NATIONAL TRANSPORTATION SAFETY BOARD

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

March 3, 2021

Aircraft Performance & CDTI Study

by John O'Callaghan

Location:	Soldotna, Alaska
Date:	July 31, 2020
Time:	08:27 Alaska Daylight Time (ADT) / 16:27 Coordinated Universal Time (UTC)
Aircraft:	De Havilland DHC-2 Beaver, registration N4982U
	Piper PA-12, registration N2587M
NTSB#:	ANC20LA074A (Beaver)
	ANC20LA074B (Piper)

CONTENTS

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A. ACCIDENT

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	ANC20LA074B (N2587M)

B. GROUP

Not Applicable

C. SUMMARY

On July 31, 2020, at about 08:27 ADT, a de Havilland DHC-2 (Beaver) airplane, N4982U, and a Piper PA-12 airplane, N2587M, were destroyed when they collided in midair near Soldotna, Alaska. Both pilots and the five passengers on the DHC-2 were fatally injured. The DHC-2 was operated as a Title 14 Code of Federal Regulations (CFR) Part 135 on demand charter flight. The PA-12 was operated as a Title 14 CFR Part 91 personal flight.

The float-equipped DHC-2, operated by High Adventure Charter, departed Longmere Lake, Soldotna, at about 08:24 bound for a remote lake on the west side of Cook Inlet. The purpose of the flight was to transport the passengers to a remote fishing location. The PA-12, operated by a private individual, departed Soldotna Airport, Soldotna, Alaska, at about 08:24 bound for Fairbanks, Alaska.

This *Aircraft Performance & CDTI Study* presents the results of using recorded Automatic Dependent Surveillance – Broadcast (ADS-B) and radar-based Traffic Information Service – Broadcast (TIS-B) data to calculate the position and orientation of each airplane in the minutes preceding the collision. This information is then used to simulate the Cockpit Display of Traffic Information (CDTI) data that could have been presented to the pilots had both airplanes been equipped to provide this information. As described further in Sections D-II and D-III, CDTI uses the ADS-B system to drive a traffic situation display in the cockpits of appropriately equipped aircraft.

The sections that follow present the ADS-B data, TIS-B data, and other information used in this *Study*, and describe the methods used to calculate aircraft speeds, orientation (pitch, yaw, and roll angles), and CDTI information from this data. The results of these calculations are presented in the Figures described throughout the *Study*.

D. DETAILS OF THE INVESTIGATION

I. The accident airplanes

The De Havilland DHC-2 Beaver

As described in Reference 1,

> The DHC-2 Beaver aircraft is an all-metal high-wing monoplane, designed to carry a pilot and seven [sic] passengers. Additional roles include that of cargo transport, ambulance, rescue operations, supply dropping, aerial survey, crop spraying and dusting. *[Note: the accident Beaver was configured for a pilot and six passengers. Further, the weight and balance section of POH only shows places for a pilot and six passengers.]*
>
> The fixed landing gear may be replaced by a twin-float installation. Retractable wheel-skis may be installed, or a ski installation can replace the wheels.
>
> … The aircraft is powered by a Pratt and Whitney "Wasp Junior" Model R-985SB3 nine-cylinder single-row radial engine, rated at 400 BHP at 5000 ft altitude. The engine drives a Hamilton-Standard constant-speed propeller; crankshaft and propeller rotation being clockwise. The supercharger is an engine-driven single-stage centrifugal type.

The seaplane version of the DHC-2 has a maximum gross weight of 5,090 lb. (see Reference 1). Figure 1 is a pre-accident photograph of N4982U, and Figure 2 is a three-view diagram of the DHC-2 seaplane, taken from Reference 1.

The Beaver's Euler angles (pitch, roll, and yaw) can be computed from the recorded ADS-B data if the airplane weight, wing area, and lift-curve, that is, lift coefficient (C_L) as a function of angle of attack (α), are known (see Section D-II). During a previous NTSB investigation, the DHC-2 lift curve and associated wing area (250 ft^2) were determined using information contained in an aerodynamic data report produced by De Havilland Aircraft of Canada (the original manufacturer of the DHC-2). In this accident, the weight of the airplanes involved could not be determined, and so the weights are assumed to be 90% of the maximum gross weight published in each airplane's Airplane Flight Manual (AFM). For the Beaver, this results in an assumed weight of 4,580 lb.

The Piper PA-12

N2587M was registered as a PA-12, but the airplane had been extensively modified. At the time of the accident, the airplane's fuselage had been replaced with a "wide body" Piper PA-18 fuselage, and the landing gear, wheels, tail surfaces, and elevator control system had also been replaced with PA-18 components, as described in Reference 3. Furthermore, the registration number "N1904T" was painted on the airplane's rudder, instead of the actual "N2587M" registration number (see Figure 3 and additional discussion of the registration number in Reference 3).

Since the accident airplane was modified with many PA-18 parts, a description of the Piper PA-18-150 Super Cub is provided here for reference. The PA-18-150 is a single-engine, two-seat (tandem) high-wing airplane with a conventional tail and landing gear (taildragger), powered by a 150 SHP Lycoming O-320 reciprocating engine, with a maximum gross weight of 1,750 lb. Figure 4 is a three-view diagram of a standard PA-18-150, taken from Reference 2 (per Reference 3, the "wide body" fuselage used on N2587M is 4 inches wider than standard). The PA-12-150 gross weight is 1,750 lb.; accordingly, the weight of N2587M at the time of the accident is assumed to be 90% of this weight, or 1,580 lb.

The lift curve and wing area (178.5 ft^2) for the PA-12-150 determined during a previous NTSB investigation are assumed to apply to N2587M, and are used with the assumed gross weight in the analysis of the ADS-B data to estimate the Piper's pitch and roll angles throughout the flight (see Section D-II).

II. Recorded ADS-B, TIS-B, and radar data for Beaver N4982U and Piper N2587M

Piper N2587M was equipped with ADS-B, but Beaver N4982U was not. "ADS-B Out" capability enables an aircraft to broadcast its three-dimensional position (latitude, longitude, and altitude) to other ADS-B equipped aircraft and to ADS-B ground stations. "ADS-B In" capability enables an aircraft to receive traffic messages from ADS-B Out equipped aircraft and from ADS-B ground stations. In addition, traffic messages concerning non-ADS-B equipped aircraft within FAA radar coverage are broadcast to ADS-B equipped aircraft through an ADS-B function known as "Traffic Information Service – Broadcast" (TIS-B). ADS-B messages concerning the Piper N2587M and TIS-B messages concerning Beaver N4982U were included in the recorded ADS-B traffic data for the area of the accident. These data were provided to the NTSB by the FAA and used in the performance calculations presented in this *Study*.

As noted above, TIS-B messages concern non-ADS-B equipped aircraft that are detected by FAA radars. Two FAA radar sites tracked the Beaver and the Piper: the long-range Air Route Surveillance Radar (ARSR) located near Kenai, Alaska (ENA), and the short-range Airport Surveillance Radar (ASR) located near Ted Stevens Anchorage International Airport, Anchorage, Alaska (ANC). The ARSR, ASR, and ADS-B systems are described briefly below.

Description of ARSR and ASR Radar Data

In general, two types of radar are used to provide position and track information for aircraft cruising at high altitudes between airport terminal airspaces, and for those operating at low altitude and speeds within terminal airspaces.

Air Route Surveillance Radars (ARSRs) are long range (250 nm) radars used to track aircraft cruising between terminal airspaces. ARSR antennas rotate at 5 to 6 RPM, resulting in a radar return every 10 to 12 seconds. Airport Surveillance Radars (ASRs) are short range (60 nm) radars used to provide air traffic control services in terminal areas. ASR antennas rotate at 13 to 14 RPM, resulting in a radar return every 4.3 to 4.6 seconds.

Primary and Secondary Radar Returns

A radar detects the position of an object by broadcasting an electronic signal that is reflected by the object and returned to the radar antenna. These reflected signals are called *primary returns.* Knowing the speed of the radar signal and the time interval between when the signal was broadcast and when it was returned, the distance, or range, from the radar antenna to the reflecting object can be determined. Knowing the direction the radar antenna was pointing when the signal was broadcast, the direction (or bearing, or azimuth) from the radar to the object can be determined. Range and azimuth from the radar to the object define the object's position.

The strength or quality of the return signal from the object depends on many factors, including the range to the object, the object's size and shape, and atmospheric conditions. In addition, any object in the path of the radar beam can potentially return a signal, and a reflected signal contains no information about the identity of the object that reflected it. Many times, these difficulties make distinguishing individual aircraft from each other and other objects (e.g., flocks of birds) based on primary returns alone unreliable and uncertain.

To improve the consistency and reliability of radar returns, aircraft are equipped with transponders that sense beacon interrogator signals broadcast from radar sites, and in turn broadcast a response signal. Thus, even if the radar site is unable to sense a weak reflected signal (primary return), it will sense the response signal broadcast by the transponder and be able to determine the aircraft position. The response signal can also contain additional information, such as the identifying "beacon code" for the aircraft, and the aircraft's pressure altitude (also called "Mode C" altitude). Transponder signals received by the radar site are called *secondary returns*. Both the Piper and the Beaver were broadcasting beacon code 1200, which is used by aircraft flying under Visual Flight Rules (VFR). Consequently, the beacon code 1200 returns corresponding to each airplane have to be filtered out from all the beacon code 1200 returns in the recorded data, based on the time, location, and direction of flight of the returns (the ADS-B data for the Piper and the TIS-B data for the Beaver, described below, are helpful reference points in this process. The relatively low traffic density at the time and location of the accident also reduces the difficulty in identifying the relevant returns).

Recorded Radar Data

Recorded data from the ENA ARSR and the ANC ASR were obtained from the Federal Aviation Administration (FAA), and include the following parameters:

- UTC time of the radar return, in hours, minutes, and seconds.
- Transponder beacon code associated with the return (secondary returns only)
- Transponder reported altitude in hundreds of feet associated with the return (secondary returns only). The transponder reports pressure altitude. The altitude recorded in the file depends on the site recording the data; some sites record both pressure altitude, and pressure altitude adjusted for altimeter setting (MSL altitude). Others record just the MSL altitude. The file for this case contains only pressure altitude. The altimeter setting for the time of the accident (29.93 "Hg) results in an MSL altitude about 9 ft higher than the pressure altitude. The resolution of the altitude data in the radar file is ± 50 ft.
- Slant Range from the radar antenna to the return, in nm. The accuracy of this data is ±1/16 nm or about ± 380 ft.
- Azimuth relative to magnetic north from the radar antenna to the return. The ANC ASR uses a magnetic variation of 21° E to determine magnetic azimuth. The ENA ARSR records azimuth relative to true north (no correction for magnetic variation is required). Azimuth from both radar sites is reported in Azimuth Change Pulses (ACPs). ACP values range from 0 to 4096, where 0 = 0° and 4096 = 360°. Thus, the azimuth to the target in degrees is:

  (Azimuth in degrees) = (360/4096) x (Azimuth in ACPs) = (0.08789) x (Azimuth in ACPs)

  The accuracy of azimuth data is ± 2 ACP or ± 0.176º.

- The latitude and longitude of the return computed by the radar system data processing algorithms. The latitude and longitude reported in the file are in good agreement with what would be computed from the range and azimuth data recorded in the file (see below).[1]

To determine the latitude and longitude of radar returns from the range and azimuth data recorded by the radar, and the corresponding position uncertainties associated with the uncertainties in range and azimuth, the geographic location of the radar antenna must be known.

The coordinates of the ANC ASR antenna are:

61° 09' 23.61" N latitude; 150° 02' 24.43" W longitude; elevation 366 feet

The coordinates of the ENA ARSR antenna are:

60° 36' 56.15" N latitude; 151° 16' 58.99" W longitude; elevation 186 feet

ANC is about 48 nm northeast of the accident site, and ENA is about 11 nm northwest of the site. The ENA and ANC radar data are plotted in Figures 5-7 and discussed further below.

The position determined from radar returns is in general much less accurate than that provided by satellite-based Global Positioning System (GPS) reports, particularly when the antenna is far from the aircraft, which increases the uncertainty in the radar position. The ANC ASR has a higher sample rate than the ENA ARSR (1 sample every 4.5 seconds vs. 1 sample every 12 seconds), but is much further away from the accident site, and so the ANC returns have a larger area of position uncertainty ("uncertainty box") than the ENA returns. Fewer returns for both airplanes were recorded by ANC, compared to ENA (only one return from the Beaver was recorded by ANC). Hence, ENA provides a more complete record of the airplane's tracks, even though it has a lower sample rate. The TIS-B data for the Beaver is recorded mostly at 1 sample every 12 seconds, indicating that the source of the data is primarily the ENA ARSR.

Since TIS-B data are derived from radar returns, there is a larger uncertainty in TIS-B positions compared to GPS-based ADS-B positions. In addition, the ADS-B data is recorded more frequently than radar data (at 1 sample per second, compared to 1 sample every 12 seconds for the ARSR data). Consequently, in this *Study* the positions of the airplanes and the location of the collision are determined using the Piper ADS-B positions; the Beaver TIS-B positions are adjusted as necessary to result in a collision with the Piper at the end of the Piper ADS-B data.

Section D-III of this *Study* presents a simulation of traffic information that CDTI displays could have provided to the pilots of the accident airplanes, had both airplanes been equipped to receive and present this information.[2] Since CDTI is an application of the ADS-B system, to better understand the operation and benefit of CDTI, it is helpful to begin with a brief description of the ADS-B system itself.

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[1] The ENA computed coordinates match the ENA recorded coordinates very well. The ANC computed coordinates differ by up to about 100 ft. from the recorded coordinates. The reason for this difference is unknown, but might be because the nominal 21° magnetic variation reported for ANC is rounded from a value with a fractional component.

[2] The Piper was equipped with CDTI, but the Beaver was not. See the discussion in Section D-III.

Introduction to the ADS-B system

According to a 2007 "Fact Sheet" published by the FAA,[3] 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 GPS satellite constellation instead 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) has been 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). ADS-B Out is not required in the area of the accident. There is no requirement for ADS-B In anywhere in the NAS.

The ADS-B capabilities that enhance a pilot's awareness of airborne traffic in his vicinity are described in Advisory Circular (AC) 20-172B, "Airworthiness Approval for ADS-B In Systems and Applications." Per the AC,

> ADS-B In refers to an appropriately equipped aircraft's ability to receive and display other aircraft's ADS-B information and ground station broadcast information, such as TIS-B [Traffic Information Services – Broadcast] and ADS-R [Automatic Dependent Surveillance – Rebroadcast]. The information can be received by an appropriately equipped aircraft on either or both of two radio frequency (RF) links: 1090 ES [Extended Squitter] or 978 MHz UAT [Universal Access Transceiver]. The received information is processed by onboard avionics and presented to the flight crew on a display.

ADS-B In avionics enable several aircraft surveillance applications. The applications most relevant to this accident are the enhanced visual acquisition (EVAcq) and ADS-B Traffic Advisory System (ATAS) applications. AC 20-172B describes these applications as follows:

> The enhanced visual acquisition application (EVAcq) … displays ADS-B traffic on a plan view (bird's eye view) relative to own-ship. This application is designed to support only the display and alerting of ADS-B traffic, including ADS-R, TIS-B, and TCAS [Traffic Collision Avoidance System] derived traffic. … The traffic information assists the flight crew in visually acquiring traffic out the window while airborne. EVAcq does not relieve the pilot of see and avoid responsibilities under 14 CFR 91.113b. This application is expected to improve both safety and efficiency by providing the flight crew enhanced traffic awareness. …
>
> ADS-B Traffic Advisory System (ATAS) is an Automatic Dependent Surveillance-Broadcast (ADS-B) In application intended to reduce the number of mid-air collisions and near mid-air collisions involving general

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

> aviation aircraft. Previously known as Traffic Situation Awareness with Alerts (TSAA), the name ATAS has been used in this AC as well as TSO-C195b to be more consistent with existing traffic advisory systems. ATAS provides voice annunciations to flight crews to draw attention to alerted traffic and also adds visual cues to the underlying basic traffic situation awareness application (e.g., Enhanced Visual Acquisition [EVAcq] or Basic Airborne Situation Awareness [AIRB]) in installations where a Traffic Display is available. The ATAS application uses ADS-B information, and where available Automatic Dependent Surveillance-Rebroadcast (ADS-R) and Traffic Information Service-Broadcast (TIS-B) information to provide the flight crew with indications of nearby aircraft in support of their see-and-avoid responsibility. ATAS is the only ADS-B application with an aural-only implementation (via an annunciator panel). All other applications require a traffic display as defined by the CDTI [Cockpit Display of Traffic Information] requirements.

