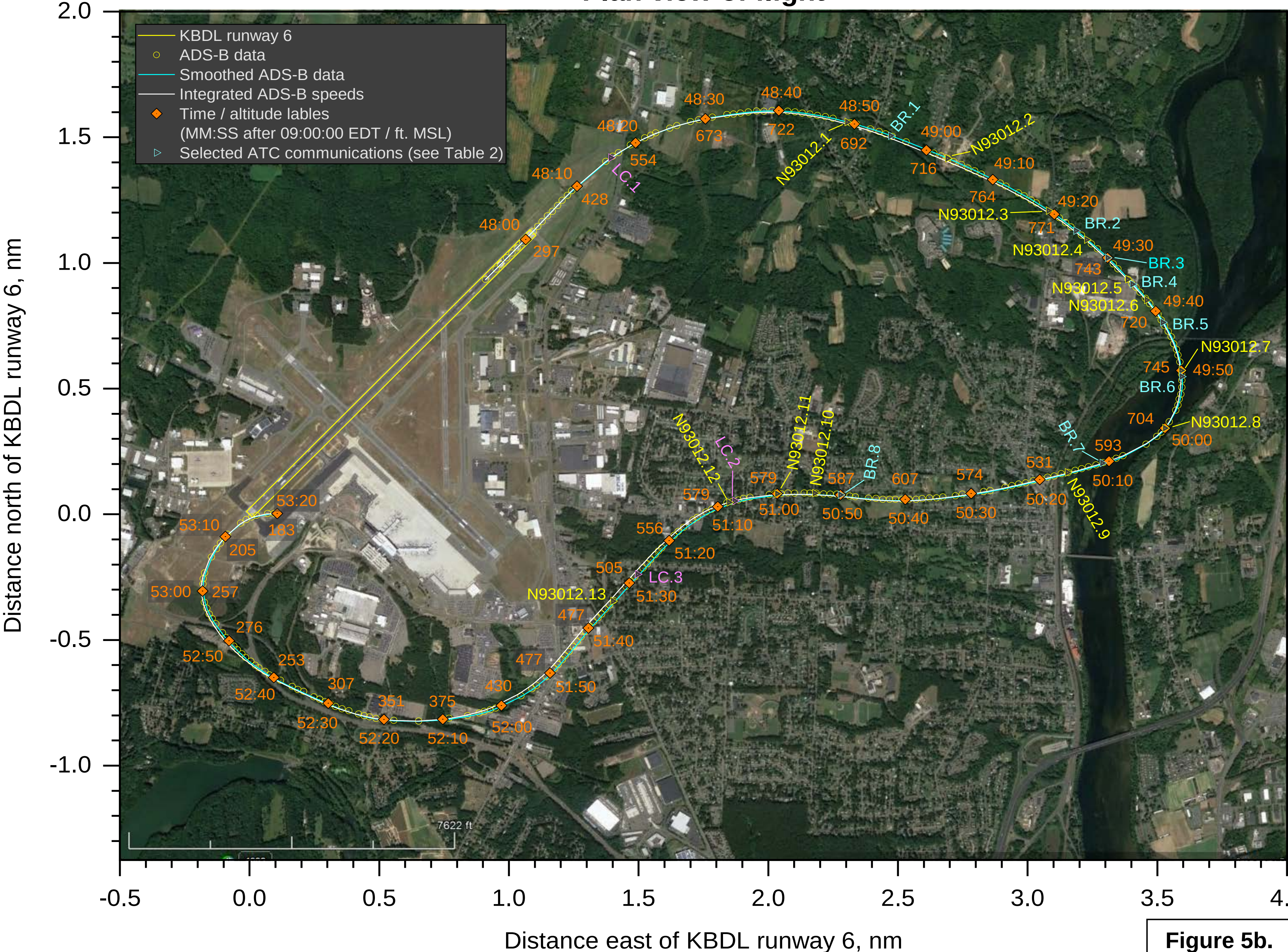


Figure 5b.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

Plan view of flight (detail)

