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AIRCRAFT PERFORMANCE & COCKPIT VISIBILITY STUDY

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A. ACCIDENT

Location: Longmont, Colorado
Date: September 17, 2022
Time: 08:53 Mountain Daylight Time (MDT)
14:53 Coordinated Universal Time (UTC)
Aircraft: Cessna 172S, registration N2117Y
Sonex Aircraft Xenos-B, registration N255BF

B. AIRCRAFT PERFORMANCE GROUP

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

Members: N/A

C. SUMMARY

On September 17, 2022, about 08:53 MDT, a Cessna 172S, N2117Y, and a Sonex Aircraft (Sonex) Xenos-B, N255BF, were destroyed when they were involved in a mid-air collision near Longmont, Colorado. The flight instructor and the student pilot aboard the Cessna and the pilot aboard the Sonex sustained fatal injuries. The Cessna was operated as a Title 14 *Code of Federal Regulations* (CFR) Part 91 instructional flight. The Sonex was operated as a Title 14 CFR Part 91 personal flight.

A review of air traffic control (ATC) flight track data revealed the Cessna departed Rocky Mountain Municipal Airport (KBJC), Denver, Colorado, about 08:43, and the Sonex departed Platte Valley Airpark (18V), Hudson, Colorado, about 08:38. The airplanes climbed to about 7,000-7,500 ft. above mean sea level (MSL) and were operating under visual flight rules (VFR).

The Cessna flew northbound and the Sonex flew westbound toward the Longmont area. After the Cessna completed a left 360° turn, it continued northbound and then turned eastbound shortly before the collision. The flight track data of the two airplanes merged and subsequently showed both airplanes rapidly descending. Fragmented sections of the outboard left wings of both airplanes were found in a field below the point where the two flight tracks merged.

Both airplanes impacted nose down in a rural area with a ground elevation of about 5,100 ft. MSL. The main wreckage site of the Cessna was in a field about 1,800 ft. southeast of the wing fragments. The main wreckage site of the Sonex was adjacent to a tree about 1,100 ft. southwest of the wing fragments.

At the time of the accident, both airplanes transmitted a transponder code of 1200 (VFR) and neither airplane was in radio contact, nor was required to be in contact with ATC. Both airplanes operated within the Mode-C veil of the Denver International Airport Class B airspace that required Automatic Dependent Surveillance – Broadcast (ADS-B) “Out” transmissions.

The Cessna was equipped with ADS-B “In/Out” equipment and transmitted ADS-B data during the accident flight. The Sonex did not transmit ADS-B data during the accident flight; ATC records indicated the Sonex last transmitted ADS-B data on July 14, 2022.

This *Aircraft Performance & Cockpit Visibility Study* presents the results of using recorded ADS-B data for the Cessna and Traffic Information Service – Broadcast (TIS-B) data for the Sonex to calculate the position and orientation of each airplane in the minutes preceding the collision. This information is then used to estimate the approximate location of each airplane in the other airplane pilot’s field of view (the “visibility study”), and to recreate the Cockpit Display of Traffic Information (CDTI) data that could have been presented to the pilots, considering the avionics installed on both airplanes. As described further in section D.4, 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, weather data, and other information used in this *Study*, and describe the methods used to calculate aircraft speeds, orientation (pitch, yaw and roll angles), CDTI information, and cockpit visibility from this data. The results of these calculations are presented in the Figures and Tables described throughout the *Study*.

D. DETAILS OF THE INVESTIGATION

D.1. The accident airplanes

D.1.1. The Cessna 172S Skyhawk (C172S)

The C172S is a single-engine, four-seat high-wing airplane with a conventional tail, powered by a 180 SHP Lycoming IO-360-L2A reciprocating engine, with a maximum gross weight of 2,550 lb. Per FAA registration records, N2117Y was manufactured in 2004. Figure 1 is a pre-accident photograph of N2117Y, and Figure 2 shows a 3-view diagram of the C172S, taken from Reference 1. Table 1 lists some dimensions of the airplane, as well as the estimated weight of N2117Y at the time of the accident (2,364 lb.) provided by the Cessna operator (Spartan Education, LLC).