The cockpit display that presents traffic information to the pilot in a plan or "birds eye" view as stated in the EVAcq and ATAS application descriptions is the Cockpit Display of Traffic Information, or CDTI. For this accident, simulated CDTI displays for both the Piper and the Beaver were created for a (hypothetical) scenario in which both aircraft were equipped with all the components necessary to support a CDTI display with ATAS alerts. (In reality, only the Piper was equipped with ADS-B Out and In and CDTI.) The CDTI simulations are described in Section D-III.

Recorded ADS-B data provided by the FAA

The FAA provided the NTSB with the recorded ADS-B data (including TIS-B messages) within a 30 nm radius of the accident site, up to an altitude of 7,500 ft. MSL, for the time covering the flights of the Beaver and the Piper. This information was used to determine the tracks of the airplanes prior to the accident, and to recreate the traffic information that could have been presented on (hypothetical) CDTI displays for both airplanes (these re-creations are discussed in Section D-III).

The recorded ADS-B / TIS-B data includes the following parameters for all aircraft:

- UTC time of the report, in hours, minutes, and seconds. EDT = UTC – 4 hours.
- Aircraft identifying information (in a parameter called "ModeSId").
- 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.)
- GPS-based geometric altitude in feet, to the nearest 25 ft. (ADS-B data only)
- North-south and east-west components of ground speed, to a resolution of 1 kt., as reported in the ADS-B message from the aircraft (for ADS-B reports) or determined from radar tracking algorithms (for TIS-B reports).
- Rate of climb, to a resolution of 1 ft./min., as reported in the ADS-B message from the aircraft (or ADS-B reports) or determined from radar tracking algorithms (for TIS-B reports).
- Numerous parameters documenting the quality and accuracy of each reported GPS position (for GPS-based position reports only – not radar-based TIS-B reports).

In general, the sample rate of ADS-B (GPS-based) reports is a consistent 1 sample / sec (1 Hz). For radar-based (TIS-B) reports, the sample rate depends on the number of radars tracking the aircraft and the sample rate of each radar (typically about 1 sample every 4.5 sec (0.22 Hz) for short-range ASRs, and 1 sample every 12 seconds (0.083 Hz) for long-range ARSRs). The Piper ADS-B data is sampled at 1 Hz; the sample rate of the TIS-B data for the Beaver is about 0.083 Hz, and can be gleaned from Figures 6 and 7.

Presentation of the ADS-B, TIS-B, and radar data

To calculate performance parameters from the ADS-B and TIS-B data (such as groundspeed, track angle, pitch and roll angles, etc.), it is convenient to express the position of the airplanes in rectangular Cartesian coordinates. The Cartesian coordinate system used in this *Study* is centered on the Soldotna Airport (PASX) runway 7 threshold, and its axes extend east, north, and up from the center of the Earth. The ADS-B, TIS-B, and radar data for the Beaver and Piper are converted into this coordinate system using the WGS84 ellipsoid model of the Earth. The coordinates of the PASX runway 7 threshold are:

Latitude: 60° 28’ 29.8631” N
Longitude: 151° 03’ 07.5236” W
Elevation: 95.4 ft. MSL

Figure 5a presents the radar, ADS-B, and TIS-B data for the accident airplanes, plotted in terms of nautical miles north and east of the PASX runway 7 threshold.[4] Figure 5b is similar to Figure 5a, but presents the data over a *Google Earth* satellite images of the area.

Figure 5 also presents the adjustments made to the data in order to enforce certain constraints on the airplanes’ trajectories, to reduce the “noise” in the performance calculations resulting from position uncertainty in the data, and to interpolate the TIS-B data for the Beaver and the ADS-B data for the Piper to common 1 Hz sample times (see “Estimates of airplane performance based on ADS-B and TIS-B data,” below). The constraints used to adjust the trajectories are:

- The requirement for a collision (airplanes at the same place and altitude at the same time);
- The time of the collision, assumed to correspond to the point where the interpolations of the airplanes’ east coordinates coincide (i.e., at 08:26:32.3 ADT).

These constraints are discussed further below. The final trajectories used for the airplane performance calculations presented in this *Study* are depicted by the curves labeled “Piper integrated & shifted ADS-B velocities” and “Beaver interpolated & shifted TIS-B positions” in Figure 5 (hereafter referred to as the “smooth tracks.”

Estimates of airplane performance based on ADS-B and TIS-B data

The ADS-B positions for the Piper are GPS based and very accurate, but still contain some error or uncertainty. This uncertainty, combined with the relatively high sample rate of the data (1 Hz), results in spurious “noise,” or unrealistic spikes and variations, in the computed ground speed. If not removed or otherwise corrected, the noise in the computed ground speed propagates into all the other performance calculations.

The TIS-B positions for the Beaver are ARSR-based and have much greater uncertainty and error than the GPS-based ADS-B positions for the Piper. However, the large time interval between ARSR samples (12 seconds) tends to reduce the noise in the computed groundspeed. The effect of the

[4] Several Figures in this *Study* have an “a” and a “b” version, which present the same information but at different scales, or with different background images. When the *Study* refers to a Figure with two or more versions without specifying the version, all versions are meant to be included in the reference.

sample rate on the noise in the ground speed calculation using both the ADS-B and TIS-B data can be discerned by noting that

$$\epsilon_V = \frac{\epsilon_x}{\Delta t} \quad [1]$$

Where ϵ_x is the error in position, Δt is the time between data samples, and ϵ_V is the resulting error in the computed ground speed. For the same ϵ_x, ϵ_V is inversely proportional to Δt. In the present case, there is more noise in the ground speed computed from the "raw" (uncorrected) ADS-B positions than from the radar-based TIS-B positions (even though the ADS-B positions are more accurate) because Δt is twelve times greater for the TIS-B data than the ADS-B data. However, the low sample rate of the TIS-B data can make the computed ground speed deceptively "smooth," and obscure real changes in ground speed that might be captured with a higher sample rate.

As noted above, the north-south and east-west components of ground speed, as computed by on-board avionics, are included in the ADS-B messages from the Piper. These speed components are very smooth and can be combined to produce a smooth total ground speed. However, when these components are integrated over time, the resulting positions do not perfectly match the recorded ADS-B positions. In this *Study,* small biases are applied to the recorded ADS-B ground speed components so that when these components are integrated over time, the resulting start and end positions match the recorded ADS-B positions. A similar approach is used to compute the Piper pressure altitude; the vertical speed recorded in the ADS-B data is integrated over time to give the airplane's change in altitude, and the result is shifted to lie in between the recorded pressure altitude uncertainty bands (see Figure 7). The integrated positions are then used as the basis for ground speed and other performance calculations.

For the Beaver performance calculations, the Beaver TIS-B north and east positions are smoothed with a running-average algorithm, and then interpolated to the 1 Hz sample rate of the Piper ADS-B data using cubic splines. The Beaver and Piper positions are required at the same sample times in order to compute the separation distance between the airplanes, and the closure rate (the speed at which the airplanes are converging on each other).

Note in Figure 5 that the Beaver TIS-B positions lie about 0.05 nm (300 ft.) south of the ENA ARSR returns, and are not consistent with a collision with the Piper at the end of the Piper ADS-B data (the reason for this offset is unknown). Consequently, for this *Study* the Beaver TIS-B positions are shifted to the north so as to intersect the Piper ADS-B trajectory at the end of the ADS-B data, which is assumed to correspond to the collision point (within the distance covered over the 1 second sample interval of the data). The integrated Piper position (described above) is also shifted by about 12 ft. to match the geometry of the collision determined from evidence in the wreckage.[5] The resulting time and location of the collision are specified below and in Figures 5-7. Figure 6 plots the airplanes' north and east positions as a function of time.

The ADS-B data for the Piper includes pressure altitude, measured barometrically, and geometric altitude, measured by GPS. The TIS-B data for the Piper includes only pressure altitude (barometric altitude based on an altimeter setting of 29.92 "Hg.) These altitudes are plotted in Figure 7. To correct both the Beaver and Piper pressure altitude data to indicated altitude MSL, the pressure altitudes for both airplanes are adjusted for the local area altimeter setting of 29.93 "Hg (from the PASX 08:56

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[5] In an email to the NTSB Aircraft Performance Specialist, the NTSB Operational Factors Group Chairman noted that propeller slash marks were observed in the aft portion of the Beaver's left float.

ADT Meteorological Aerodrome Report (METAR)); this puts the airplanes' indicated altitudes about 9 ft. higher than the pressure altitudes. In addition, the resulting Piper indicated altitude is shifted down by about 8 ft. to match the geometry of the collision. Interestingly, the Piper GPS-based geometric altitude is about 25 ft. *lower* than the pressure altitude, even though the indicated altitude is higher (see Figure 7). This difference might be due to the accuracy limits of the GPS-based altitude.

Since the Piper altitude data is based on an integration of the recorded Piper vertical speed (see above), it is smooth, and is used in the performance calculations directly. The Beaver altitude, reported in the TIS-B data, has a resolution of 25 ft. The Beaver altitude used in the performance calculations was determined by first smoothing the recorded altitude while respecting the ±12.5 ft. uncertainty bands around the data, and then interpolating the data to the sample times of the Piper ADS-B data using a cubic spline. The final altitudes used in the performance calculations are depicted by the curves labeled "Piper integrated & shifted ADS-B vertical velocity" and "Beaver interpolated indicated altitude" in Figure 7.

Once 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).

The winds aloft for the performance calculations were taken from a 10:00 ADT Global Data Assimilation System (GDAS) computer model for the accident site, provided by an NTSB meteorologist. The wind speed and direction, and static air temperature, from the GDAS model are plotted as a function of altitude in Figure 8. The 08:56 ADT PASX METAR stated: wind calm, visibility 10 statute miles, overcast clouds at 8,500 feet, temperature 15° C, dew point 11° C, altimeter 29.93 "Hg.

As noted above, this *Study* uses aerodynamic data for both airplanes derived during previous investigations, and gross weights of 4,580 lb. and 1,580 lb. are assumed for the Beaver and Piper, respectively. The Beaver is assumed to be at climb flaps, and the Piper is assumed to be flaps up.[6]

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 (i.e., C_L vs. α). The results of the Beaver and Piper performance calculations for each airplane are presented below.

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[6] Per an email from the Investigator In Charge (IIC).

Estimated collision time, location, and geometry

The green and blue lines in Figures 5-7 depicting the flight tracks of the Beaver and Piper, respectively, are consistent with the ADS-B and TIS-B data for these airplanes, and with the constraints noted above. The tracks intersect at 08:26:30.3, close to the wreckage locations of both airplanes. The wreckage locations and flight tracks plotted in Figure 5 suggest that after the collision, both airplanes quickly descended to the ground along their original tracks.

Regarding the wreckage of the airplanes, Reference 3 states that the Beaver main wreckage site

> … contained the majority of the [Beaver] wreckage including the fuselage, right wing, and vertical tail …. A portion of one of the floats was suspended in a tree, close to the right wing and fuselage. Green paint transfer marks were present on portions of the left side of the empennage …. The left wing was separated from the aircraft and estimated to be 50 yards from the fuselage.

Reference 3 states that the Piper main wreckage site

> … contained the [Piper] wreckage and the [Beaver] horizontal stabilizer …. The [Piper] came to rest nose down, in a near vertical orientation. The [Beaver] horizontal stabilizer was embedded within the right-wing structure of the [Piper].

The groundspeeds and track angles of the Beaver and Piper corresponding to the tracks shown in Figures 5-7 indicate that at the time of the collision, the velocity vector of the Piper *relative to the Beaver* was 138 kt. along a heading of 89° (these and other details about the tracks are discussed further below). Since the Beaver was heading about 290° at the time of collision, the Piper would have been moving at an angle of 89° - 290° = -201° = +159° relative to the Beaver's centerline. The smaller angle between the centerline and a line drawn 159° to the centerline is 180° - 159° = 21°; the Piper would have cut across the Beaver's centerline from forward left to aft right at an angle 21° to the centerline. Similarly, the velocity vector of the Beaver *relative to the Piper* was 138 kt. along a heading of 269°. Since the Piper was heading about 67° at the time of collision, the Beaver would have been moving at an angle of 269° - 67° = 202° relative to the Piper's centerline. The smaller angle between the centerline and a line drawn 202° to the centerline is 202° - 180° = 22°; the Beaver would have cut across the Piper's centerline from forward right to aft left at an angle 22° to the centerline.

The smooth Beaver and Piper tracks plotted in Figures 5-7 result in the following time and coordinates for the collision:

Time of collision = 08:26:32.3 ADT
East coordinate = 1.78 nm east of PASX runway 7 threshold
North coordinate = 1.66 nm north of PASX runway 7 threshold
Altitude = 1,210 ft. MSL

The north and east positions of the Beaver and the Piper are presented as a function of time in Figure 6. This Figure presents the Beaver TIS-B data, the Piper ADS-B data, the radar data for both airplanes, and the smoothed tracks (shown as lines) used for the performance calculations.

The altitudes of the Beaver and the Piper are presented as a function of time in Figure 7. The barometric pressure altitudes recorded in the ADS-B, TIS-B, and radar data are presented, as well as the pressure altitudes corrected to true MSL altitude using an altimeter setting of 29.93 "Hg and adjusted to match the collision geometry (shown as the green and blue lines). The rates of climb and other performance calculations for the airplanes are based on these adjusted MSL altitudes. Note that the adjusted MSL altitudes respect the uncertainty bands corresponding to each source data pressure altitude point, after 9 ft. is added to the pressure altitude bands to account for the 29.93 "Hg altimeter setting.

Figure 9 shows the true airspeed, calibrated airspeed, groundspeed, and rate of climb calculated from the smooth trajectories for the Beaver and the Piper. Figure 9 indicates that at the time of the collision, the Beaver's groundspeed was about 78 knots, and the Piper's groundspeed was about 70 knots. The "Piper ADS-B recorded ground speed" is the ground speed computed from the north and east velocity components recorded in the Piper's ADS-B data. The "Piper computed ground speed" differs slightly from this recorded ground speed because of the biases applied to the speed to make the integration of the computed speed (yielding positions) match the recorded positions. The effects of numerical integration and differentiation with sparsely sampled data also introduce small differences between the recorded and computed speed; these effects are more apparent in the differences between the "Piper computed rate of climb" and the "Piper ADS-B recorded rate of climb;" the computed rate of climb is the result of differentiating the integration of the recorded rate of climb. If the sample rate were higher, the differences between these parameters would be reduced.

The recorded data indicates that during the minute preceding the collision, both airplanes were climbing, with the Piper leveling off at about 1,200 ft. about 12 seconds prior to the collision, and with the Beaver climbing continuously, with a brief reduction in the rate of climb between 12 and 7 seconds before the collision. The oscillations in the Beaver's speed and rate of climb between 08:26:10 and 08:26:25 are the result of the cubic spline interpolation between the Beaver's sparse TIS-B data points. The oscillations show a correspondence between a reduction in airspeed and an increase in rate of climb, as expected, but the magnitude of the oscillation may be different than that resulting from the interpolation.

Figure 10 shows the separation distance between the two airplanes and the closure rate. The Figure indicates that the closure rate was about 140 knots at the time of the collision.[7]

Figure 11 presents the pitch, flight path, roll, heading, and ground track angles calculated from the smooth tracks for the Beaver and the Piper. The oscillations in the Beaver's pitch and flight path angles between 08:26:10 and 08:26:25 correspond to the oscillations in the Beaver's rate of climb, discussed above. The Beaver's track angle at the time of the collision was about 288°, and the Piper's track angle was about 67°. Therefore, the collision angle (the smallest angle between the ground tracks of the aircraft at the time of impact)[8] is about 41° (288° - 67° - 180°), with the Beaver approaching the Piper from ahead and to the right, and the Piper approaching the Beaver from ahead and to the left (see Figure 5).