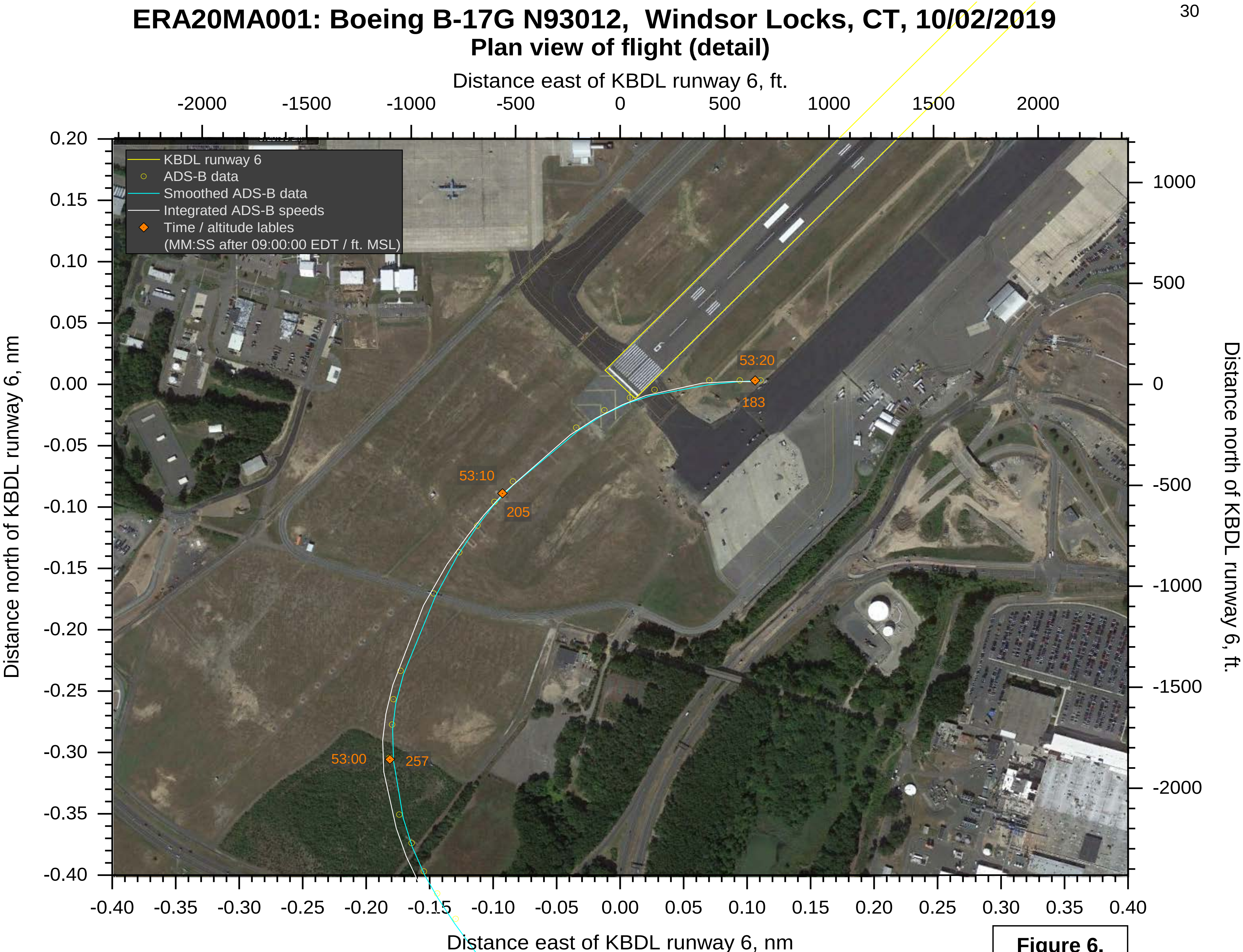


Figure 6.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

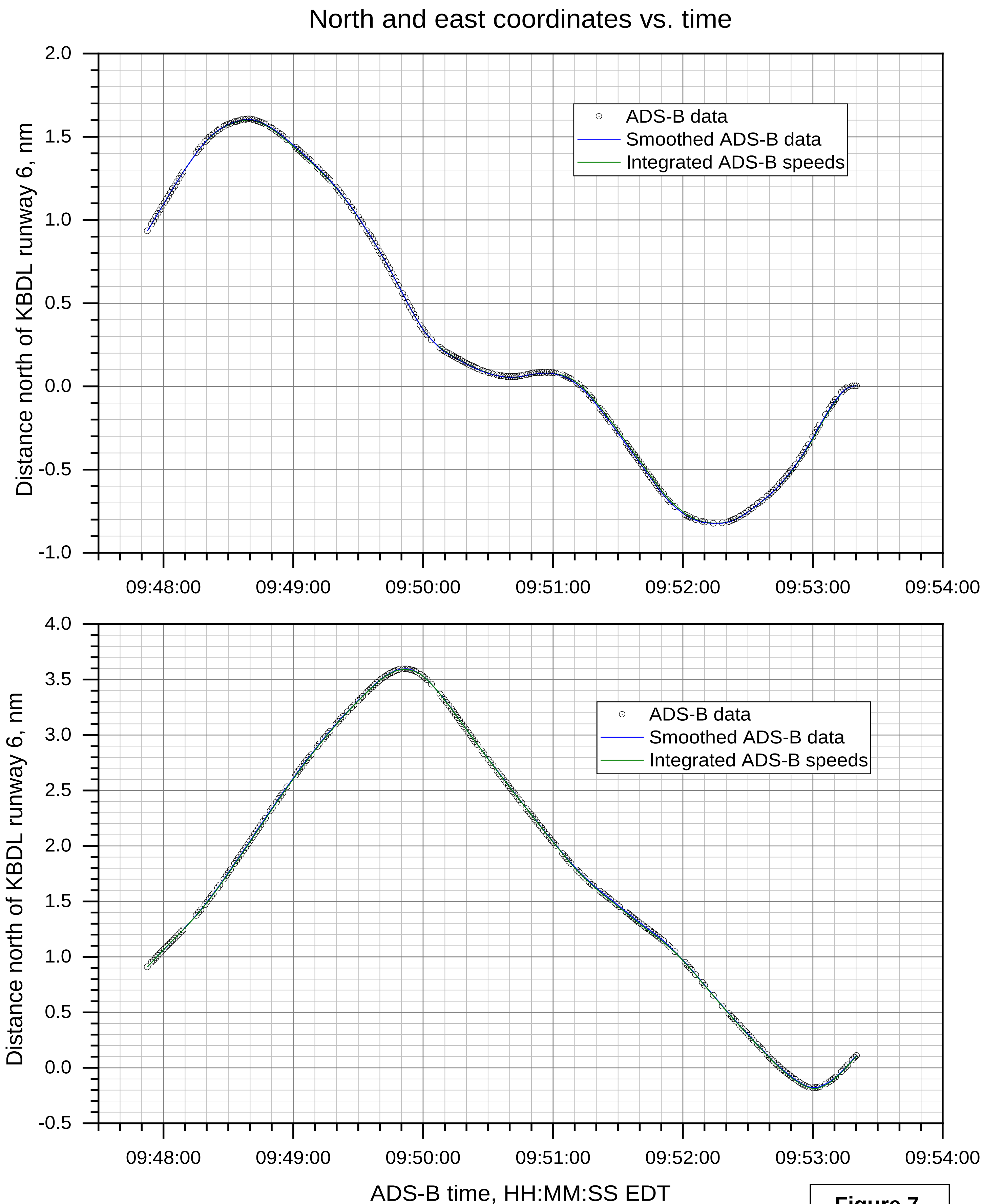


Figure 7.

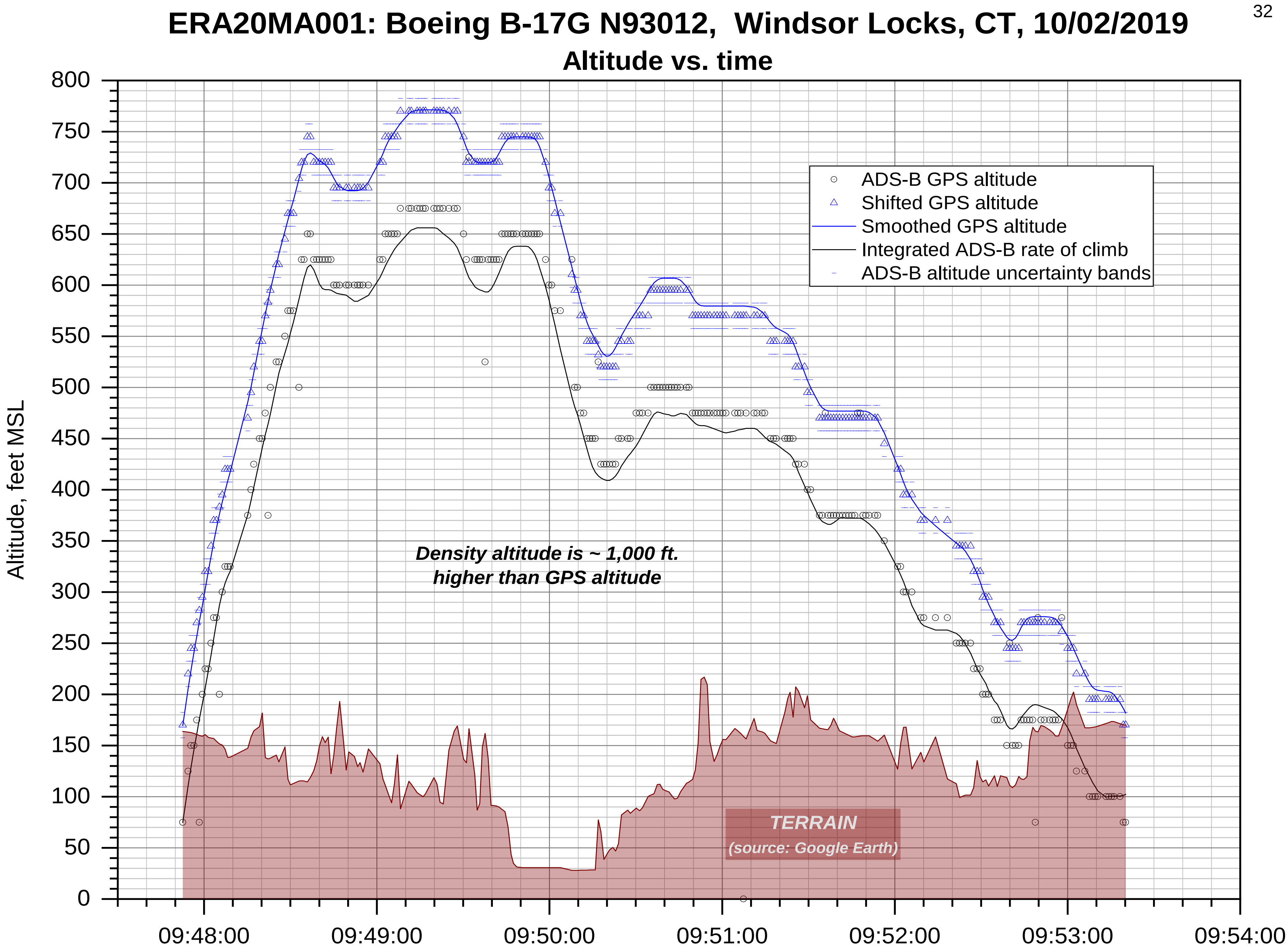

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019
Altitude vs. time
Altitude, feet MSL
ADS-B time, HH:MM:SS EDT
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
09:48:00
09:49:00
09:50:00
09:51:00
09:52:00
09:53:00
09:54:00
ADS-B GPS altitude
Shifted GPS altitude
Smoothed GPS altitude
Integrated ADS-B rate of climb
ADS-B altitude uncertainty bands
Density altitude is ~ 1,000 ft.
higher than GPS altitude
TERRAIN
(source: Google Earth)

Figure 8.