Item	Value
<i>Reference dimensions (from References 1 & 2):</i>	
Wing area	175.5 ft. ² (from Reference 2)
Wing span	36 ft. - 1" (see Figure 2)
<i>Mass properties for N2117Y:</i>	
Gross weight at time of accident	2,364 lb. (estimate provided by Operator)

Table 1. Relevant geometry and gross weight for Cessna N2117Y.

Aerodynamic information for the C172 (specifically, the lift coefficient (C_L) as a function of angle of attack (α)) was provided to the NTSB by Textron Aviation (Textron) during a previous investigation. This information is used along with the wing area and weight shown in Table 1 to estimate N2117Y's pitch and roll angles from ADS-B data (see section D.2.4).

The geometry of an exemplar C172 owned by an NTSB employee was measured with a laser scanner in support of the cockpit visibility study described in section D.3 and Appendix A.

D.1.2. The Sonex Xenos-B

The Sonex Xenos-B is a single-engine, V-tail, two-seat, low-wing motorglider / light sport homebuilt airplane that can be powered using several engine options. N255BF was equipped with an AeroVee 2.1 80 HP engine, and was painted white with red and black trim. An internet search did not yield any pre-accident photographs of N255BF, but Figure 3 is a photograph of an exemplar Xenos-B. A 3-view diagram of the Xenos-B provided by Sonex is presented in Figure 4. Table 2 lists some dimensions of the airplane, as well as the estimated weight of N255BF at the time of the accident (1,225 lb.) provided by the NTSB Investigator In Charge (IIC).

Item	Value
<i>Reference dimensions (see Figure 4):</i>	
Wing area	158 ft. ²
Wing span	45 ft. - 7.5"
<i>Mass properties for N255BF:</i>	
Gross weight at time of accident	1,225 lb. (estimate provided by IIC)

Table 2. Relevant geometry and gross weight for Sonex N255BF.

The lift curve (C_L vs. α) of the Xenos-B is estimated using the geometry of the airplane and textbook methods, and assuming that the airplane's pitch attitude is 0° at a speed of 120 mph (104 KTAS). The result is used together with the wing area and weight shown in Table 2 to estimate N255BF's pitch and roll angles from TIS-B data.

The Sonex Waix airplane has a cockpit geometry identical to that of the Xenos. An exemplar Waix provided by Sonex was surveyed with a laser scanner in support of the cockpit visibility study described in section D.3 and Appendix A.

D.2. Recorded ADS-B and TIS-B data for Cessna N2117Y and Sonex N255BF

Both airplanes involved in the midair collision were equipped with ADS-B equipment. As noted above, the Cessna was transmitting ADS-B data at the time of the accident, but the Sonex was not transmitting ADS-B data; the last ADS-B transmissions from the Sonex were recorded on July 14, 2022. However, the Sonex was tracked by FAA surveillance radar, and the radar returns from the Sonex were broadcast to ADS-B equipped aircraft (including the Cessna) as TIS-B targets. TIS-B is described in further detail below.

“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. Traffic messages concerning non-ADS-B equipped aircraft within FAA radar coverage are broadcast to ADS-B equipped aircraft through TIS-B (which is an ADS-B function). The ADS-B and TIS-B messages concerning the accident airplanes were used in the performance and cockpit visibility calculations presented in this *Study*.

Section D.4 of this *Study* presents recreations of the traffic information that could have been presented on the CDTI displays of the accident airplanes, given the installed and portable electronic devices available to each pilot. 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.

D.2.1. Introduction to the ADS-B system

According to a 2007 “Fact Sheet” published by the FAA,¹ 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 by establishing their positions using Global Navigation Satellite System (GNSS) instead of by ground radar.² This GNSS-based surveillance is enabled through the “Automatic Dependent Surveillance - Broadcast” (ADS-B) system. As described in the FAA fact sheet,

¹ See: http://web.archive.org/web/20150403151639/http://www.faa.gov/news/fact_sheets/news_story.cfm?newsid=8145

² The GNSS system includes the Global Positioning System (GPS) constellation of satellites.