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[7] Theoretically, the closure rate should exactly match the relative speed between the airplanes at the collision, which is 138 kt. per the discussion above. The small difference in the closure rate calculation is due to numerical effects with a relatively low sample rate of 1 Hz. At a higher sample rate, the difference would be reduced.

[8] The collision angle is not to be confused with the angles the velocity vectors of the airplanes *relative to each other* make with each airplane's centerline, as discussed above. The relative velocity depends on the airplanes' groundspeeds, as well as their track angles; the collision angle as defined here only depends on the track angles.

III. Cockpit Display of Traffic Information (CDTI) Study

NTSB CDTI simulation description

The Automatic Dependent Surveillance – Broadcast (ADS-B) system, and the enhanced visual acquisition (EVAcq) and ADS-B Traffic Advisory System (ATAS) applications of the ADS-B system, were introduced above in Section D-II. As mentioned there, the cockpit display that presents traffic information to the pilot in a plan or "birds eye" view per the EVAcq and ATAS application descriptions is the Cockpit Display of Traffic Information, or CDTI. For this accident, simulated CDTI displays for both the Beaver and the Piper were created based on the information[9] that would have been displayed to the pilot of each airplane assuming that both airplanes were equipped with:

- ADS-B Out and In capability
- Avionics capable of running the ATAS application
- A CDTI for displaying traffic information
- An audio system capable of annunciating the ATAS aural alerts

AC 20-172B describes the symbol requirements for the CDTI, which are more completely defined in RTCA document DO-317B, "Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications (ASA) System." These requirements specify that, among other things,

- The position of the ownship symbol should allow the display of traffic in all directions around the ownship, and indicate the direction of travel of the ownship (in the NTSB simulations, the ownship symbol is a white triangle with the direction of motion towards the top of the display (12 o'clock position)).
- Traffic symbols that are not proximate (i.e., not within 6 nmi and ±1,200 ft. of the ownship) should be cyan-colored and open (not filled). In the NTSB simulations, these symbols are open cyan-colored arrowheads.
- Traffic symbols that are proximate should be cyan and filled. In the NTSB simulations, these symbols are filled cyan arrowheads.
- Traffic that generates an ATAS alert should be displayed with yellow symbols enclosed in a circle. In the NTSB simulation, these symbols are filled yellow arrowheads enclosed in a yellow circle.

DO-317B also specifies the aural annunciations that should accompany an ATAS traffic alert. The components of the annunciation include the alert "traffic," followed by the relative traffic bearing expressed as a clock position (e.g., "two o'clock"), the relative altitude ("high," "low," or "same altitude"), the range to the target in nautical miles, and optionally, the vertical tendency[10] (e.g., "descending"). The example of a complete annunciation given in DO-317B is "traffic, two o'clock, high, two miles, descending." The aural annunciation is provided both when a traffic target first generates an ATAS alert (by the algorithm predicting that the ownship will penetrate a "protected airspace zone" (PAZ) around the target), and again when the algorithm predicts that the ownship will

[9] ADS-B traffic information for the Beaver and Piper was provided to the NTSB by the FAA, based on recorded ADS-B and TIS-B information during the flight time both airplanes were aloft, for all aircraft within a 30 nm radius of the accident site and up to an altitude of 7,500 ft. MSL.

[10] The vertical tendency will only be annunciated when the computed rate of climb or descent is at least 500 ft./min.

penetrate a smaller, "collision airspace zone" (CAZ) around the target.[11] The NTSB simulations incorporate these elements of the aural annunciation of ATAS alerts.

It should be noted that while the simulation images presented in Figures 13-17 are representative of a CDTI that complies with the DO-317B MOPS, they do not duplicate the implementation or presentation of any particular operational display exactly. The actual images presented to a pilot depend on the range scale and background graphics selected by the pilot (which could reflect various implementations and combinations of moving maps, terrain elevation data, and weather information, rather than the simple black background presented in Figures 13-17).

CDTI equipment installed on Piper N2587M

The Beaver was not equipped with any ADS-B equipment, but the Piper was equipped with ADS-B Out and In capability, and a CDTI that included aural and visual alerts of potential collision threats. Per Reference 3,

> Purchase records provided to the NTSB revealed that in early 2016, the aircraft owner purchased multiple avionics components to install a Garmin G3X Touch system in the aircraft …. Major avionics components purchased were as follows:
>
> - 1 - GDU460 Display
> - 1 – GTX23ES Remote Transponder
> - 1 – GPS20A WAAS GPS Receiver
> - 1 – GDL39R Portable ADS-B and GPS Receiver
> - 1 – GTR20 Remote Comm Radio
> - 1 – GMC307 Autopilot Controller
> - 2 – GSA28 Autopilot servos (pitch and roll axis)
> - 1 – G5 Electronic Flight Instrument
>
> … The Garmin 3X Touch system installed was a non-certified version and intended for installation on experimental aircraft only. There was no record of the avionics installation as a major repair and alteration in the aircrafts' FAA airworthiness records.

The Garmin G3X Touch Pilot's Guide (Reference 4) describes the system's ADS-B / TIS-B traffic display and alerting functions as follows:

> **TRAFFIC SOURCE**
>
> The G3X is compatible with three different traffic sources; TIS-A traffic via a Garmin Mode S Transponder, TAS [Traffic Avoidance System] via a GTS 800, or ADS-B/TIS-B traffic via a compatible ADS-B device. …
>
> …
>
> **TAS TRAFFIC ANNUNCIATIONS**
>
> The G3X displays traffic symbolically on the Map Page, and the Traffic Warning Window (Inset Map) in the lower left corner of the display(s).
>
> When a traffic advisory (TA) is detected, the following automatically occur:
>
> • The Traffic Warning Window (Inset Map) is enabled and displays traffic.

[11] Per DO-317B, the size of the PAZ depends on the closure rate between the aircraft, increasing as the closure rate increases. The size of the CAZ is constant at a 500 ft. radius and a height of ±2000 ft.

• A flashing black-on-yellow 'TRAFFIC' annunciation will appear in the upper right corner of the Attitude Indicator for five seconds and remains displayed until no TAs are detected in the area.

• A single "Traffic" voice alert is generated

Arrows are depicted on the traffic message if traffic is outside the Synthetic Vision field of view. The arrow points in the direction of the traffic.

…

DATA LINK TRAFFIC (OPTIONAL)

The ADS-B receiver is a receive-only data link radio with on-board GPS, 978 MHz (Universal Access Transceiver frequency band), and 1090 MHz Extended Squitter (1090 ES) receivers. It is designed to receive, process, and output traffic (ADS-B air-to-air, and TIS-B traffic information), and weather (Flight Information Service-Broadcast (FIS-B)) information to the G3X Touch system through an RS-232 serial connection or Bluetooth connection.

ADS-B (Automatic Dependent Surveillance-Broadcast) is a surveillance technology deployed across the United States as the cornerstone of the FAA's Next Generation Air Transportation System (NextGen). ADS-B enables improved surveillance services, both air-to-air and air-to-ground, especially in areas where radar is ineffective due to terrain or where it is impractical or cost prohibitive. Initial applications of air-to-air ADS-B are for "advisory" use only, enhancing a pilot's visual acquisition of other nearby ADS-B equipped aircraft either when airborne or on the airport surface.

For the purpose of distinguishing between levels of ADS-B service, there are three classifications of aircraft or system capability; ADS-B In, ADS-B Out, and ADS-B participating. ADS-B In refers to the capability to receive ADS-B information. ADS-B Out refers to the capability to transmit ADS-B information. ADS-B participating refers to the capability to both send and receive ADS-B information. Aircraft lacking either ADS-In, ADS-B Out, or both ADS-B capabilities may also be referred to as ADS-B nonparticipating aircraft.

Currently, rule-compliant ADS-B Out capability in the United States requires a TSO'ed SBAS-enabled GPS, such as a Garmin GPS 400W or similar, and one of two possible data links: 1090 ES transponder or a 978 MHz UAT. Either data link system is capable of transmitting the aircraft's position, velocity, identification, and other information every second to compatible aircraft and ground stations called Ground Based Transceivers (GBTs).

Because 1090 ES transponders and UATs operate on different frequencies, aircraft not similarly equipped cannot transmit/receive data link information directly to/from each other. Instead, operation within range of a GBT is required to receive data link information on both frequencies. The ADS-B receiver is unique in its ADS-B In capability since it can receive data link information from both 1090 ES transponders and UATs.

Thus, the ADS-B receiver receives traffic information directly from any ADS-B Out aircraft within range as well as the rebroadcast of ADS-B information from any nearby GBT. This rebroadcast is called Automatic Dependent Surveillance-Rebroadcast (ADS-R) and is automatically triggered by the detection of an ADS-B participating aircraft within the service volume of the GBT. As a 978 MHz (UAT frequency) receiver, the ADS-B receiver can receive both the Traffic Information Service-Broadcast (TIS-B) and Flight Information Service-Broadcast (FIS-B) provided in conjunction with ADS-R services when in range of a GBT.

FIS-B service is provided continuously, but ADS-R including TIS-B will only be broadcast by a GBT when an ADS-B participating aircraft is within the GBT's defined service volume. In this case, a GBT will only rebroadcast TIS-B information relative to the ADS-B participating aircraft. **Only traffic that is within 15 nm lateral and 3,500' vertical of the ADS-B participating aircraft is provided in the broadcast.** Non-participating traffic aircraft located farther than 15 nm laterally and 3,500' vertically from the participating aircraft is are excluded from the information transmitted by the GBT.

TIS-B traffic information includes non-participating aircraft detected by ATC surveillance radar. As TIS-B data is derived from ATC surveillance radar data, TIS-B traffic position updates typically occur every three to thirteen seconds. **Therefore, TIS-B traffic may be displayed with degraded positional accuracy. Aircraft without operating transponders are invisible to TIS-B. Aircraft operating outside of the ATC radar coverage area are also not displayed.**

Since the ADS-B receiver is a receive-only device, even when used onboard an aircraft equipped with a qualifying GPS and 1090 ES transponder, a GBT may not identify it as an ADS-B participating aircraft. The squitter of some 1090 ES transponders must be configured to communicate that the aircraft has 978 MHz receive capability in order to be identified as an ADS-B participating aircraft.

TRAFFIC DESCRIPTION

ADS-B traffic operation is similar to the [Traffic Avoidance Systems] discussed previously, but ADS-B adds additional symbology. The symbols used to display ADS-B traffic are shown in [Figure 12]. The traffic identifier and altitude are displayed below the traffic symbol. A small up or down arrow next to the traffic symbol indicates that the traffic is climbing or descending at a rate of at least 500 feet per minute. The vector line that extends from the traffic symbol is an indication of the intruder aircraft track. For directional traffic symbols, the arrow head points in the direction of aircraft's ground track.

Traffic Advisories (TA)

The GDL Device automatically adjusts its Traffic Advisory (TA) sensitivity level to reduce the likelihood of nuisance TA alerts during various phases of flight. TAs are issued for traffic when they are predicted to be within a specified volume of airspace around your aircraft in a specified amount of time. The protected volume and time interval varies based on the current geodetic altitude and groundspeed. Thus, the protected volume of airspace increases with altitude and ground speed. Refer to the following table for details.

Altitude (Geodetic)	Look Ahead Time (sec.)	Vertical Separation (ft.)	Horizontal Separation (nm.)
Below 5,000	30	+/-850	.35
5,000-10,000	40	+/-850	.55
10,000-20,000	45	+/-850	.80
20,000-42,000	48	+/-850	1.10
Above 42,000	48	+/-1,200	1.10

Traffic Advisories

…

TRAFFIC ALERTS (ADS-B TIS-B)

A traffic voice alert is generated whenever the number of Traffic Advisories on the G3X display increases. Limiting Traffic Advisories only reduces the "nuisance" alerting due to proximate aircraft. For example, when the first Traffic Advisories appear on the display, the user is alerted audibly. So long as a single aircraft remains on the display, no further voice alert is generated. If a second (or more) aircraft appears on the screen, a new voice alert is sounded. Traffic Advisories can only be issued when the GDL Device knows its own altitude and the altitude of the intruder aircraft.

If the number of Traffic Advisories on the traffic display decreases and then increases, a new voice alert is sounded. The traffic voice alert is also generated whenever TIS-B service becomes available. The traffic voice alerts are as follows:

- "Traffic"—TIS-B/ADS-B traffic alert received.
- "Traffic Not Available"—TIS-B/ADS-B service is not available or out of range.

Traffic Warning Window

The Traffic Warning Window is shown, when the GDL Device issues a traffic advisory (TA). The Traffic Warning Window shows a small pop-up map in the lower left corner. The Range Rings on the pop-up alert are spaced every whole mile/kilometer/nautical mile. Press the CLR Key to remove the Traffic Warning Window.

DISPLAYING TRAFFIC DATA

> Traffic is displayed by default on the Map Page and in the Traffic Warning Window. Traffic Symbol and Traffic Label (i.e., relative altitude, altitude trend and absolute motion vectors) settings selects the maximum range at which traffic labels or symbols are shown. Traffic Labels can also be turned off.
>
> Traffic information is also displayed on the PFD when Synthetic Vision is enabled. …

The Pilot's Guide also indicates that the traffic alerts can be disabled by the pilot, though they will be "reset to 'enabled' on the next power cycle." The display of traffic on the G3X Map Page and the Primary Flight Display (PFD) can also be turned off.

It is not known whether the G3X on the accident flight had traffic alerts enabled or disabled. If they were disabled, the pilot would have had to have taken action to disable them after powering on the system on the accident flight, since they are enabled by default on each power cycle.

Although the G3X does not implement the DO-317B algorithms described above, it still provides traffic symbology similar to the DO-317B standards, generates traffic advisories based on a predicted penetration of protected airspace around the ownship, and issues aural alerts concerning those advisories (though without the directional information contained in the DO-317B alerts). If the G3X system was turned on during the accident flight, it seems plausible that the system would have generated a Traffic Advisory and corresponding aural alert concerning the Beaver. However, it cannot be determined conclusively whether such an alert was generated. According to information received from the FAA by the NTSB Air Traffic Control (ATC) specialist[12] assigned to this case,

- [Piper N2587M] was transmitting ADS-B out, and was a client for UAT-in.
- [Beaver] N4982U was not ADS-B equipped, and indicated 9 UAT uplinks between 08:25:56 and 08:26:49.
- Data indicated that [N2587M] was on the UAT SSB [single side band] at the time the TIS-B messages about N4982U were broadcast.
- Nobody can definitively say that messages were actually received by [N2587M], only that the information was broadcast, and [N2587M] was on the system at the same time.
- It would be accurate to say there was an opportunity for [N2587M] to have received the TIS-B broadcast information on N4982U that occurred during the same time he was on the UAT SSB.

If the G3X did in fact generate an alert concerning the Beaver, it may have appeared similar to alerts that would have been generated by a DO-317B compliant system. The results of the NTSB simulations of DO-317B systems for this case are described below.

NTSB CDTI simulation results: Piper N2587M

Selected images from the NTSB simulation of a CDTI display for the Piper are presented in Figures 13a-17a. The Piper ADS-B data starts at 08:25:39 and 1,100 ft. MSL, presumably shortly after the Piper climbed high enough to be seen by the ADS-B ground station. The TIS-B data starts at 08:25:24 and 700 ft. MSL, about 20 seconds (and two radar returns) after the start of the Beaver ENA ARSR returns. A proximate traffic target representing the Beaver first appears in the CDTI simulation for the Piper at 08:25:51 (see Figure 13a), shortly after the first TIS-B return from the Beaver is recorded (after the Piper ADS-B data starts). At this point, the target representing the Beaver is at the Piper's 3 o'clock position, 1.6 nm distant, 300 ft. below the Piper, and heading

[12] This information was forwarded by the ATC Specialist to other NTSB investigators in an email dated 10/16/2020.

westward towards the Piper. (If the Beaver had been equipped with ADS-B Out, then presumably it could have appeared on the Piper's CDTI as soon as both airplanes became visible to each other.) At the 5 nm CDTI range used in Figure 13, a second traffic target appears at the Piper's 11 o'clock position, less than a mile away, 400 ft. above the Piper, and heading westward.[13]

At 08:26:00, as the Piper turns right from a northerly heading towards a northeasterly heading, the traffic target representing the Beaver moves from the Piper's 3 o'clock position to its 2 o'clock position; see Figure 14a. At 08:26:06 (26.3 seconds before the collision), as the Piper continues to turn to the right, the Beaver moves to the Piper's 1 o'clock position and generates a traffic alert, changing from a filled cyan arrowhead to a filled yellow arrowhead surrounded by a yellow circle (see Figure 15a). An accompanying aural alert states "traffic, 1 o'clock, same altitude, 1 mile." At this time, the Beaver is 1.3 nm away and about 250 ft. below the Piper.[14] This alert results from the ATAS algorithm predicting that the Piper will penetrate the Beaver's PAZ. The CDTI on the Beaver also generates an alert concerning the Piper at this same time (see Figure 15b).