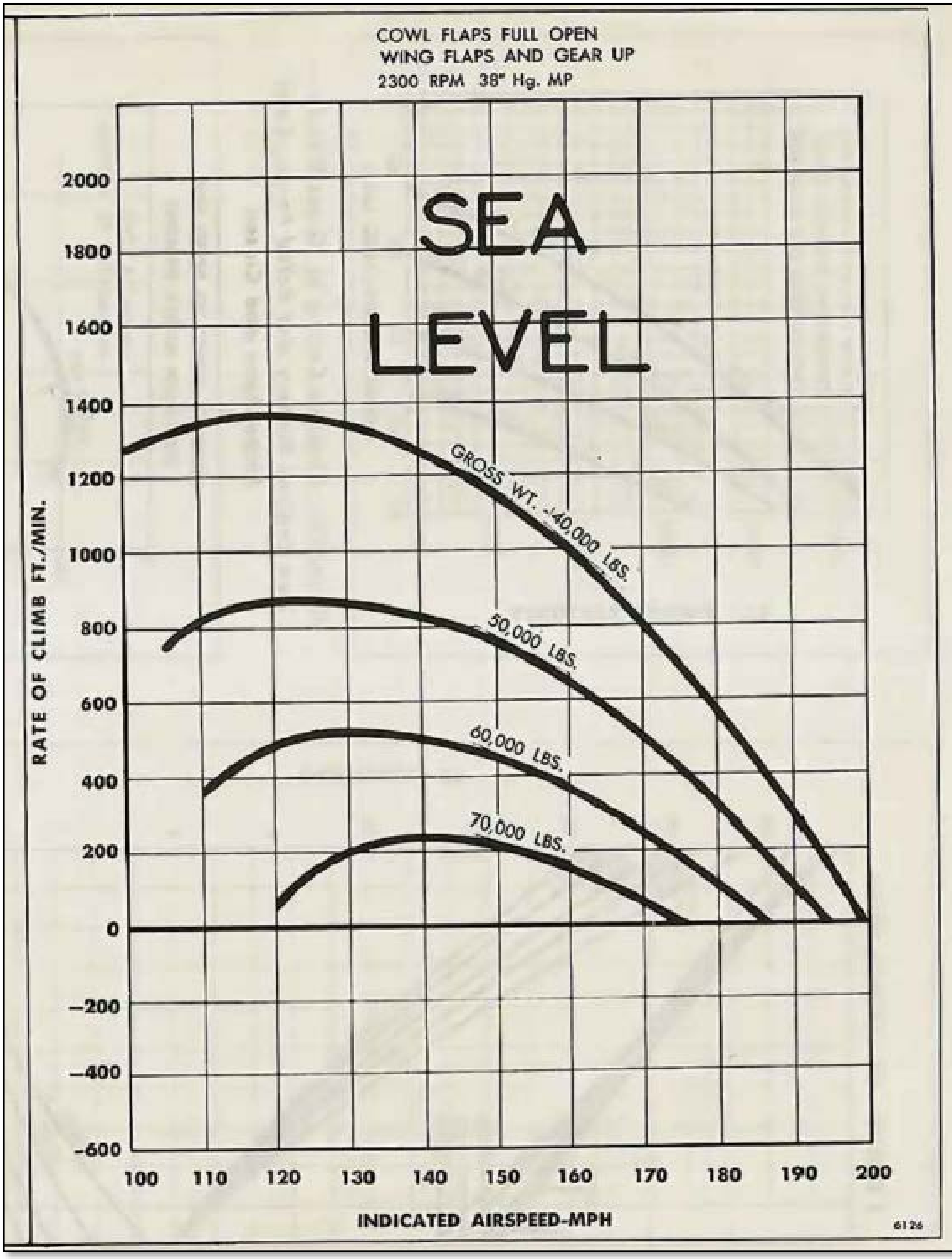


Figure 9. Sea level rate of climb vs. airspeed chart, from Reference 1.

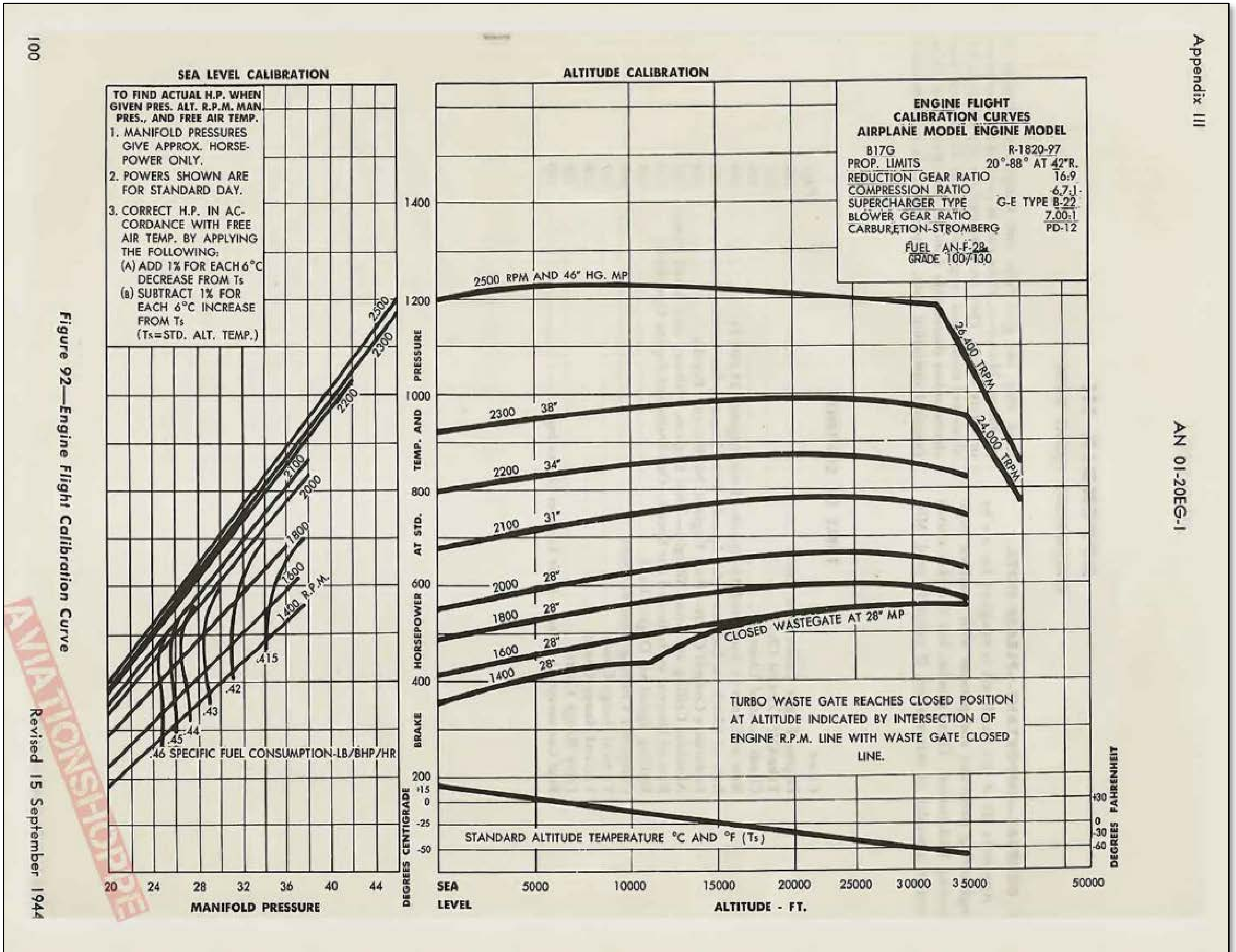


Figure 10. Engine flight calibration curves, from Reference 1.