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).

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 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 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, recreations of the traffic information that *could* have been presented on the CDTI displays available to the Cessna and the Sonex pilots were produced using recorded ADS-B and TIS-B traffic data provided by the FAA. Both the Cessna and the Sonex pilots had ADS-B In-based CDTI visual displays available to them (described in section D.4). However, the ADS-B system on the Sonex was not configured properly, and therefore did not broadcast any ADS-B Out information, and was likely incapable of displaying any ADS-B In information. Nonetheless, the Sonex was detected by FAA surface radar³, and so traffic information corresponding to the Sonex should have been broadcast to ADS-B In aircraft (including the Cessna) as TIS-B targets, and been available for display on each aircraft’s CDTI.⁴

The Cessna pilots were using the *ForeFlight* application running on a portable Apple iPad device, and likely received visual alerts and aural annunciations of traffic based on traffic proximity criteria applied by *ForeFlight*, which differ from the criteria used in the ATAS application.

The Sonex was equipped with a Garmin GNS 430W panel-mounted GNSS receiver, but as described in Reference 3, post-accident examination of this device indicated that its ARINC 429 and RS-232 channels were configured to “Off,” and so the airplane could not broadcast ADS-B information. It is also likely that the Sonex pilot would not have had any ADS-B In traffic information available to him on his CDTI.

The CDTI recreations, and the traffic display and alerting capabilities of the equipment available to each pilot, are described further in section D.4.

³ The NTSB asked the FAA for the original data from all the radar sites that tracked the Sonex (and that contributed to the construction of the TIS-B reports concerning the Sonex that were broadcast to all ADS-B In equipped aircraft). However, the NTSB’s request was made after the retention period for such radar data had expired, and so the data was no longer available. Only the resulting TIS-B reports for the Sonex were available for consideration in this *Study*.

⁴ NTSB staff requested that the FAA confirm that information regarding the Sonex would have been available to ADS-B In-equipped aircraft as TIS-B targets, but as of the publication of this *Study* the FAA has not responded.

D.2.2. Recorded ADS-B data provided by the FAA

The FAA provided the NTSB with recorded ADS-B and TIS-B data within a 25 nm radius of Vance Brand Airport, Longmont, Colorado (KLMO), and below 12,000 ft., from 14:30 UTC to 15:00 UTC (08:30 to 09:00 MDT). This information was used to determine the tracks of the Cessna and Sonex prior to the accident, and to recreate the traffic that could have been presented on each airplane's CDTI display (these recreations are discussed in section D.4). The ADS-B data file provided by the FAA is available on the NTSB public docket for this accident.

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

- UTC time of the report, in hours, minutes, and seconds. MDT = UTC - 6 hours.
- Aircraft identifying information (in a parameter called "ModeSId").
- Latitude and longitude, to a resolution of 0.01 arc-seconds (≈ 1 ft.) For the Cessna, these positions are GNSS-based (ADS-B data); for the Sonex, they are radar-based (TIS-B data).
- Pressure altitude in feet, to the nearest 25 ft. (an uncertainty band of ± 12.5 ft.)
- For the Cessna only (ADS-B data): GNSS-based geometric altitude, to the nearest 25 ft. (an uncertainty band of ± 12.5 ft.) The GNSS altitude is the height above the WGS84 ellipsoid, which differs from MSL altitude by the height of the geoid.⁵ At the accident site, MSL altitude is 56 ft. above GNSS altitude.⁶
- North-south and east-west components of ground speed, to a resolution of 1 kt., as reported in the ADS-B messages 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 messages from the aircraft (for ADS-B reports) or determined from radar tracking algorithms (for TIS-B reports).
- For the Cessna, numerous parameters documenting the source and quality of each reported GNSS position.