At 08:26:13 (19.3 seconds before the collision), the CDTI on the Beaver generates a second aural alert concerning the Piper as a result of the ATAS algorithm predicting that the Beaver will penetrate the Piper's CAZ (see Figure 16b). Interestingly, the second alert on the Piper regarding the Beaver does not come until 10 seconds later; the reason for this difference is not known, but might be associated with the effects of the Piper's maneuvering (right turn) on the ATAS algorithm's projection of the Piper's position. The Piper rolls wings-level at about 08:26:14, just after the second aural alert is generated on the Beaver (see Figure 11). The difference might also be associated with uncertainties in the projected Beaver position resulting from the low sample rate of the Beaver TIS-B data used in the simulation.

At 08:26:23 (9.3 seconds before the collision), the ATAS algorithm predicts that the Piper will penetrate the Beaver's CAZ, and generates a second aural alert: "traffic, 1 o'clock, same altitude, less than 1 mile, climbing." The target representing the Beaver on the Piper's CDTI remains a filled yellow arrowhead surrounded by a yellow circle (see Figure 17a). This target continues to converge on the ownship symbol on the Piper's CDTI until the collision at 08:26:32.3.

NTSB CDTI simulation results: Beaver N4982U

Selected images from the NTSB simulation of a CDTI display for the Beaver are presented in Figures 13b-17b. At 08:25:51, a proximate traffic target representing the Piper appears on the Beaver's CDTI at the 11 o'clock position, 1.6 nm distant, 300 ft. above the Beaver, and headed northwards, across the Beaver's projected flight path (see Figure 13b). At the 5 nm CDTI range used in Figure 13, a second traffic target appears at the Beaver's 12 o'clock position, about 2 miles away, 700 ft. above the Beaver, and heading westward.

At 08:26:00, as the Piper turns right from a northerly heading towards a northeasterly heading, the traffic target representing the Piper remains at the Beaver's 11 o'clock position and rotates to reflect the Piper's change in heading (see Figure 14b). At 08:26:06 (26.3 seconds before the collision), the

[13] Additional traffic would be displayed at higher CDTI ranges. For example, at a 10 nm CDTI range, another traffic target appears to the northwest, 7 nm distant, and 900 ft. above the Piper. For clarity, the selected CDTI range in the Figures of this *Study* is set to 5 nm, and so targets beyond this range are not displayed.

[14] The DO-317B aural alert annunciates that a traffic target is at the "same altitude" as the ownship if the altitude difference between the target and the ownship is less than 300 ft.

Piper generates a traffic alert, changing from a filled cyan arrowhead to a filled yellow arrowhead surrounded by a yellow circle (see Figure 15b). An accompanying aural alert states “traffic, 11 o’clock, same altitude, less than 1 mile.” At this time, the Piper is 1.3 nm away and about 250 ft. above the Beaver.[15] This alert results from the ATAS algorithm predicting that the Beaver will penetrate the Piper’s PAZ. The CDTI on the Piper generates an alert concerning the Beaver at this same time.

As noted above, at 08:26:13 (19.3 seconds before the collision), the ATAS algorithm predicts that the Beaver will penetrate the Piper’s CAZ, and generates a second aural alert: “traffic, 11 o’clock, same altitude, less than 1 mile.” The target representing the Piper on the Beaver’s CDTI remains a filled yellow arrowhead surrounded by a yellow circle (see Figure 16b). This target continues to converge on the ownship symbol on the Beaver’s CDTI until the collision at 08:26:32.3. The Beaver’s CDTI display at 08:26:23, when the CDTI on the Piper generates a second aural alert concerning the Beaver, is depicted in Figure 17b.

E. CONCLUSIONS

This *Aircraft Performance Radar & Cockpit Visibility Study* presents the results of using recorded ADS-B and TIS-B data to calculate the position and orientation of each airplane in the minutes preceding the collision. This information is then used to simulate the traffic information that could have been presented to the pilots, had both airplanes been equipped with CDTI displays.

The position, speed, Euler angles, separation distance, and closure rate of both airplanes are presented in Figures 5-11. Selected images from simulations depicting the traffic information that could have been presented on CDTI displays (had both airplanes been so equipped) are presented in Figures 13-17.

Radar data for the Beaver starts at 08:25:01 at an altitude of 500 ft. MSL, and TIS-B data for the Beaver starts at 08:25:24 at an altitude of 700 ft. MSL. The data shows that after the Beaver departed Longmere Lake towards the east, it turned right and climbed to the northwest on a ground track of about 288°.

Radar data for the Piper starts at 08:24:26 at an altitude of 600 ft. MSL, and ADS-B data for the Piper starts at 08:25:39 at an altitude of 1,100 ft. MSL. The data shows the Piper departed PASX runway 7 and turned northbound. At about 08:25:50, while climbing through 1,100 ft. over the Sterling Highway, the Piper turned right towards the northeast. The airplane leveled off at about 1,200 ft. on a ground track of about 70° at 08:26:20, about 12 seconds before the collision.

The Beaver and Piper converged as shown in Figure 5 until they collided at the following time and coordinates:

---

[15] The DO-317B aural alert annunciates that a traffic target is “less than one mile” away if the computed distance to the target is less than 1.1 nm. In the CDTI simulation for the Beaver, at 08:26:06 the computed separation from the Piper is 1.06 nm, and so the aural alert announces that the Piper “less than one mile” away. In the CDTI simulation for the Piper, at 08:26:06 the separation distance is 1.2 nm, which is annunciated as “one mile.” The small difference in separation distance between the simulations (which affects the content of the aural alerts) results from ADS-B data being used as the “traffic” data for the Piper, and TIS-B data being used as the “traffic” data for the Beaver. The different sources and sample rates of the data driving the “traffic” targets in each simulation might also explain why the Beaver is depicted as 300 ft. below the Piper in Figure 14a, but the Piper is depicted as only 200 ft. above the Beaver in Figure 14b. The “ownship” data for each simulation is based on the “true” positions of the airplanes as depicted in Figure 5.

Time of collision = 08:26:32.3 Alaska Daylight Time
East coordinate = 1.78 nm east of PASX runway 7 threshold
North coordinate = 1.66 nm north of PASX runway 7 threshold
Altitude = 1,210 ft. MSL

The closure rate at the time of collision was about 140 kt., with the Beaver approaching the Piper from ahead and to the right, and the Piper approaching the Beaver from ahead and to the left (see Figure 5).

If both airplanes had been equipped with ADS-B Out and In, and with CDTI displays capable of ATAS alerts, it is possible that both pilots could have been made aware of the presence of the other airplane at least as soon as they were within line-of-sight of each other (say, by the time the Beaver climbed to 500 ft. MSL), or by 08:25:01 (about a minute and a half before the collision). Simulations of CDTI displays for both airplanes (that assume both airplanes were equipped as described above) indicate that at 08:26:06 (26.3 seconds before the collision), each airplane would have received an aural and visual ATAS alert concerning the other, as they penetrated each other's PAZ. The Beaver would also have received a second ATAS alert 19.3 seconds prior to the collision, as the ATAS algorithm predicted it would penetrate the Piper's CAZ, and the Piper would have received a second ATAS alert 9.3 seconds prior to the collision, as the ATAS algorithm predicted it would penetrate the Beaver's CAZ. The CDTI displays on both aircraft would have depicted the airplanes in alert status (solid yellow arrowheads enclosed in a yellow circle) converging on each other up until the collision.

The Beaver was not equipped with ADS-B equipment or CDTI. However, the Piper was equipped with a Garmin G3X Touch system that included ADS-B Out and In capability and a CDTI capable of producing aural alerts (though the alerting algorithm and aural alert phraseology of the G3X Touch differ from those of the ATAS algorithm described in DO-317B). The pilot can disable traffic alerts on the system, and it is not known whether the alerts were enabled on the accident flight (though the alerts are automatically enabled with each power cycle). In addition, while the FAA confirmed that there was an opportunity for the Piper to have received TIS-B messages regarding the Beaver, it cannot be determined conclusively that the Piper in fact received those messages. If the Piper did receive the TIS-B messages and the G3X system was on with alerts enabled, then the system could have generated visual alerts and a single aural alert concerning the Beaver similar to those depicted in the CDTI simulations presented in this *Study*.

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

F. REFERENCES

1. Viking Air Ltd., *DHC-2 Beaver Airplane Flight Manual*, document PSM1-2-1, Revision 11 – July 08, 2002.
2. Piper Aircraft Corporation, Owner's Handbook, PA-18 Super Cub, issued February 1975, revised September 18, 1981. Piper Part # 761 611.
3. National Transportation Safety Board, Office of Aviation Safety, *Systems Group Chairman's Factual Report, de Havilland DHC-2 (Beaver) / Piper PA-12 (Super Cruiser), Soldotna, Alaska, July 31 2019, NTSB #ANC20LA074AB,* January 29, 2021.
4. Garmin Ltd., *G3X™ Pilot's Guide,* document # 190-01115-00 Rev. Q, April 2019.

G. GLOSSARY

Acronyms

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-R	Automatic Dependent Surveillance – Rebroadcast
ADT	Alaska Daylight Time
ASA	Aircraft Surveillance Applications
ATAS	ADS-B Traffic Advisory System
ATC	Air Traffic Control
CAZ	Collision Airspace Zone
CDTI	Cockpit Display of Traffic Information
CFR	Code of Federal Regulations
EVAcq	Enhanced visual acquisition
FAA	Federal Aviation Administration
GDAS	Global Data Assimilation System weather computer model
GPS	Global Positioning System
METAR	Meteorological Terminal Air Report
MOPS	Minimum Operational Performance Standards
MSL	Mean Sea Level
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NTSB	National Transportation Safety Board
NWS	National Weather Service
PAZ	Protected Airspace Zone
PASX	Soldotna Airport, Soldotna, Alaska
SSB	Single side band
TIS-B	Traffic Information Services – Broadcast
TSAA	Traffic Situation Awareness with Alerts
UAT	Universal Access Transceiver
UTC	Universal Coordinated Time
VMC	Visual Meteorological Conditions
VFR	Visual Flight Rules

FIGURES

Figure 1. Pre-accident photo of DHC-2 Beaver N4982U (photo copyright by Gary Kegel / Airport-Data.com).

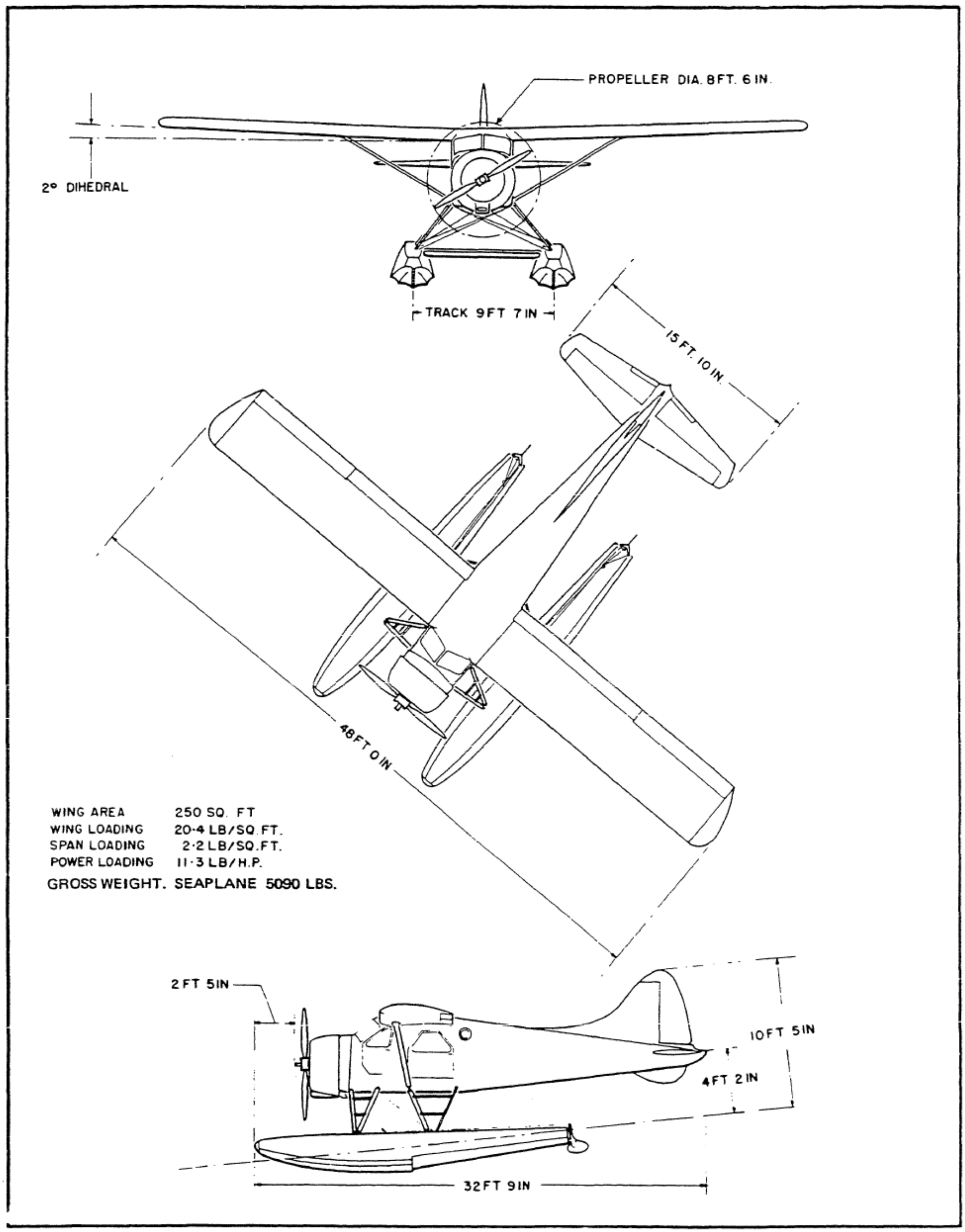


Figure 2. Three-view drawings of the DHC-2 Beaver seaplane, from Reference 1.

Figure 3. Pre-accident photo of Piper N2587M (courtesy of pilot's family). Note that the registration number "N1904T" is painted on the rudder, instead of the actual "N2587M" registration number (see additional discussion of the registration number in Reference 3).