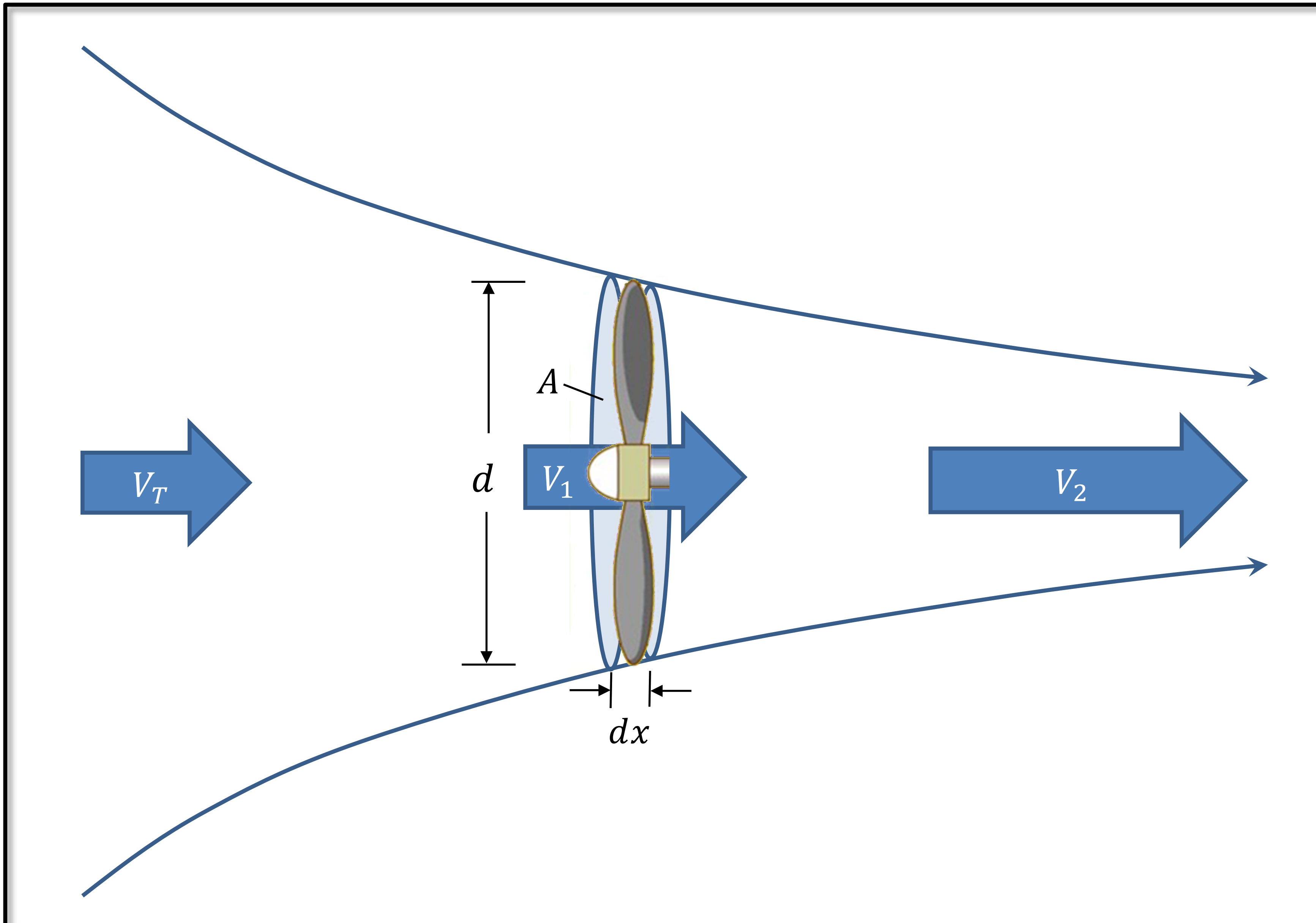


Figure 11. Diagram of a stream tube of air being accelerated through a propeller.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

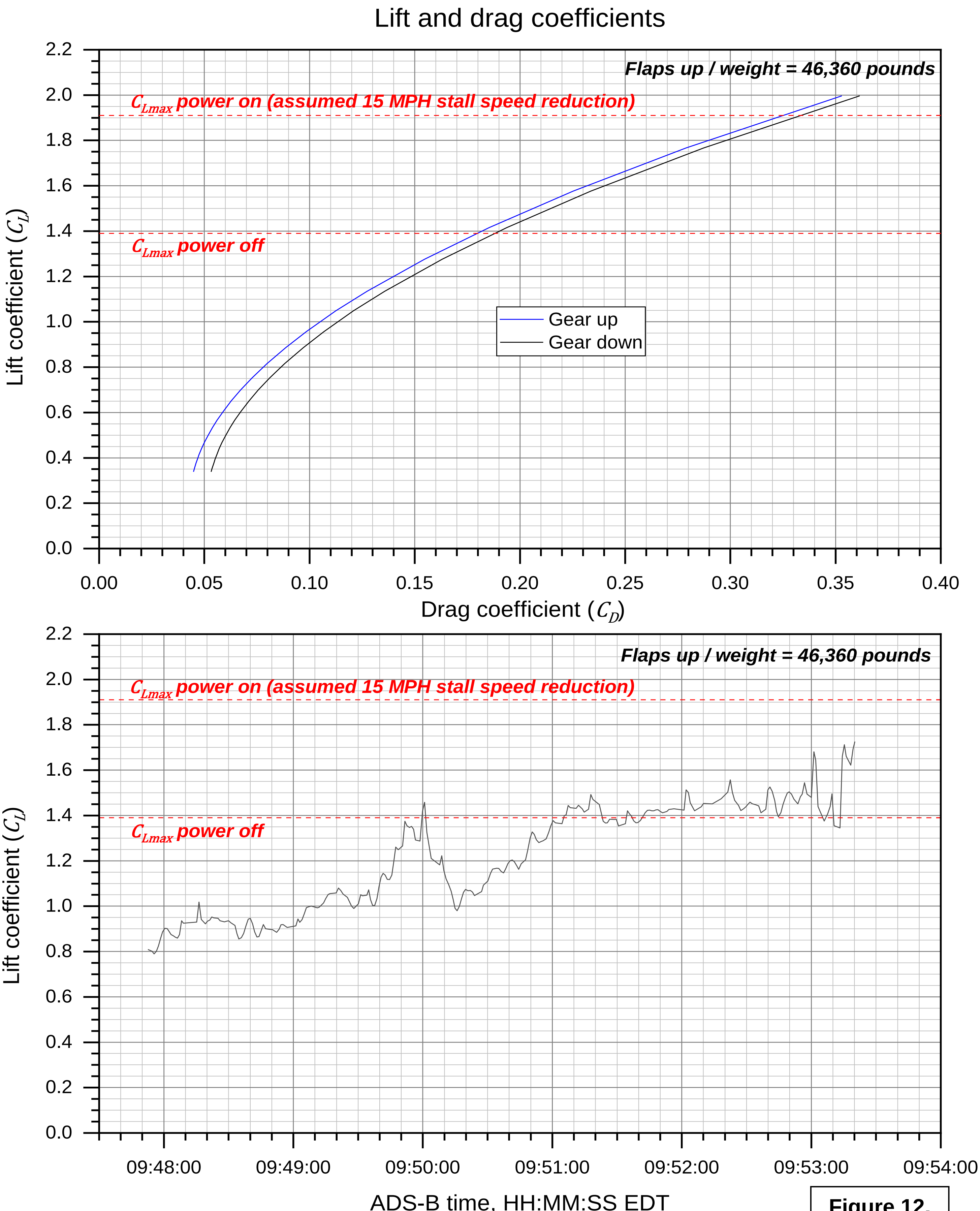
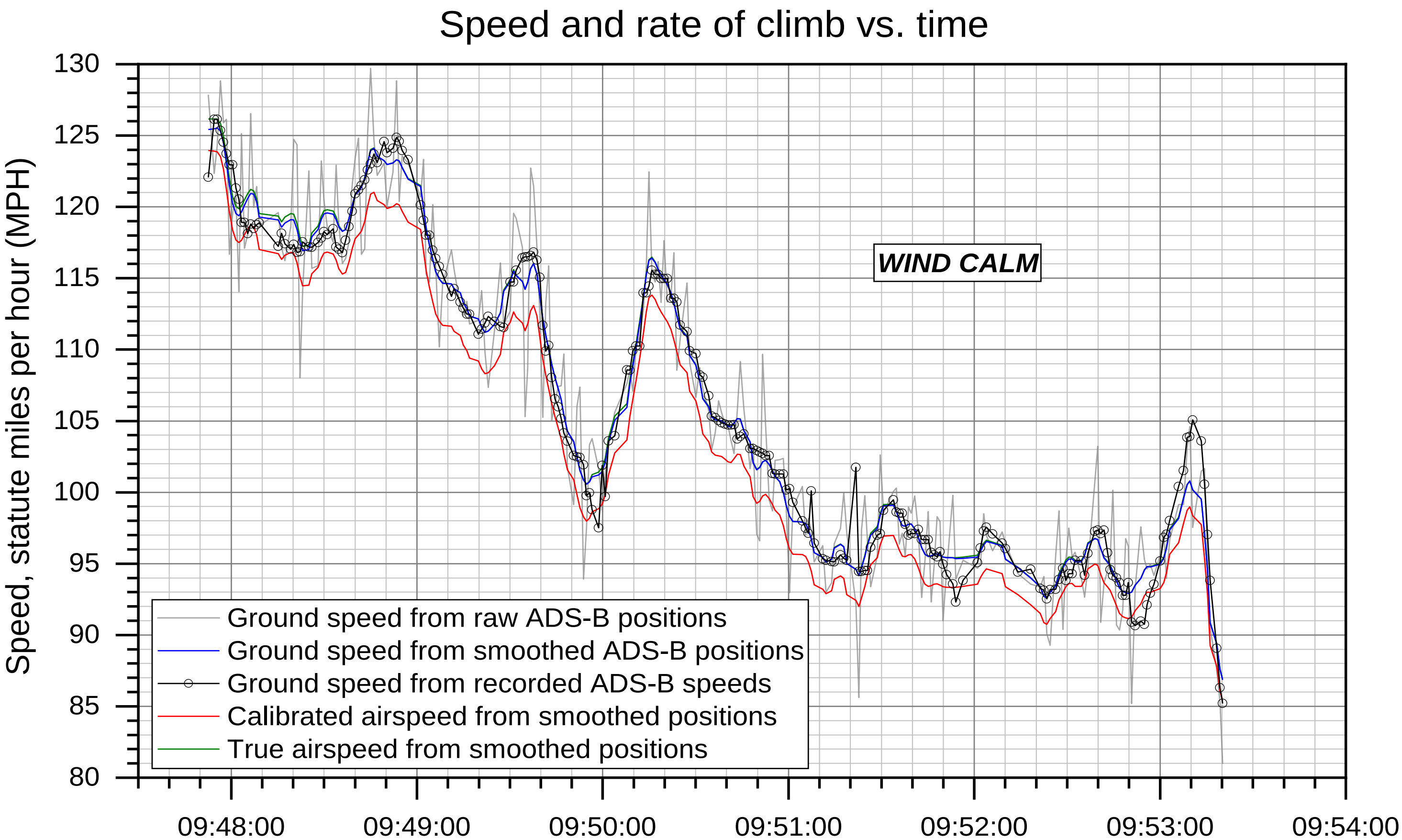