The sample rate of the GNSS-based ADS-B data for the Cessna is about 1 sample per second (1 Hz). The sample rate of the radar-based TIS-B data for the Sonex is about 1 sample every 4.6 seconds (0.22 Hz). The sample rates of the data for each aircraft can be gleaned from Figures 6 and 7.

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

⁶ Per <https://geographiclib.sourceforge.io/cgi-bin/GeoidEval>, the geoid at the accident site is about 17 m (56 ft.) below the surface of the WGS84 ellipsoid.

D.2.3. Presentation of the ADS-B and TIS-B data

To calculate performance parameters from the surveillance 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. The Cartesian coordinate system used in this *Study* is centered on the collision location, and its axes extend east, north, and up from the center of the Earth. The collision location is defined by the point where the recorded longitude coordinates of the airplanes coincide, and by the latitude and altitude coordinates of the Cessna at that time:

40° 06' 10.15" N / 105° 07' 21.83" W / 6,939 ft. MSL

The surveillance data from the Cessna and Sonex are converted into this coordinate system using the WGS84 ellipsoid model of the Earth.

Figure 5 presents this information for the accident airplanes, plotted in terms of nautical miles north and east of the collision point.⁷ Figure 5c presents the flight tracks overlaid on a VFR sectional Chart image 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 Sonex and the ADS-B data for the Cessna 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 (the airplanes must be in the same place and at the same 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 (08:53:01.6 MST).

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 "Smoothed Cessna track" and "Sonex track from integrated TIS-B ground speed" in Figure 5 (hereafter referred to as the "smooth tracks"). Note that the Sonex track just described is used only for performance calculations (of speeds and flight angles), whereas the reported TIS-B positions depicted by the dashed-blue line in Figure 5 labeled "Sonex TIS-B shifted north to force collision" are used for the Cockpit Visibility Study described in section D.3. The smooth track (solid blue line in Figure 5) provides a less-noisy and relatively accurate calculation of performance parameters,

⁷ 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.

whereas the shifted TIS-B positions are better measures of the absolute location of the airplane for calculating the relative positions of the Cessna and the Sonex (which strongly affect the visibility of one airplane from the other).

D.2.4. Estimates of airplane performance based on ADS-B and TIS-B data

The ADS-B positions for the Cessna are GNSS-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 Sonex are radar-based and have much greater uncertainty and error than the GNSS-based ADS-B positions for the Cessna. However, the larger time interval between radar samples (4.6 seconds) tends to reduce the noise in the computed groundspeed. The effect of the 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 almost five 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 Cessna. These speed components are very smooth and can be combined to produce a smooth total ground speed. In general, when the ground speed components recorded in ADS-B files are integrated over time, the resulting positions generally match the recorded ADS-B positions very well. However, in this case, the airplane positions obtained by integrating the ground speed components recorded in the Cessna’s ADS-B data do not match the recorded GNSS positions well enough to be used to compute additional parameters. Consequently, to obtain relatively smooth ground speeds that are more consistent with the ADS-B position data, a running-average smoothing algorithm is used to smooth the Cessna ADS-B east and north positions before their time derivatives are computed as the corresponding components of ground speed. A similar running-average approach is used to smooth the Cessna ADS-B geometric

altitude. The smoothed altitude lies within the recorded geometric altitude uncertainty bands (see Figure 7). The smoothed positions and altitude are used as the basis for ground speed and other performance calculations, as described below.

For the Sonex performance calculations, the positions obtained from integrating the ground speeds recorded in the TIS-B data do not match the corresponding TIS-B positions perfectly, as shown in Figure 5; however, the shapes of the integrated and recorded tracks are similar enough that the additional performance parameters computed from the integrated track are representative of those that would be computed from the recorded track, but smoother.

The Cockpit Visibility Study described in section D.3 requires that the Cessna and Sonex track data be defined at common time points. Since the Cessna data is recorded at a higher sample rate, its sample times are used as the basis for the Visibility Study, and the Sonex ground speed components are interpolated using cubic splines to this time basis before being integrated to yield the Sonex track. Consequently, the additional performance parameters computed from the integrated track are also defined at the sample times of the Cessna ADS-B data.