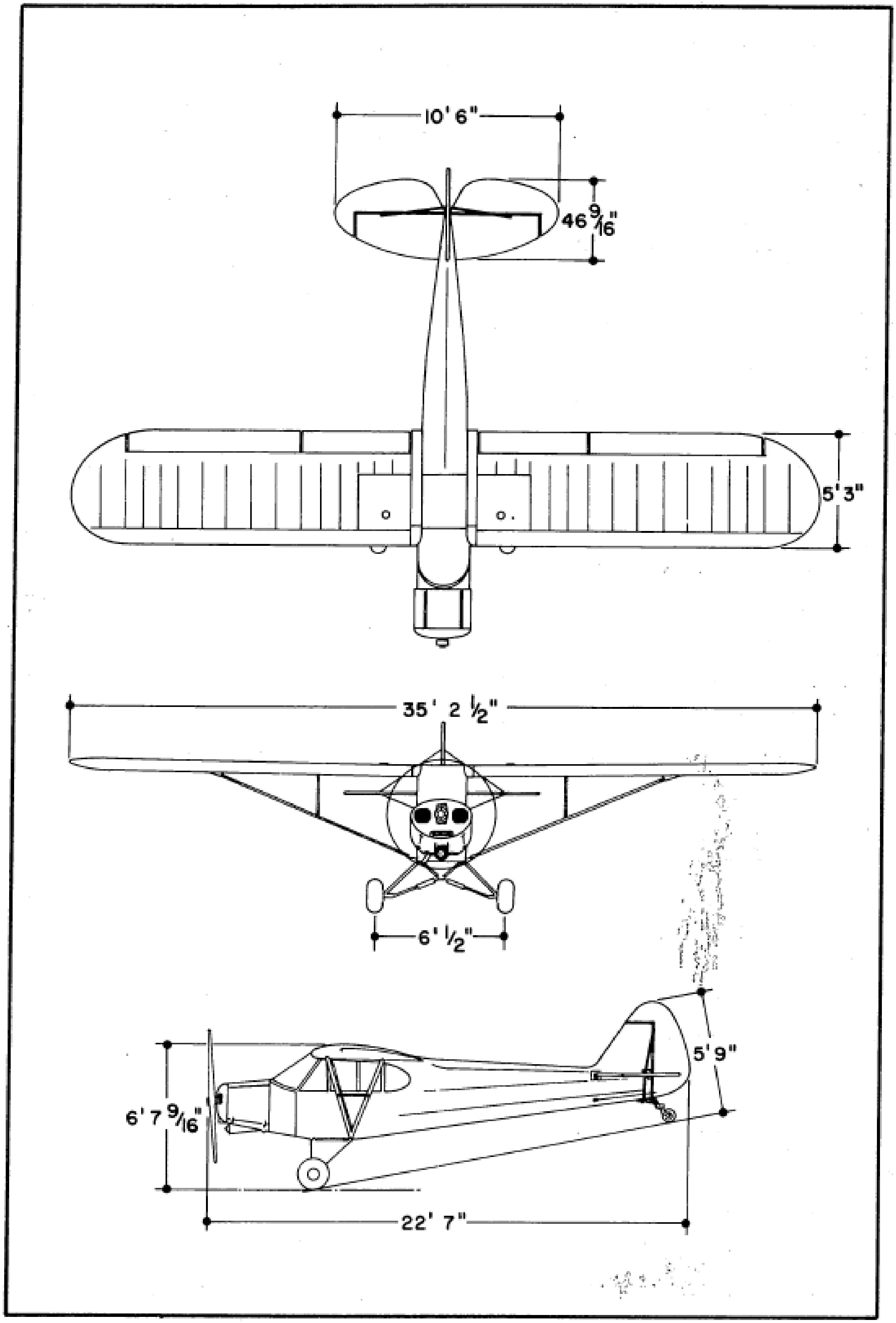


Figure 4. 3-view of Piper PA-12-150, from Reference 2.

ANC20LA074AB: Midair collision, DHC-2 Beaver N4982U / Piper PA-12 N2587M, Solotna, AK, 7/31/2020

Plan view of ADS-B and TIS-B data for Beaver and Piper (grid background)

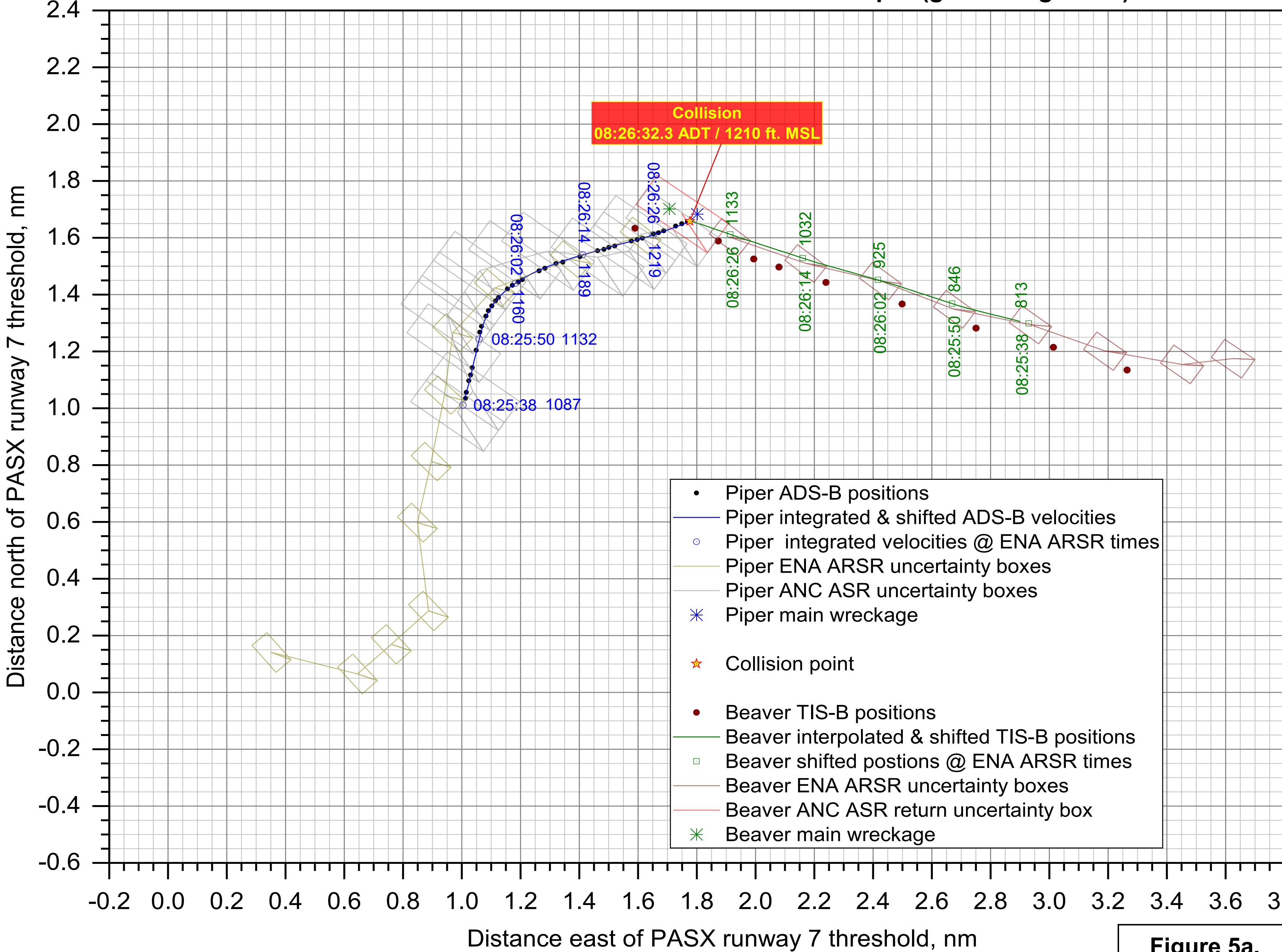


Figure 5a.

ANC20LA074AB: Midair collision, DHC-2 Beaver N4982U / Piper PA-12 N2587M, Solotna, AK, 7/31/2020

Plan view of ADS-B and TIS-B data for Beaver and Piper (satellite image background)

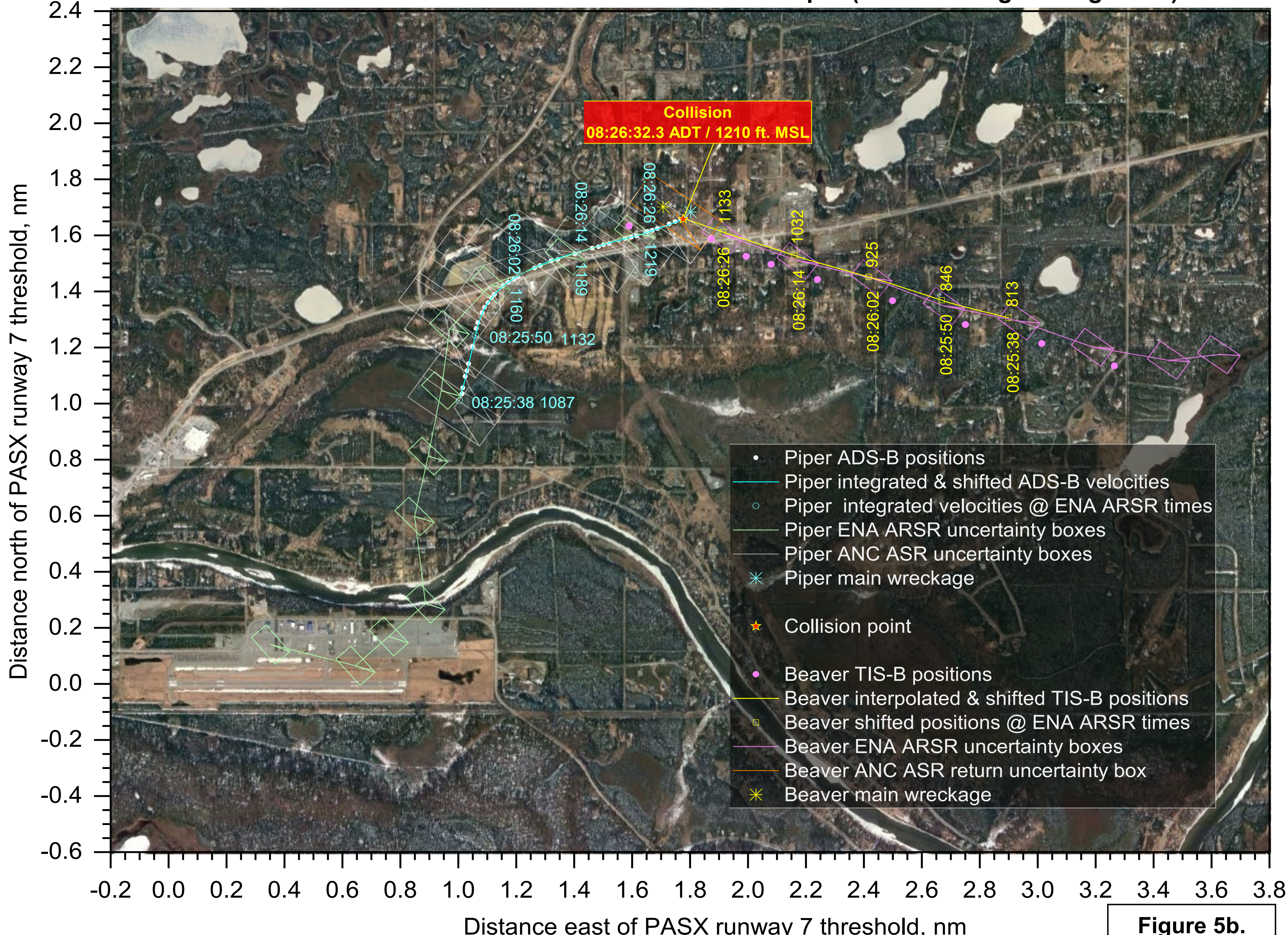


Figure 5b.

ANC20LA074AB: Midair collision, Beaver N4982U / Piper N2587M, Solotna, AK, 7/31/2020

Beaver and Piper north and east coordinates vs. time

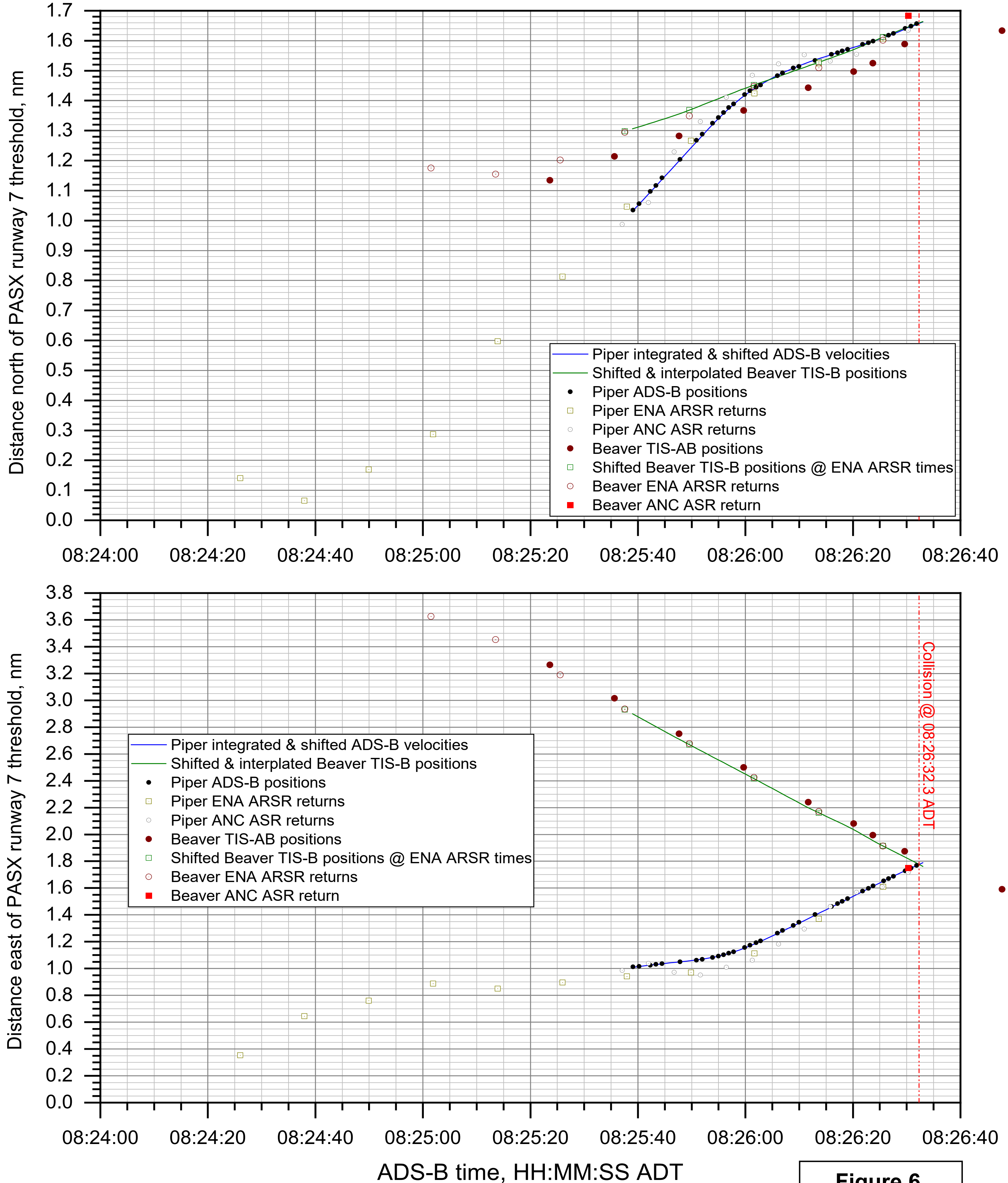
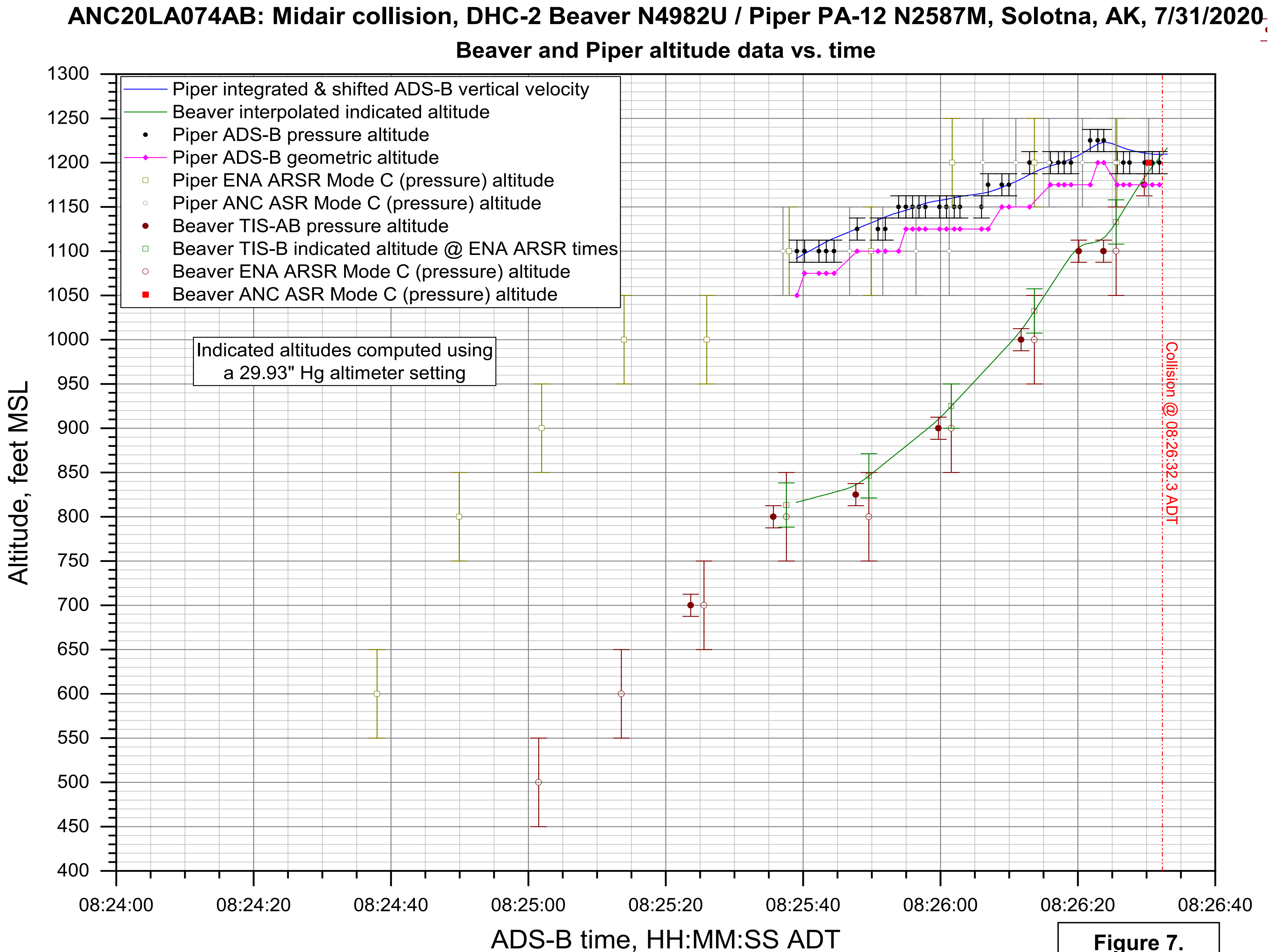


Figure 6.