Figure 12.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019



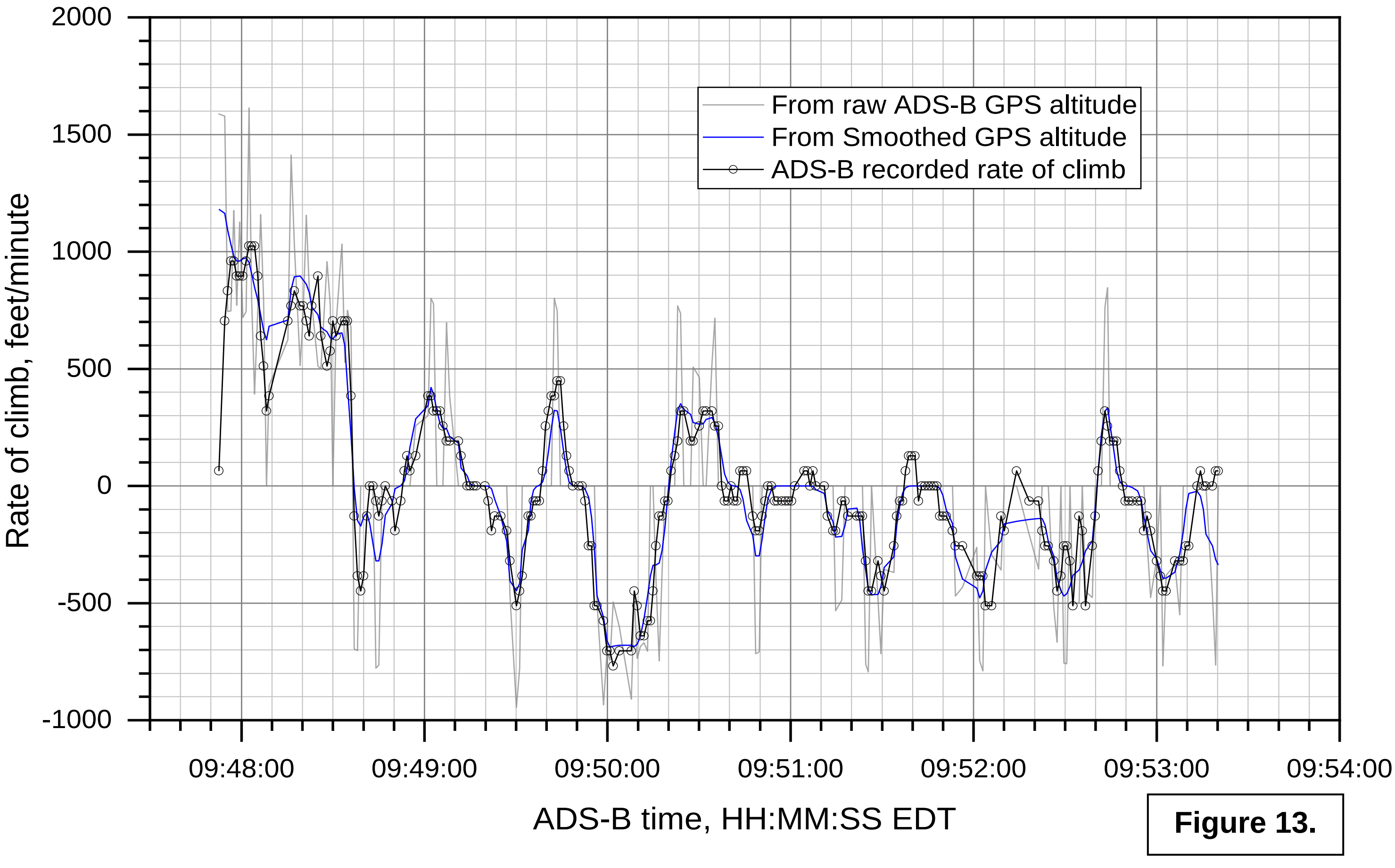


Figure 13.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

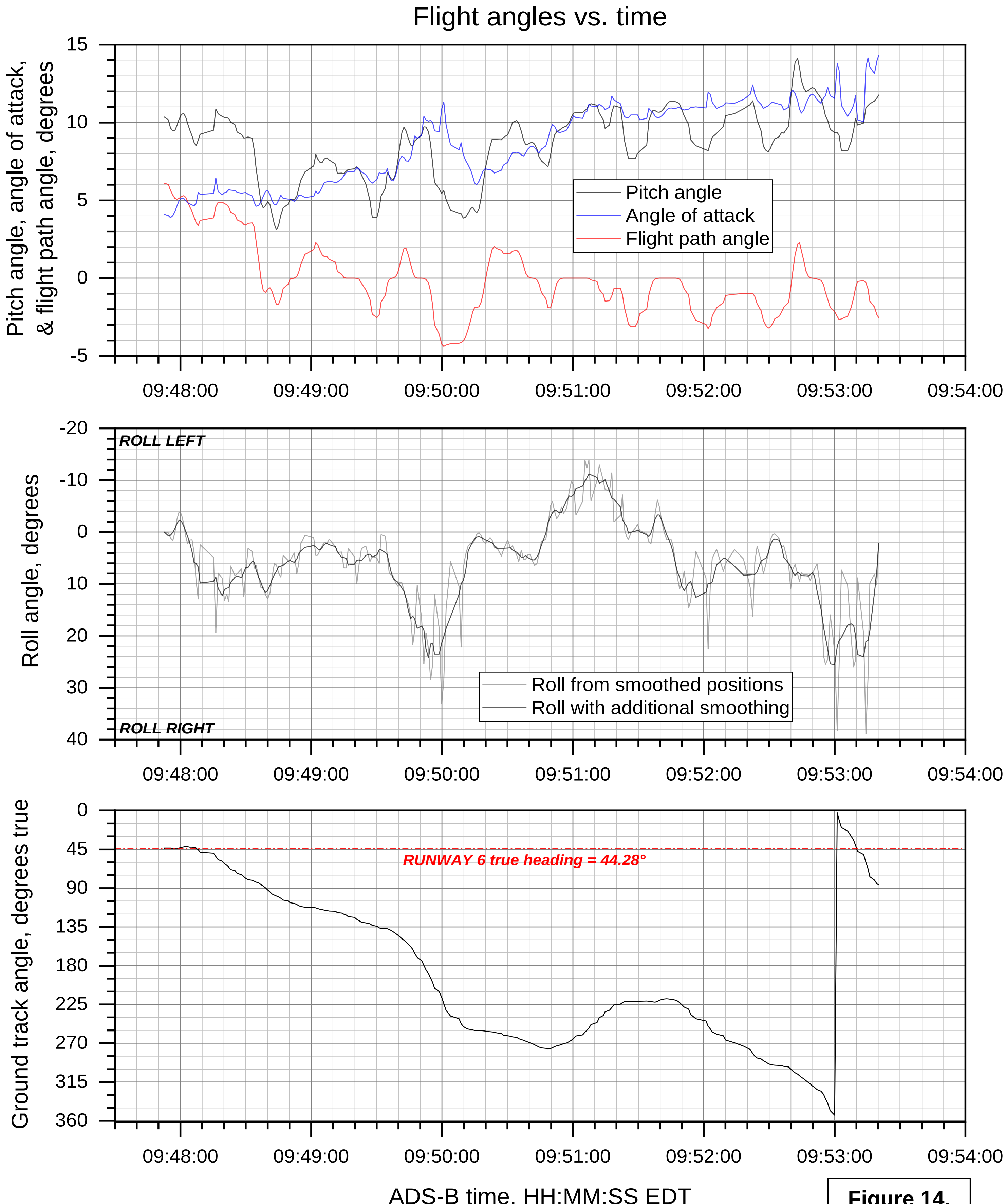
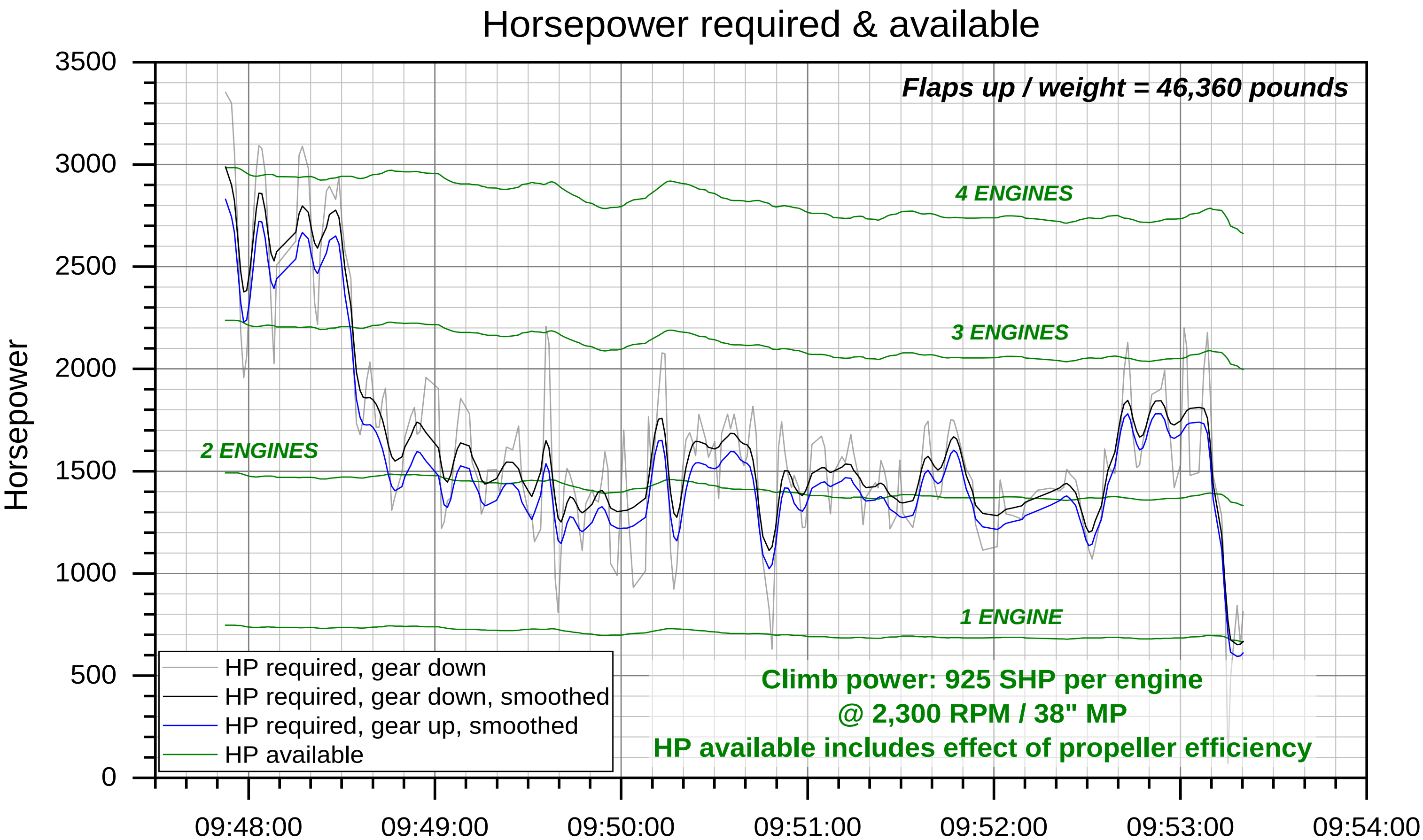