Note in Figures 5 and 6 that the Sonex TIS-B positions lie about 0.06 nm (365 ft.) south of the Cessna ADS-B returns at the time that the two airplanes share the same east (longitude) coordinate, and so are not consistent with a collision with the Cessna at that time (the reason for this offset is unknown). Consequently, for this *Study* the Sonex TIS-B positions are shifted to the north so as to intersect the Cessna ADS-B trajectory at the time both airplanes share the same longitude coordinate, which is assumed to correspond to the collision time. 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 Cessna includes pressure altitude, measured barometrically, and geometric altitude, measured by GNSS. The TIS-B data for the Sonex includes only pressure altitude (barometric altitude based on an altimeter setting of 29.92 "Hg.) These altitudes are plotted in Figure 7. The Sonex geometric altitude is obtained by raising the Sonex pressure altitude upwards to match the recorded Cessna geometric altitude at the collision time. The altitudes used in the performance calculations are depicted by the curves labeled "Cessna smoothed altitude" and "Sonex altitude shifted to force collision" in Figure 7.

Once the position (latitude, longitude, and altitude) of an airplane is known as a function of time, its orientation (i.e., the Euler angles: pitch, roll, and heading) 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., the flight is coordinated).

In this *Study*, the winds aloft are based on a High Resolution – Rapid Refresh (HRRR) model sounding for 09:00 MDT over the accident site, obtained from a National Oceanographic and Atmospheric Administration (NOAA) website.⁸ The wind speed, wind direction, and air temperature as a function of altitude from this model are plotted in Figure 8. The 08:55 MDT Aviation Routine Weather Report (METAR) for KLMO (5 nm north of the collision point) stated: wind calm, visibility 7 statute miles, sky clear, temperature 20° C, dew point 8° C, altimeter 30.05 "Hg.

As noted above, this *Study* uses aerodynamic properties for the Cessna provided by Textron during a previous investigation. The aerodynamic properties for the Sonex are estimated based on textbook methods. Gross weights of 2,364 lb. and 1,225 lb. are assumed for the Cessna and Sonex, respectively (see Tables 1 and 2). The flaps for both airplanes are assumed to be retracted.

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 performance calculations for each airplane are presented below.

D.2.5. Estimated collision time, location, and geometry

The solid black and blue lines in Figures 5-7 depicting the flight tracks of the Cessna and Sonex, respectively, are consistent with the ADS-B and TIS-B data for these airplanes, and with the constraints noted above. As shown in Figure 6, the east coordinates of the airplanes coincide at 08:53:01.6. The surveillance data for each airplane continue past this point for a few returns (the Cessna moving east and the Sonex moving west), and each track ends near its corresponding wreckage location. The wreckage locations and flight tracks plotted in Figure 5 suggest that after the collision, both airplanes quickly descended to the ground roughly along their original tracks while continuing to broadcast ADS-B information (for the Cessna) and respond to transponder interrogation signals (for the Sonex).

⁸ See <https://www.ready.noaa.gov/READYamet.php>.

Regarding the wreckage of the airplanes, the preliminary report of the accident (Reference 4) states:

Both airplanes impacted nose down in a rural area with a ground elevation of about 5,100 ft. MSL. The main wreckage site of the Cessna was in a field about 1,800 ft southeast of the wing fragments. The main wreckage site of the Sonex was adjacent to a tree about 1,100 ft southwest of the wing fragments.