ANC20LA074AB: Midair collision, DHC-2 Beaver N4982U / Piper PA-12 N2587M, Solotna, AK, 7/31/2020
Beaver and Piper altitude data vs. time
Piper integrated & shifted ADS-B vertical velocity
Beaver interpolated indicated altitude
Piper ADS-B pressure altitude
Piper ADS-B geometric altitude
Piper ENA ARSR Mode C (pressure) altitude
Piper ANC ASR Mode C (pressure) altitude
Beaver TIS-AB pressure altitude
Beaver TIS-B indicated altitude @ ENA ARSR times
Beaver ENA ARSR Mode C (pressure) altitude
Beaver ANC ASR Mode C (pressure) altitude
Indicated altitudes computed using a 29.93" Hg altimeter setting
Collision @ 08:26:32.3 ADT
Altitude, feet MSL
ADS-B time, HH:MM:SS ADT
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
08:24:00
08:24:20
08:24:40
08:25:00
08:25:20
08:25:40
08:26:00
08:26:20
08:26:40
Figure 7.

ANC20LA074AB: Midair collision, DHC-2 Beaver N4982U / Piper PA-12 N2587M, Solotna, AK, 7/31/2020

Winds aloft based on GDAS model sounding for 10:00 ADT

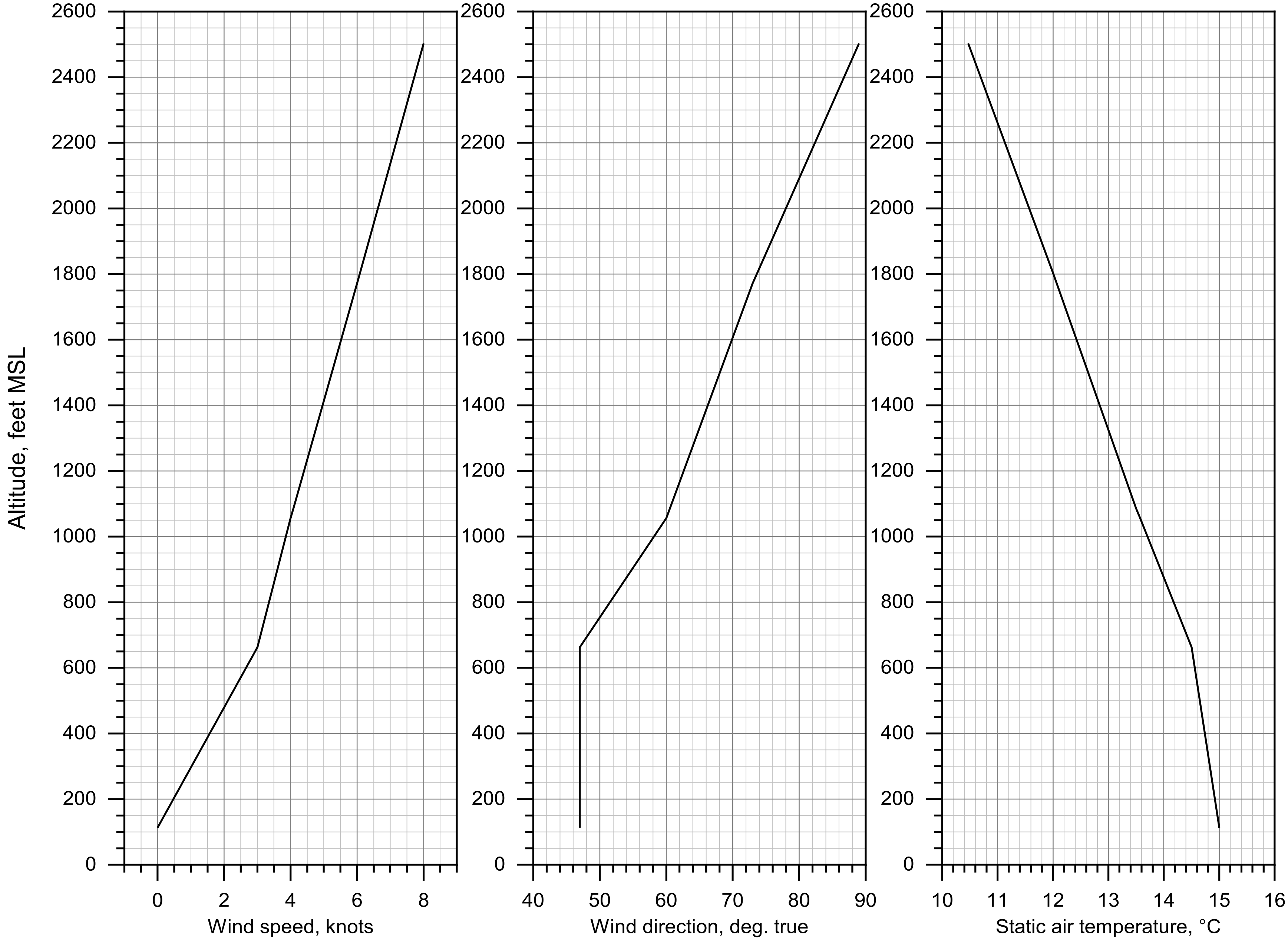


Figure 8.

ANC20LA074AB: Midair collision, Beaver N4982U / Piper N2587M, Solotna, AK, 7/31/2020

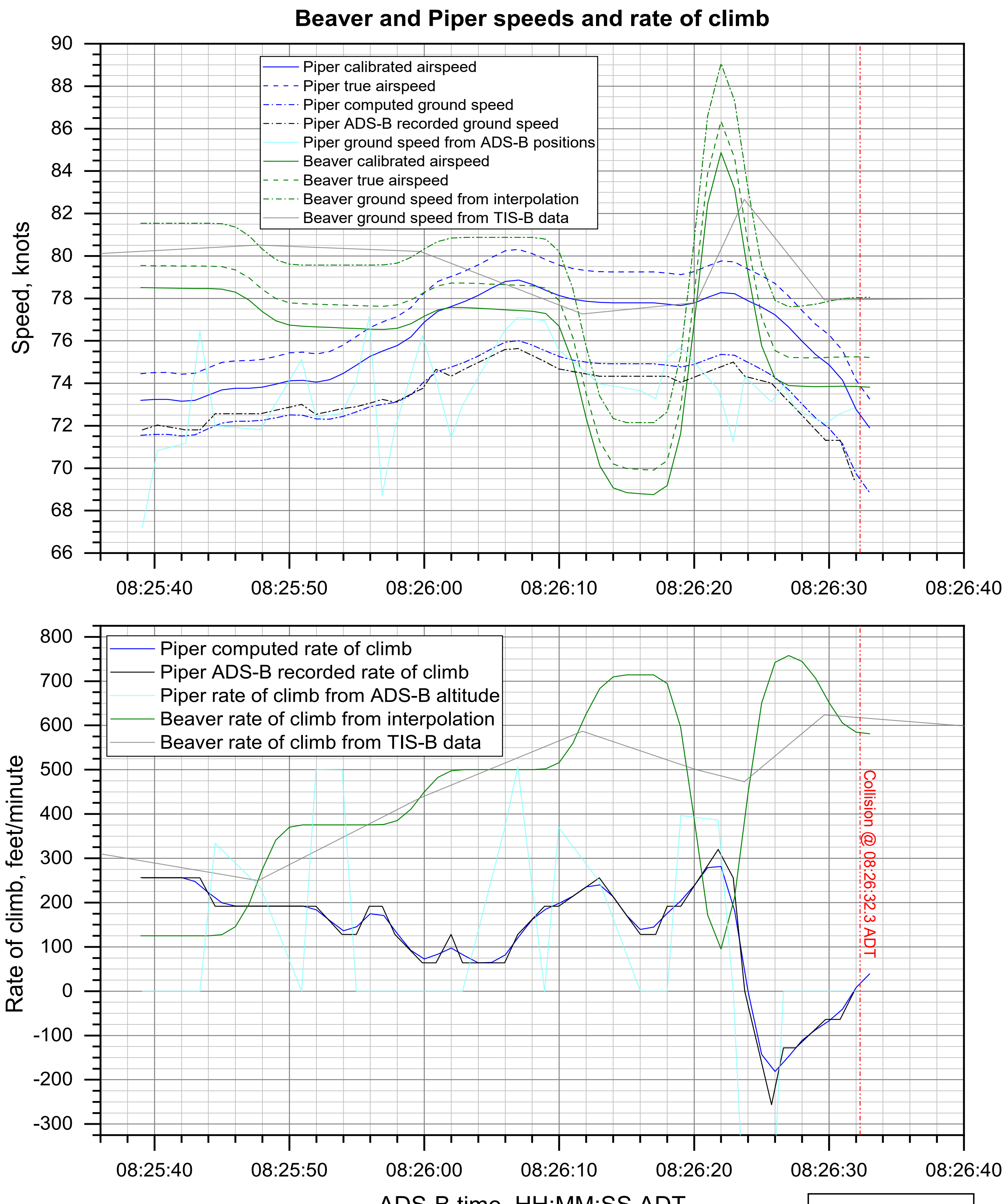


Figure 9.

ANC20LA074AB: Midair collision, Beaver N4982U / Piper N2587M, Solotna, AK, 7/31/2020

Beaver and Piper separation distance and closure rate

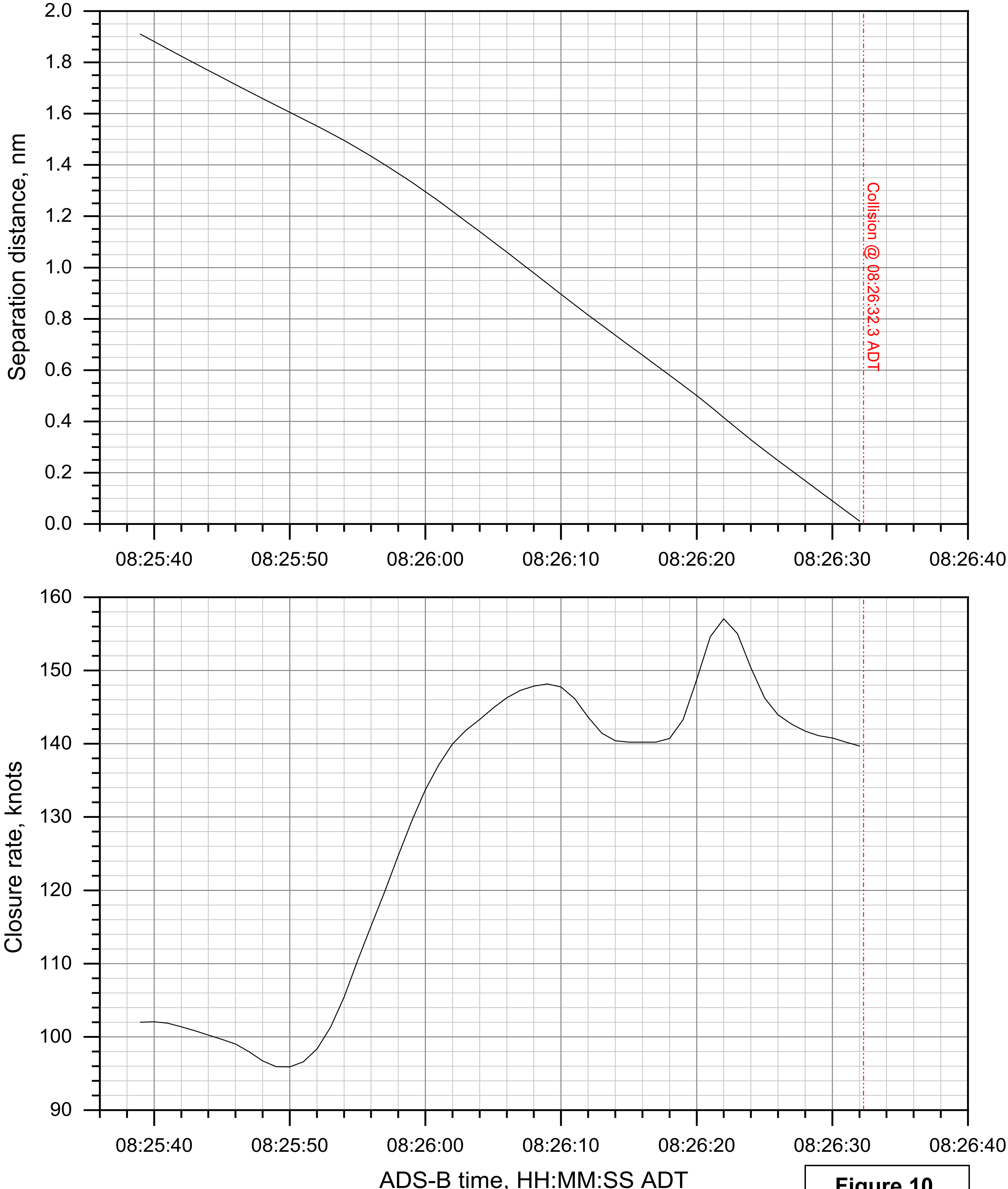


Figure 10.