Figure 14.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019



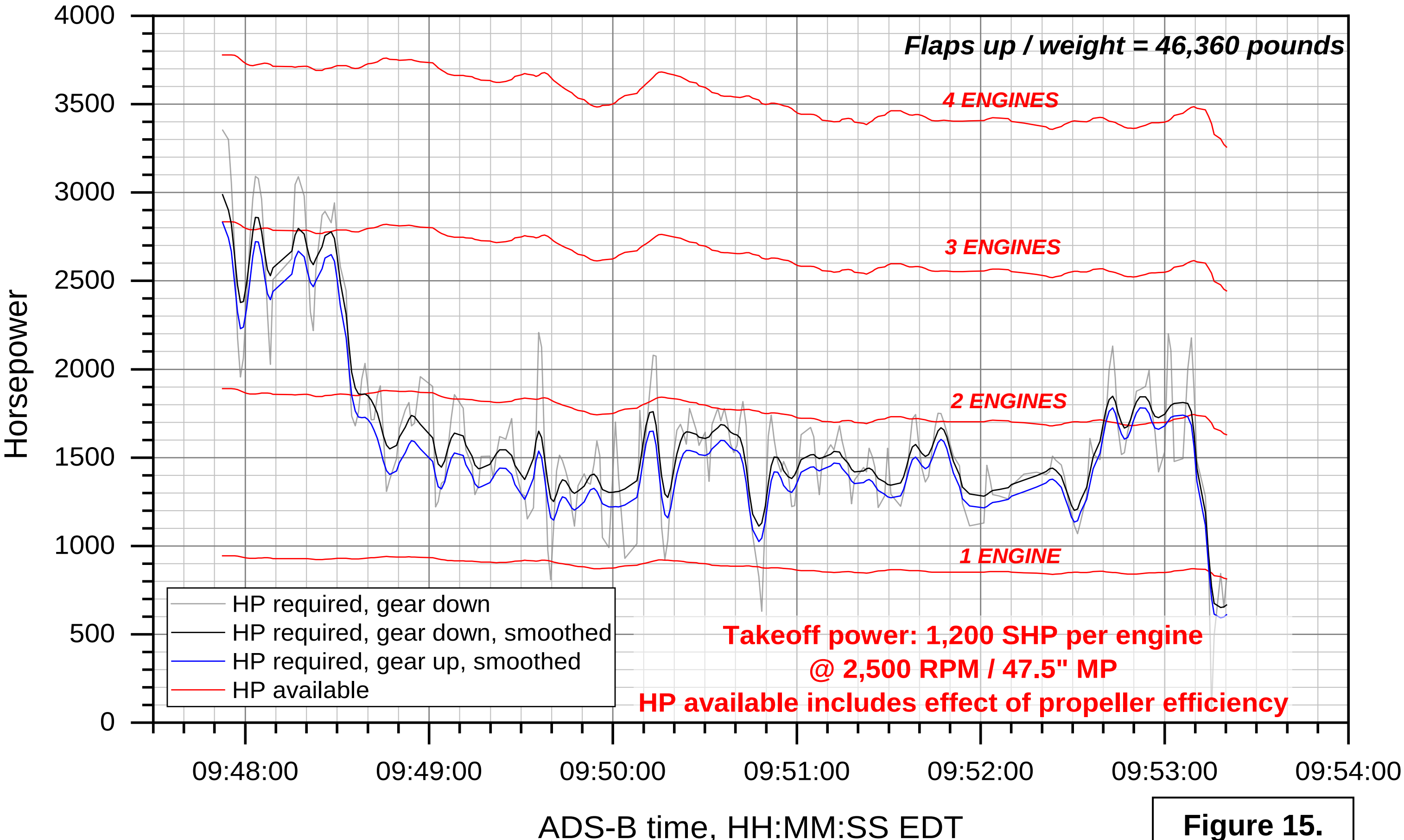


Figure 15.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

Propeller efficiency, thrust, and drag