The groundspeeds and track angles of the Cessna and Sonex corresponding to the tracks shown in Figures 5-7 indicate that at the time of the collision, the velocity vector of the Cessna *relative to the Sonex* was 189 kt. along a heading of 108° . Since the Sonex's heading was about 271° at the time of collision, the Cessna would have been moving at an angle of $108^\circ - 271^\circ = -163^\circ = +197^\circ$ relative to the Sonex's centerline. The smaller angle between the centerline and a line drawn 197° to the centerline is $197^\circ - 180^\circ = 17^\circ$; the Cessna would have cut across the Sonex's centerline from forward right to aft left at an angle 17° to the centerline. Similarly, the velocity vector of the Sonex *relative to the Cessna* was 189 kt. along a heading of 288° . Since the Cessna's heading was about 119° at the time of collision, the Sonex would have been moving at an angle of $288^\circ - 119^\circ = 169^\circ$ relative to the Cessna's centerline. The smaller angle between the centerline and a line drawn 169° to the centerline is $180^\circ - 169^\circ = 11^\circ$; the Sonex would have cut across the Cessna's centerline from forward left to aft right at an angle 11° to the centerline.

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

Time of collision = 08:53:01.6 MDT

Latitude = $40^\circ 06' 10.15''$ N

Longitude = $105^\circ 07' 21.83''$ W

Altitude = 6,939 ft. MSL

The north and east positions of the Cessna and the Sonex are presented as a function of time in Figure 6. This Figure presents the Cessna ADS-B data, the Sonex TIS-B data, the shifted Sonex data, and the smoothed tracks (shown as solid lines) used for the performance calculations.

The altitudes of the Cessna and the Sonex are presented as a function of time in Figure 7. The barometric pressure altitudes recorded in the ADS-B and TIS-B data are presented, as well as the Cessna ADS-B geometric altitude, the smoothed Cessna geometric altitude, and the Sonex pressure altitude shifted to match the Cessna geometric altitude at the time of the collision. The rates of climb and other performance calculations for the airplanes are based on these latter two altitudes (depicted by the solid black and blue lines in Figure 7).

Figure 9 shows the true airspeed, calibrated airspeed, groundspeed, and rate of climb calculated from the smooth trajectories for the Cessna and the Sonex, as well as the vertical speeds recorded in the Cessna ADS-B data and Sonex TIS-B data. Figure 9 indicates that at the time of the collision, the Cessna's groundspeed was about 105 knots, and the Sonex's groundspeed was about 85 knots. The Cessna "ADS-B recorded ground speed" is the ground speed computed from the north and east velocity components recorded in the Cessna's ADS-B data. The Cessna "ground speed from smoothed track" differs significantly from this recorded ground speed near the time of collision; the Cessna's maneuvering (a descending right turn) during this time might be part of the reason for this (the north and east speed components are likely filtered or otherwise smoothed by the avionics that compute them). The Sonex "TIS-B recorded ground speed" is also smoothed (by the radar processing algorithms), but better matches the computed "ground speed from raw TIS-B positions" (likely because the Sonex is not maneuvering very much). The Sonex computed ground speed exhibits more variations than the recorded data, which can be the result of both uncertainty in the TIS-B positions (that introduces spurious "spikes" in the computed speed) and the smoothing of the recorded data (that can suppress real variations in ground speed).

Figure 10 shows the separation distance between the two airplanes and the closure rate. The Figure indicates that the closure rate was about 195 knots at the time of the collision.⁹

Figure 11 presents the pitch, flight path, roll, heading, and ground track angles calculated from the smooth tracks for the Cessna and the Sonex. The Cessna's track angle at the time of the collision was about 115°, and the Sonex's track angle was about 279°. Therefore, the collision angle (the smallest angle between the ground tracks of the aircraft at the time of impact)¹⁰ is about 16° ($115^\circ - 279^\circ + 180^\circ$), with the Cessna approaching the Sonex from ahead and to the right, and the Sonex approaching the Cessna from ahead and to the left (see Figure 5).

Figures 5-11 indicate that in the three and a half minutes before the collision, the Cessna was flying south to north when it made an approximately level 360° left turn at about 7,500 ft. MSL centered about 2 nm southwest of the collision point. The Cessna exited the turn and continued north-northeast, and at 08:52:10 started to descend from 7,500 ft. at an average rate of about 650 ft./min., with peak descent rates of up to

⁹ Theoretically, the closure rate should exactly match the relative speed between the airplanes at the collision, which is 189 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.

¹⁰ 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.