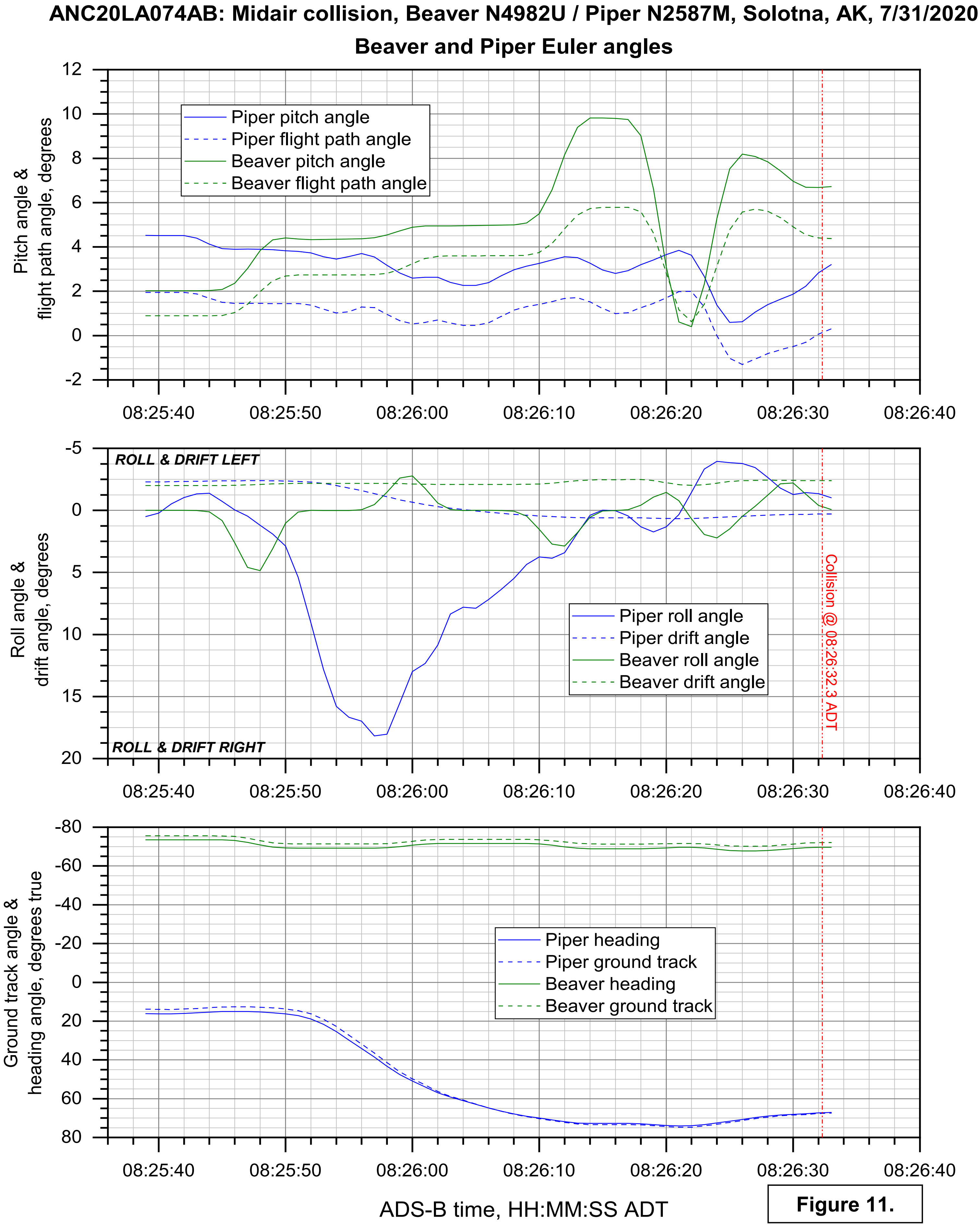
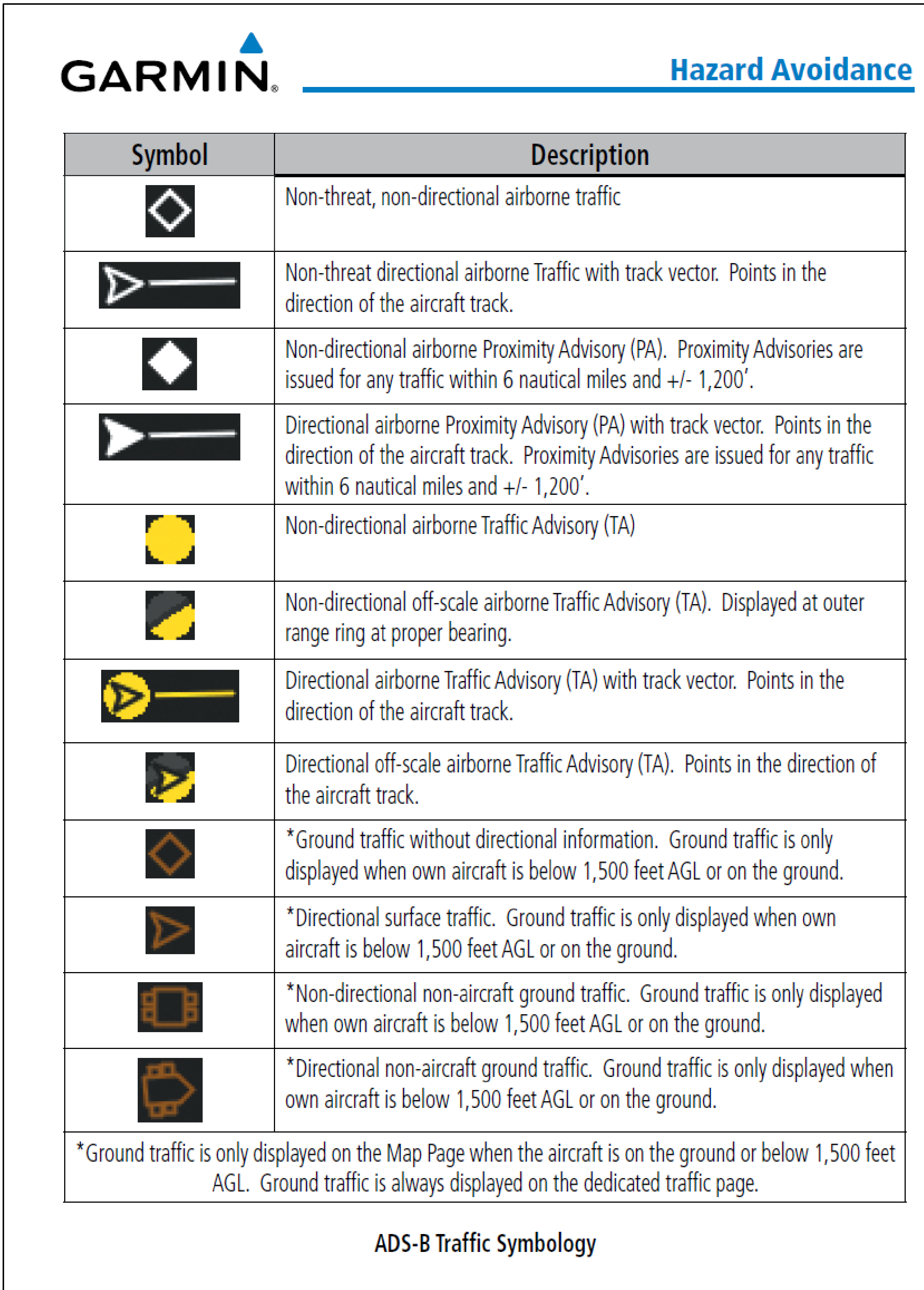

ANC20LA074AB: Midair collision, Beaver N4982U / Piper N2587M, Solotna, AK, 7/31/2020
Beaver and Piper Euler angles
Pitch angle &
flight path angle, degrees
Piper pitch angle
Piper flight path angle
Beaver pitch angle
Beaver flight path angle
Roll angle &
drift angle, degrees
ROLL & DRIFT LEFT
ROLL & DRIFT RIGHT
Piper roll angle
Piper drift angle
Beaver roll angle
Beaver drift angle
Collision @ 08:26:32.3 ADT
Ground track angle &
heading angle, degrees true
Piper heading
Piper ground track
Beaver heading
Beaver ground track
08:25:40
08:25:50
08:26:00
08:26:10
08:26:20
08:26:30
08:26:40
ADS-B time, HH:MM:SS ADT

Figure 11.



GARMIN — Hazard Avoidance

Symbol	Description
	Non-threat, non-directional airborne traffic
	Non-threat directional airborne Traffic with track vector. Points in the direction of the aircraft track.
	Non-directional airborne Proximity Advisory (PA). Proximity Advisories are issued for any traffic within 6 nautical miles and +/- 1,200′.
	Directional airborne Proximity Advisory (PA) with track vector. Points in the direction of the aircraft track. Proximity Advisories are issued for any traffic within 6 nautical miles and +/- 1,200′.
	Non-directional airborne Traffic Advisory (TA)
	Non-directional off-scale airborne Traffic Advisory (TA). Displayed at outer range ring at proper bearing.
	Directional airborne Traffic Advisory (TA) with track vector. Points in the direction of the aircraft track.
	Directional off-scale airborne Traffic Advisory (TA). Points in the direction of the aircraft track.
	*Ground traffic without directional information. Ground traffic is only displayed when own aircraft is below 1,500 feet AGL or on the ground.
	*Directional surface traffic. Ground traffic is only displayed when own aircraft is below 1,500 feet AGL or on the ground.
	*Non-directional non-aircraft ground traffic. Ground traffic is only displayed when own aircraft is below 1,500 feet AGL or on the ground.
	*Directional non-aircraft ground traffic. Ground traffic is only displayed when own aircraft is below 1,500 feet AGL or on the ground.

*Ground traffic is only displayed on the Map Page when the aircraft is on the ground or below 1,500 feet AGL. Ground traffic is always displayed on the dedicated traffic page.

ADS-B Traffic Symbology

Figure 12. Garmin G3X Touch ADS-B / TIS-B traffic symbology, from Reference 4.

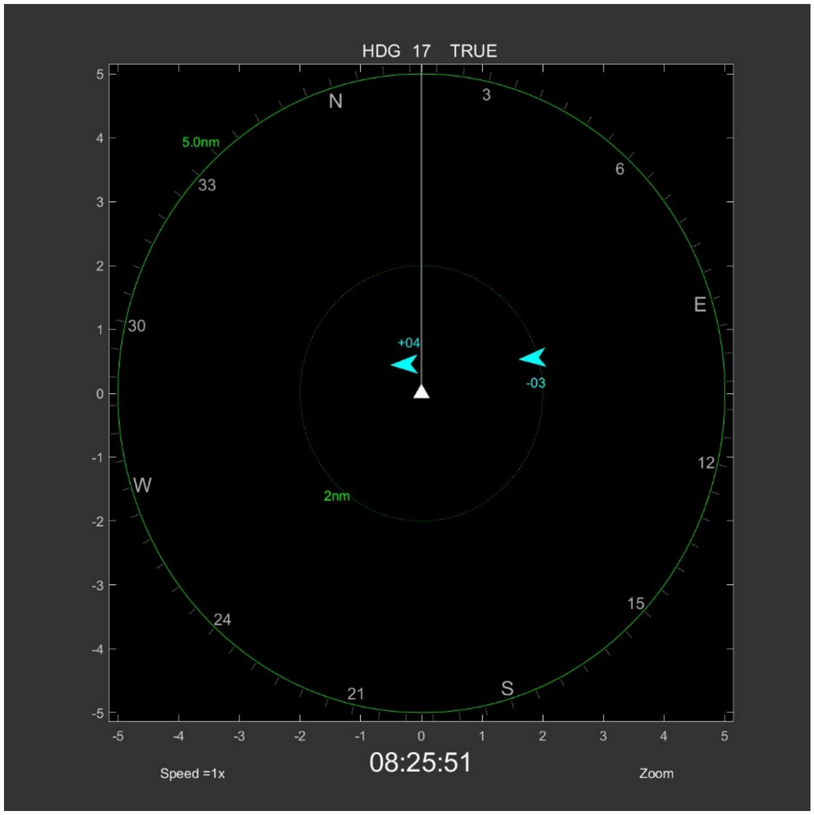


Figure 13(a). Simulated Piper CDTI at 08:25:51 (41.3 seconds before the collision).

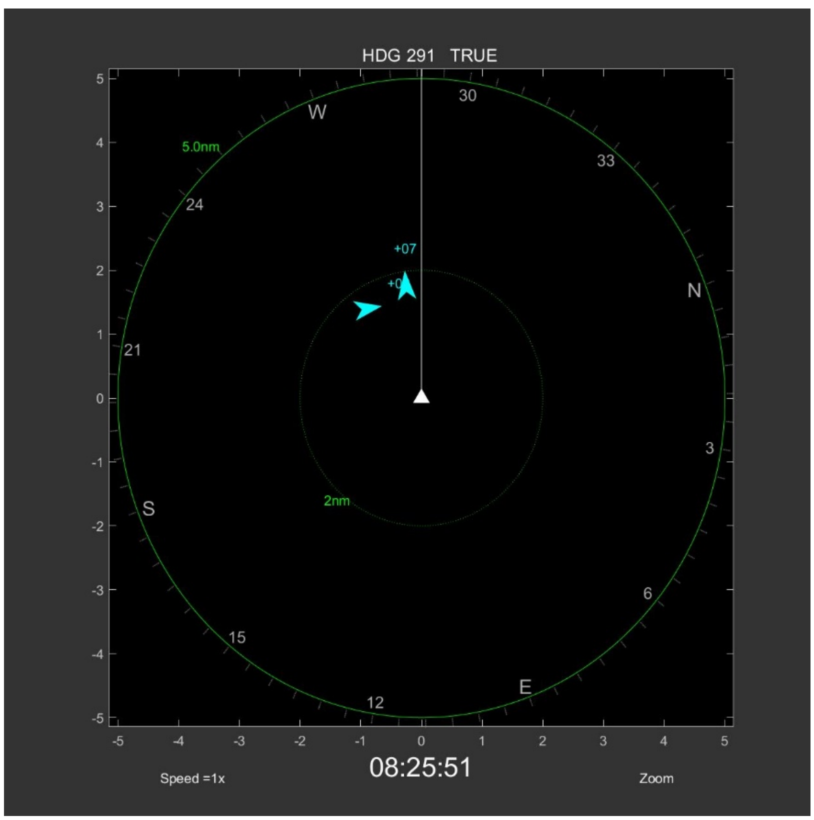


Figure 13(b). Simulated Beaver CDTI at 08:25:51 (41.3 seconds before the collision).

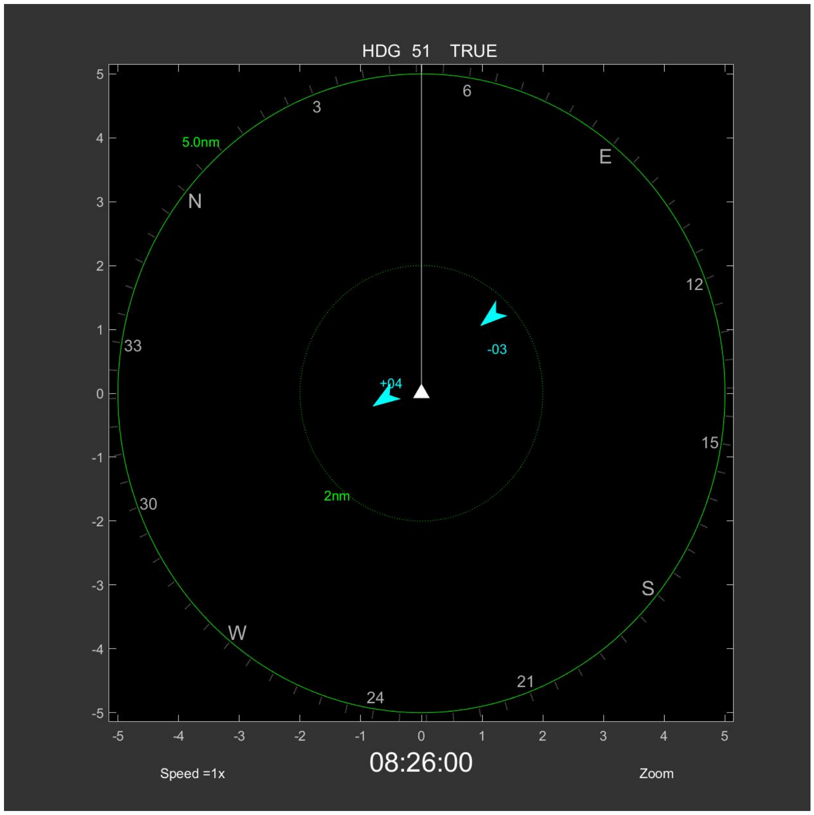


Figure 14(a). Simulated Piper CDTI at 08:26:00 (32.3 seconds before the collision).