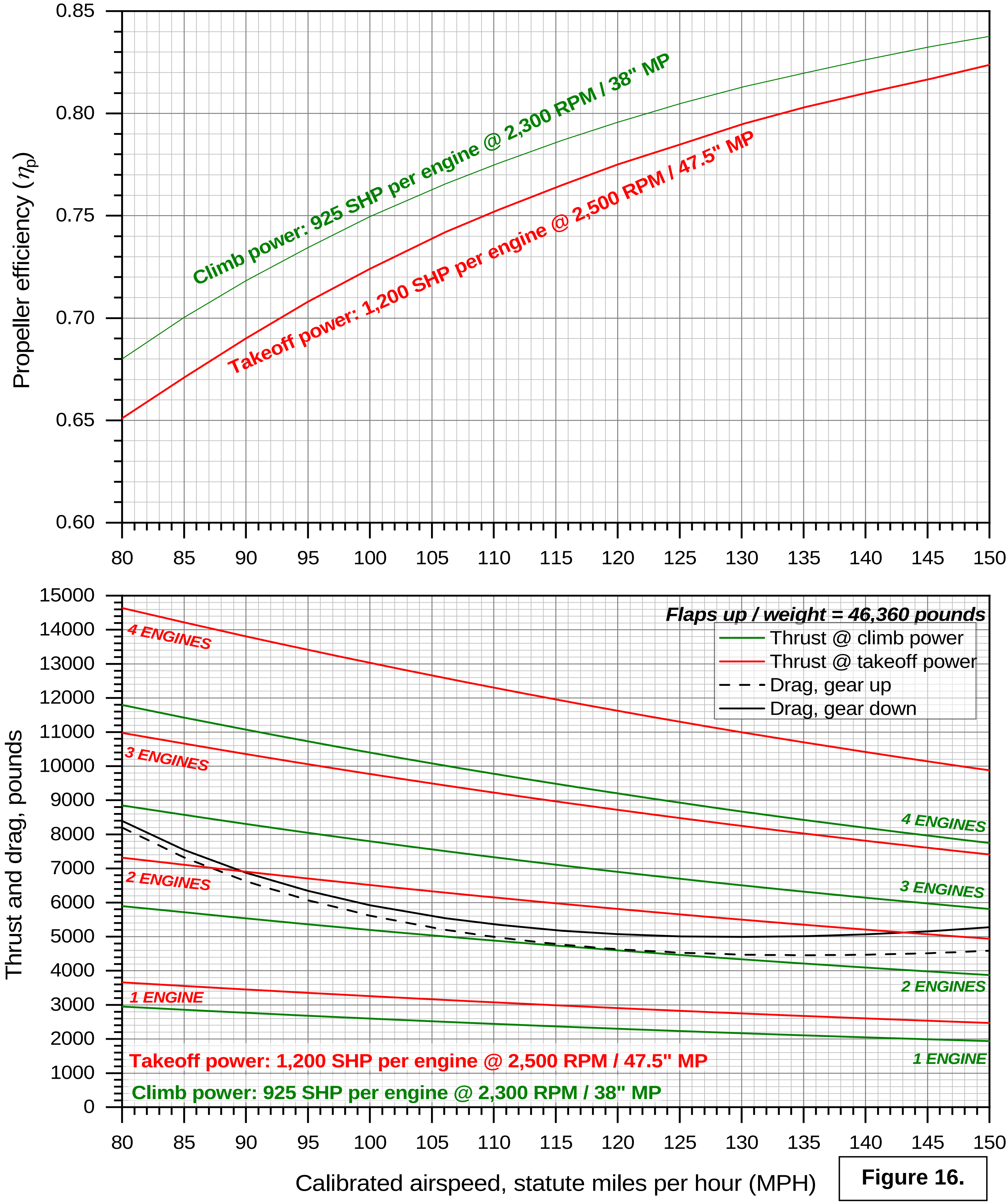


Figure 16.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

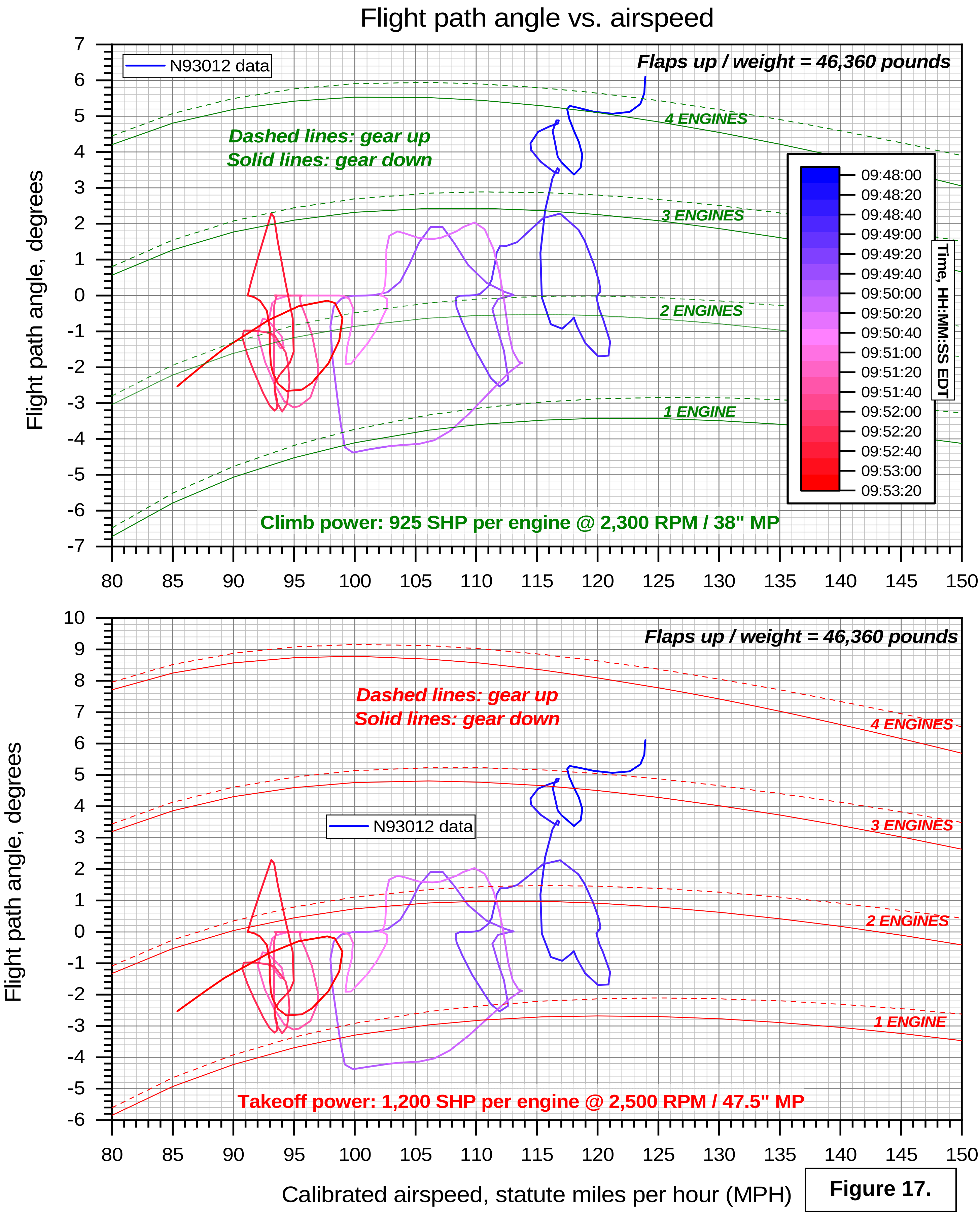
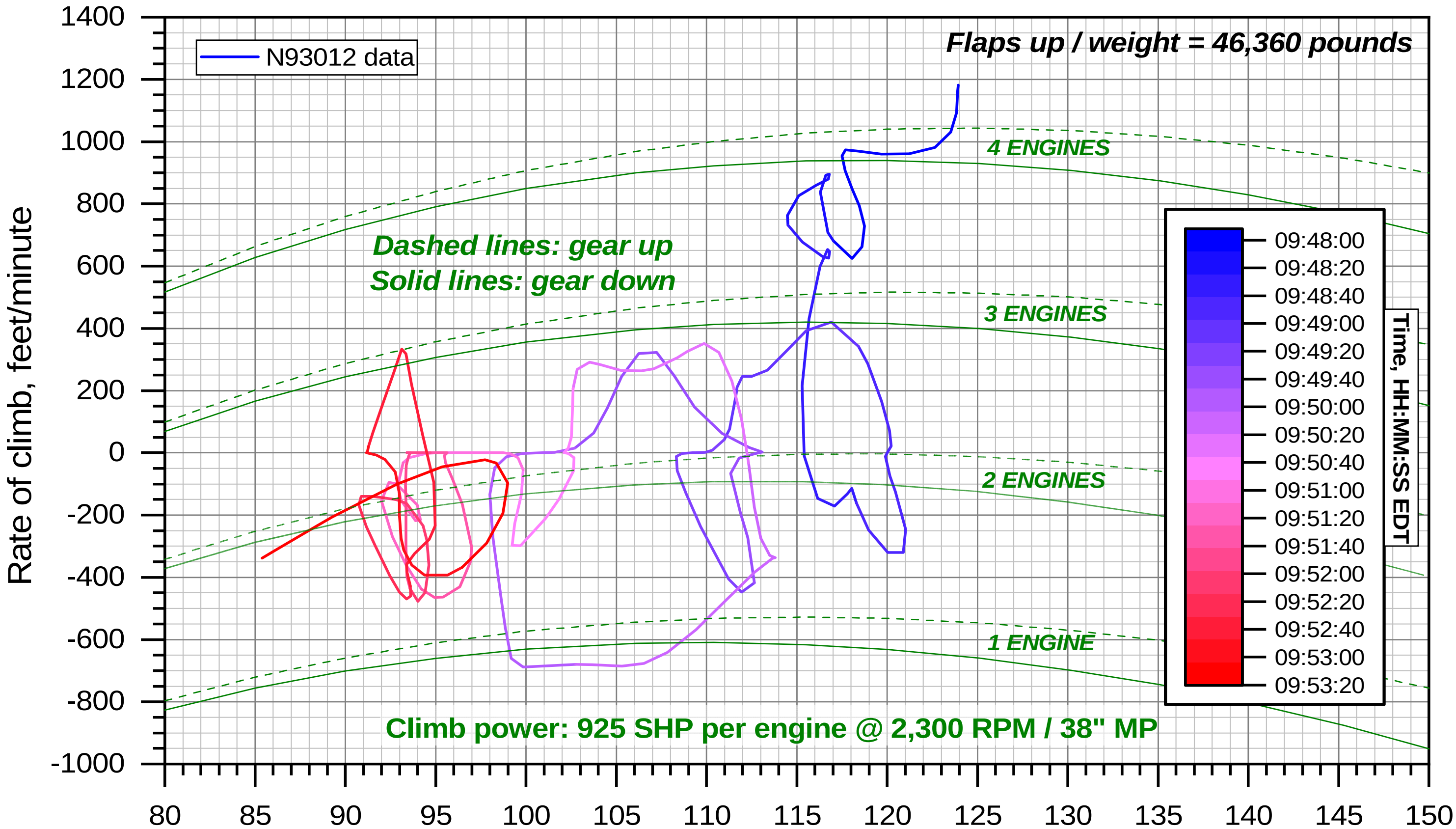


Figure 17.