2,250 ft./min. At about 08:52:32, while still descending, the Cessna turned right from a track of about 15° (true) to a track of about 55°. At 08:52:50 the Cessna rolled right to a peak roll angle of about 35°. At the time of the collision at 08:53:01.6, the Cessna had rolled back to about 5° (right) onto a track of about 115°.

Between 08:48:50 and 08:51:20, the Sonex flew approximately straight-and-level at an altitude of about 7,040 ft. on a track between 273° and 279°. At 08:51:20, the Sonex turned 12° right to a track of 291°, and at 08:52:15 its track started to drift slowly back to the left, reaching 279° at the time of the collision. At about 08:52:00 the altitude of the Sonex decreased 100 ft. from 7,040 ft. to the collision altitude of 6,940 ft. MSL.

D.3. Cockpit visibility study

D.3.1. Azimuth and elevation visibility angles

Once the position and orientation of each airplane has been determined, its position in the body axis system of the other airplane can be calculated. These relative positions then determine where the “target” aircraft will appear in the field of view of the pilot of the “viewer” aircraft.

For this *Study*, the relative positions of the two airplanes (and the visibility of each from the other) were calculated at 1-second intervals up to the collision, beginning at 08:48:00 (about 5 minutes before the collision), when the Sonex was about 8.8 nm east of the Cessna.

The “visibility angles” from the “viewer” airplane to the “target” airplane correspond to the angular coordinates of the line of sight between the airplanes, measured in a coordinate system fixed to the viewer airplane (the viewer’s “body axis” system), and consist of the azimuth angle and elevation angle (see Figure 12). The azimuth angle is the angle between the x -axis and the projection of the line of sight onto the x - y plane. The elevation angle is the angle between the line of sight itself, and its projection onto the x - y plane. At 0° elevation, 0° azimuth is straight ahead, and positive azimuth angles are to the right. 90° azimuth would be out the right window parallel to the y axis of the airplane. At 0° azimuth, 0° elevation is straight ahead, and positive elevation angles are up. 90° elevation would be straight up parallel to the z axis. The azimuth and elevation angles depend on both the position (east, north, and altitude coordinates) of the viewer and target airplanes, and the orientation (yaw, pitch, and bank angles) of the viewer. The azimuth and elevation angles of points on the target away from its center of gravity (CG) also depend on the orientation of the target.

The position, altitude, and orientation of the Cessna and the Sonex are based on smoothed and interpolated ADS-B / TIS-B data, and so are sensitive to different ways of smoothing the data, and the possibility of multiple, slightly differing trajectories and Euler angles that all result in solutions within the uncertainty bounds of the data.

Consequently, there is also some uncertainty in the visibility angles associated with any particular trajectory. The effects of these uncertainties on the visibility of each airplane from the other are considered below.

D.3.2. Azimuth and elevation angles of airplane structures from laser scans

The target airplane will be visible from the viewer airplane unless a non-transparent part of the viewer's structure lies in the line of sight between the two airplanes. To determine if this is the case, the azimuth and elevation coordinates of the boundaries of the viewer's transparent structures (windows) must be known, as well as the coordinates of the viewer's structure visible from the cockpit (such as the wings, nose, and wing struts). If the line of sight passes through a non-transparent structure (such as the instrument panel, a window post, or a wing), then the target airplane will be obscured from the viewer.

For this *Study*, the azimuth and elevation angles of the windows and structures of the Cessna and the Sonex were determined from the interior and exterior dimensions of exemplar airplanes, as measured using a FARO laser scanner.¹¹ The laser scanner produces a "point cloud" generated by the reflection of laser light off objects in the laser's path, as the scanner sweeps through 360° of azimuth and approximately 150° of elevation. The 3-dimensional coordinates of each point in the cloud are known, and the coordinates of points from multiple scans (resulting from placing the scanner in different positions) are "merged" by the scanner software¹² into a common coordinate system. By placing the scanner in enough locations so that the scanner can "see" every part of the airplane, the complete exterior and interior geometry of the airplane can be defined.