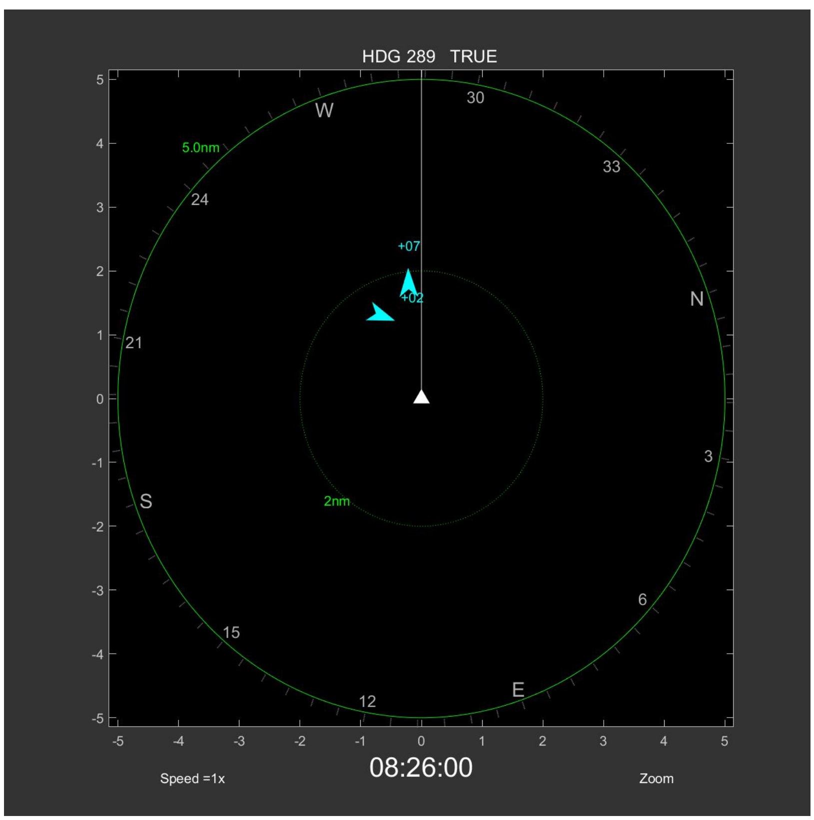
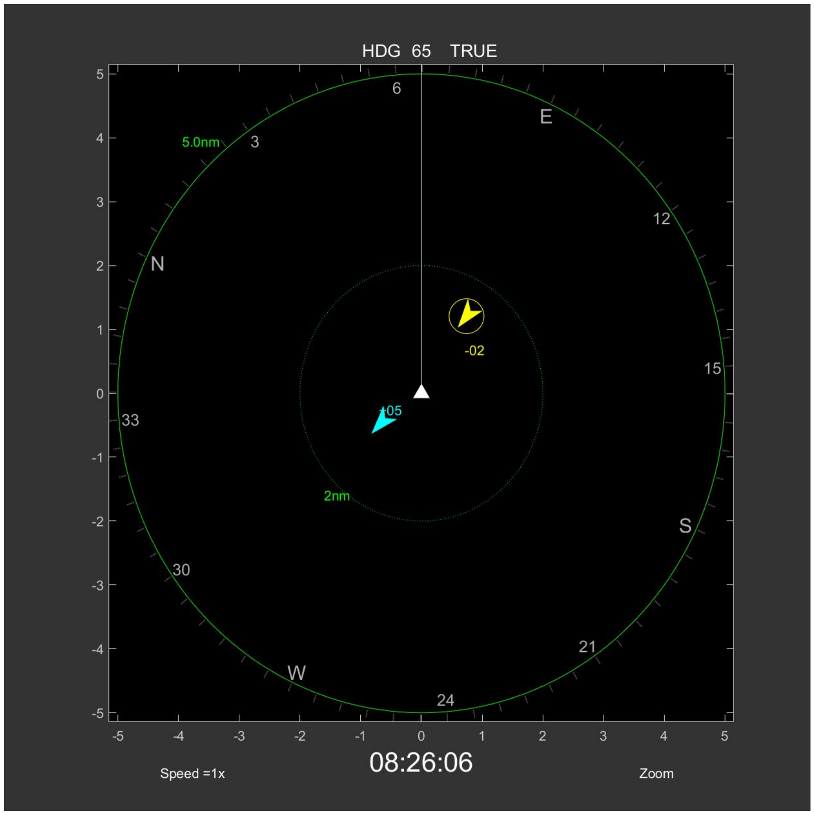
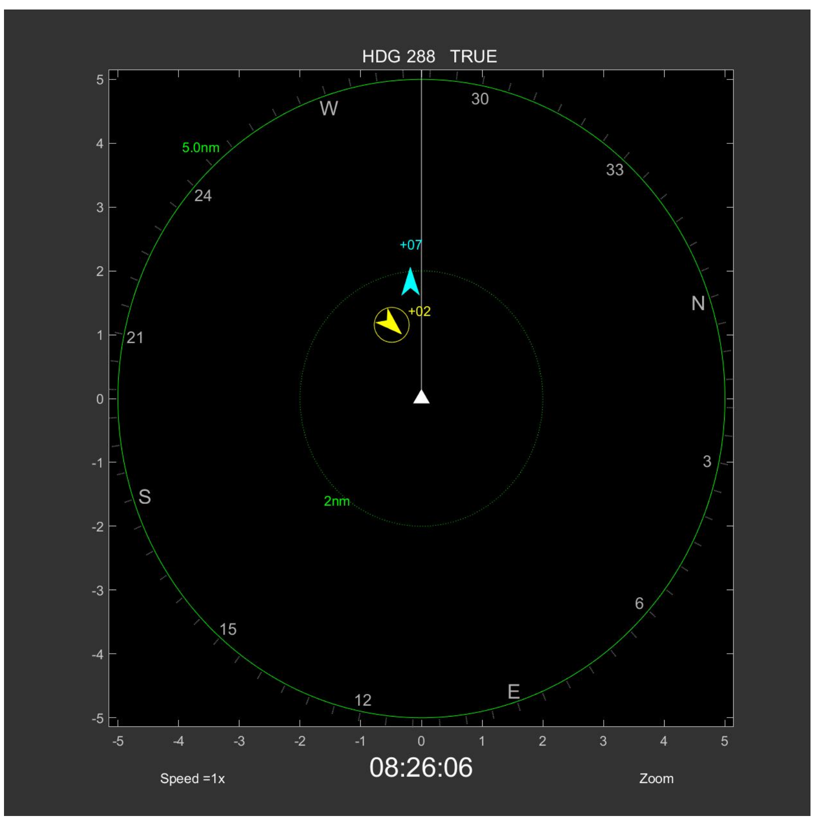


Figure 14(b). Simulated Beaver CDTI at 08:26:00 (32.3 seconds before the collision).



1st ATAS Alert:
Traffic,
1 o'clock,
same altitude,
1 mile.

Figure 15(a). Simulated Piper CDTI at 08:26:06 (26.3 seconds before the collision).



1st ATAS Alert:
Traffic,
11 o'clock,
same altitude,
less than 1 mile.

Figure 15(b). Simulated Beaver CDTI at 08:26:06 (26.3 seconds before the collision).

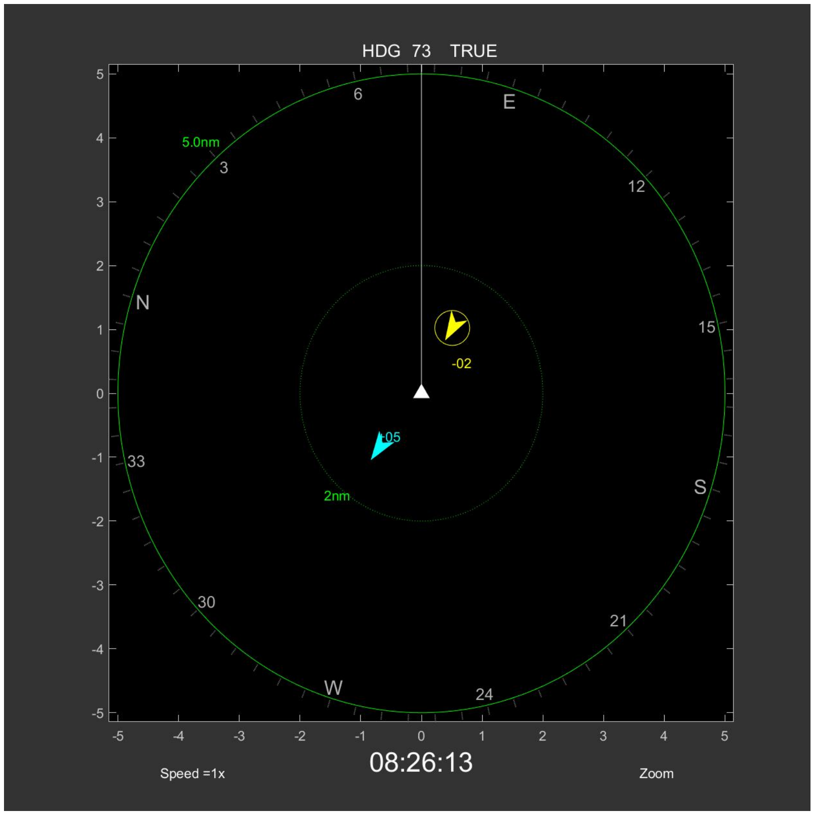
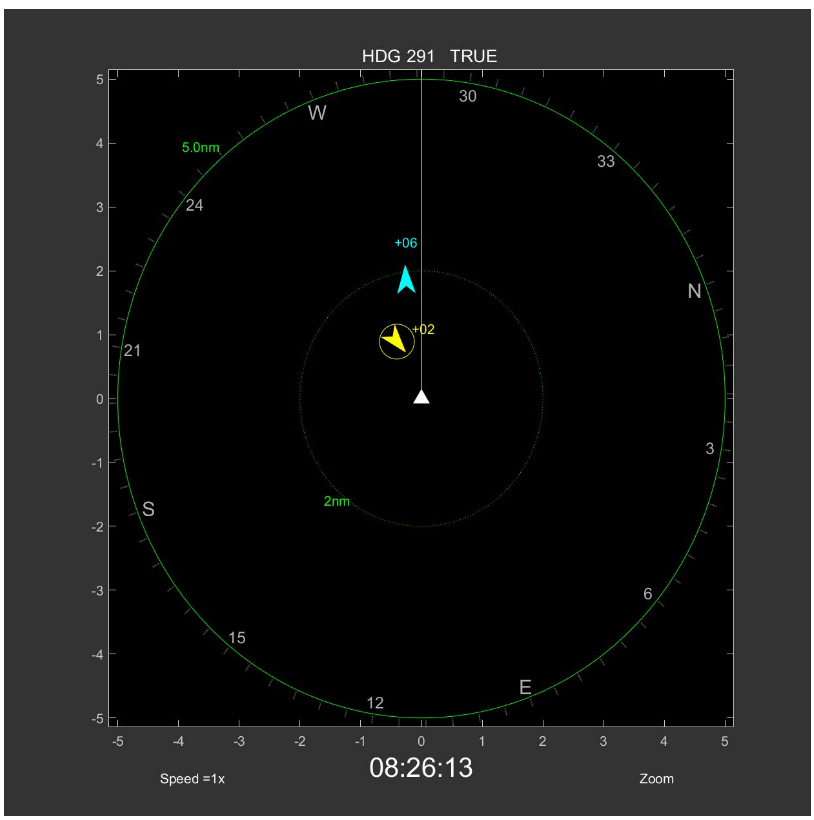
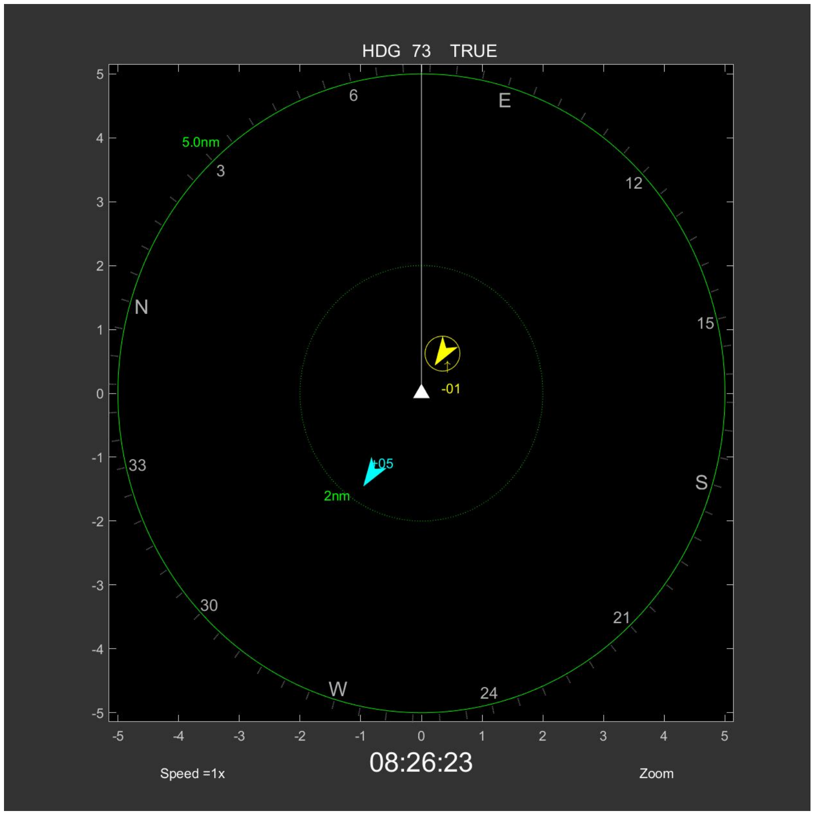


Figure 16(a). Simulated Piper CDTI at 08:26:13 (19.3 seconds before the collision).



2nd ATAS Alert:
Traffic,
11 o'clock,
same altitude,
less than 1 mile.

Figure 16(b). Simulated Beaver CDTI at 08:26:13 (19.3 seconds before the collision).



2nd ATAS Alert:
Traffic,
1 o'clock,
same altitude,
less than 1 mile,
climbing

Figure 17(a). Simulated Piper CDTI at 08:26:23 (9.3 seconds before the collision).

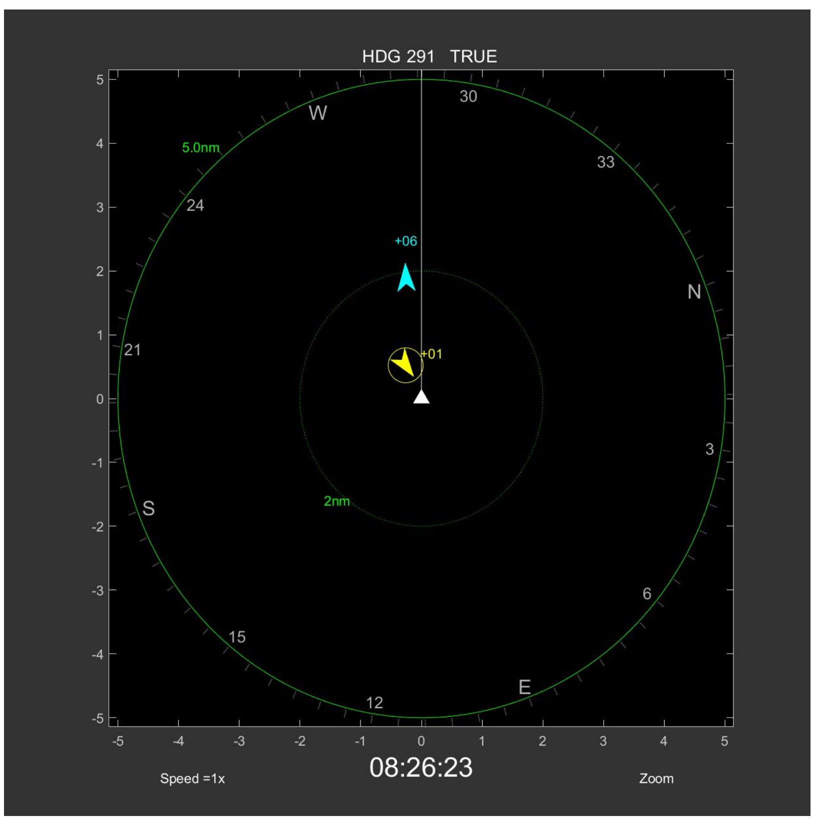


Figure 17(b). Simulated Beaver CDTI at 08:26:23 (9.3 seconds before the collision).