ERA20MA001: Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019

Rate of climb vs. airspeed



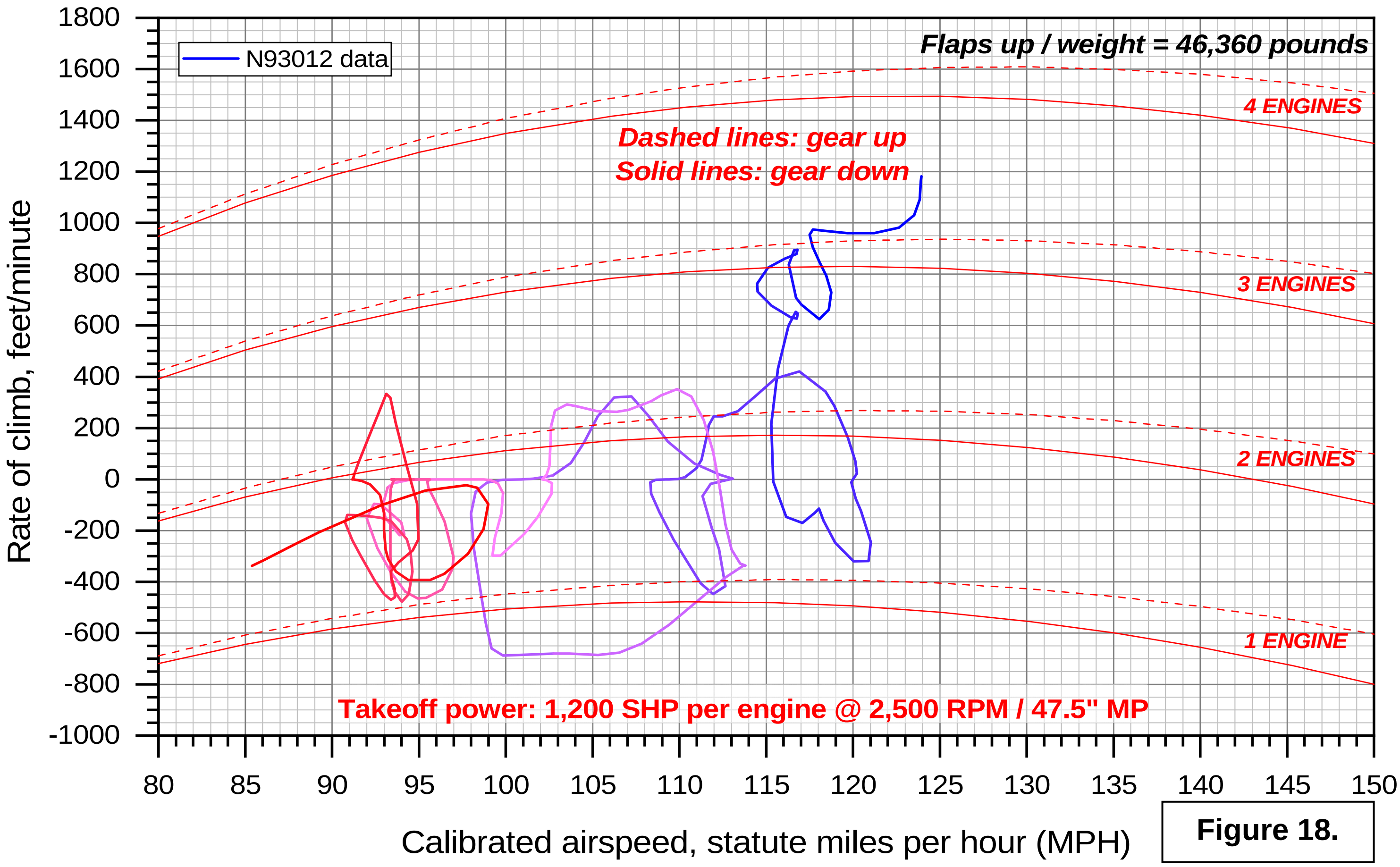


Figure 18.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A:

COLLINGS FOUNDATION CHIEF PILOT'S COMMENTS ON A DRAFT VERSION OF THE AIRCRAFT PERFORMANCE STUDY

ERA20MA001
B-17 Performance/Aerodynamic Consult

-Robert Pinksten

After careful review of the NTSB Performance study, I have the following comments and observations from my experience as a B-17 PIC and Instructor.

The airspeeds that are devised from ADSB and converted to an estimated calibrated airspeed are concerning from a controllability standpoint. The calculations made in the study showing performance required and performance available do not take into account the largest factor in determining the actual performance of a multi engine airplane with engine failure(s): VMC and controllability.

The B-17, not being a transport category airplane or ever having been intended to be one, does not have well documented VMC numbers or data for engine out performance at low speeds, so experience and testing over the years has given operators a good idea and basis on the airplane's engine out performance. The general consensus is that for one outboard engine out, 135mph IAS is satisfactory for some climb performance, and 145-155mph IAS is needed for two failed engines on one wing. The peak documented airspeed in the study is certainly nowhere near enough to utilize anywhere near full power with two engines out, or even one outboard out for that matter.

Even when operating with the required numbers stated above, the pilot is generally using asymmetric thrust on the good engines to maintain a good margin of control. IE: #4 Engine is failed, #2 and #3 will likely be at climb power or higher while #1 will be reduced, maybe towards cruise power. In the case of #3 and #4 being failed, #2 would be at maximum power, and #1 would be adjusted to maintain control, generally full rudder will be applied and yaw will be controlled with #1. The power that #1 could put out in this condition would vary with the airplane's speed. Using asymmetric thrust on the good engines is how those two numbers are derived, if you were to calculate an actual VMC speed under the 10 conditions modern airplanes are certified with, using full power at max gross with the bad engines windmilling, you would be looking at something more like 150mph for one outboard out and 190+ for two out on one wing.

At the speeds presented in the performance study, I can begin to guess the power settings possible for both 2 and 3 engine flying while taking into account controllability. In a 3 engine condition, #4 being failed, a peak CAS of 126mph and steadily decreasing to under 120mph CAS, full rudder and a considerable amount of aileron deflection might allow 40"MP+ on the #2 and #3 engines and between 18-26" on #1 at the most. That being said, one cannot take those numbers and calculate the performance being generated by that thrust.You must consider how much drag the airplane would be producing in this sideslip, as well as with considerable amounts of aileron deflection. The airplane flying handbook states a multi engine airplane may lose 80-90% of its performance after losing half of its thrust, and those numbers consider the airplane to be above VMC.

If #3 and #4 were failed, the airspeeds from the study would be catastrophic, #2 may have produced around 35”MP, and #1 would likely be around 20”MP max, that combined with the sideslip angle and drag from this situation would likely produce slightly better than power off glide performance, but not much.

To review and conclude, the thrust available from the remaining engines on the B-17 can not be considered as the performance available to the airframe, one cannot mathematically generate performance numbers without a consideration of controllability and drag caused by engine failures, the information will not apply to a real world situation. It appears that if #4 was failed and feathered, and that #3 lost some amount of power at some point, the airplane was likely flown right on the edge of being controllable with as much power as possible. Stories of B-17’s making it back to base after losing 1-2 engines in WW2 are certainly true, when they lost those engines at 30,000 feet and over 150mph in most cases. In this situation, at 700 feet and around 130mph, maintaining directional control and any sort of performance would’ve been nearly impossible.

REFERENCES

1. National Transportation Safety Board, Office of Aviation Safety, Aircraft Performance ADS-B Study, Boeing B-17G N93012, Windsor Locks, CT, 10/02/2019, NTSB #ERA20MA001. (Contact NTSB at pubinq@ntsb.gov.)
2. Federal Aviation Administration, Flight Standards Service, Airplane Flying Handbook, 2016, FAA-H-8083-3B, (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/airplane_handbook/media/airplane_flying_handbook.pdf)