For this *Study*, the scanner was placed in several locations to scan the exterior of the airplanes, and in the pilot seats to scan the interior of the airplanes. The scanner software was then used to identify the points defining the outline of the cockpit windows (from the interior scans) and exterior structures visible from the cockpit (from the exterior scans). The coordinates were transformed into the airplane's body axis system and, ultimately, into azimuth and elevation angles from the pilot's eye position. The transformation method is described in Appendix A.

The azimuth and elevation angles of the viewer airplane's windows and other structures are very sensitive to the pilot's eye location in the cockpit. If the pilot moves his head forward or aft, or from a position centered over his seat to one close to a window surface, the view out the window (and the azimuth and elevation angles of all the airplane's structures) change significantly. This potential variability in the pilot's eye

¹¹ Specifically, the FARO "Focus 3D" scanner; see <https://www.faro.com/en/Products/Hardware/Focus-Laser-Scanners>.

¹² FARO SCENE software: see <https://www.faro.com/en/Products/Software/SCENE-Software>.

position, and the consequent variability in the location of the window edges and airplane structures in the pilot's field of view, is by far the greatest source of uncertainty as to whether the target aircraft is obscured or not at a given time.

To evaluate the effect of varying eye position on the visibility of the target airplane, the azimuth and elevation angles of the cockpit windows and other airplane structures were computed for a matrix of eye positions displaced from the nominal eye positions, as described below. The pilots' "nominal" eye positions were identified by scanning an individual of approximately the same stature as the accident pilots seated in the cockpit of each airplane.¹³

In addition to the calculation of the visibility angles, this *Study* presents recreations of possible views from the pilots' seats (including simulation-based depictions of the outside world) constructed assuming the nominal eye positions as defined above.

D.3.3. Results: azimuth and elevation angle calculations

The azimuth and elevation angles from the "viewer" airplanes to the "target" airplanes are shown as a function of time in Figure 13. In the top plot, the Cessna is the "viewer" and the Sonex is the "target," and in the bottom plot, the Sonex is the "viewer" and the Cessna is the "target."

Plots of the "target" airplane elevation angle vs. azimuth angle for the 61 seconds preceding the collision are shown in Figures 14 and 15, along with the azimuth and elevation coordinates of the "viewer" airplane cockpit windows and other structures, as computed for the nominal pilot eye position from the pilots' seats. Figure 14a presents the view from the pilot's (left) seat of the Cessna, and Figure 14b presents the view from the copilot's (right) seat of the Cessna. The trajectory of the Sonex in these views is depicted by the solid multicolored line (the dashed multicolored line depicts the position of the sun in these views, and is described below). Figure 15 presents the view from the pilot's seat of the Sonex to the Cessna (the sun is behind the Sonex and out of view).

In Figures 14 and 15, the window edges are outlined with a black line, the cockpit structures are colored gray, and the windows are colored white. The trajectory of the "target" airplane over time is depicted by the multicolored line, where the color of the line at any point indicates the time corresponding to that point, per the color scale in the Figures. If the multicolored line passes through a shaded area of the plot, the "target" airplane is obscured from view by the "viewer" airplane structure.

¹³ The individual in the scans is 68" tall. Per their flight physical records, the student in the left seat of the Cessna was 71" tall, the flight instructor in the right seat of the Cessna was 69" tall, and the pilot of the Sonex was 68" tall.

To further clarify the cockpit geometry and scan points depicted in Figures 14 and 15, scanner images of the cockpits are presented in Figures 16 and 17. Figure 16a is an image of the full 360° scan from the pilot's seat of the exemplar Cessna. Figure 14b is a similar image from the copilot's seat of the exemplar Cessna. Figure 15a is an image from the pilot's seat of the Sonex, with a cardboard template placed over the instrument panel to represent the larger panel installed on N255BF. An image with this cardboard template removed, depicting the original panel installed in the exemplar Sonex, is presented in Figure 15b for comparison. The yellow and red rectangles in Figures 16 and 17 highlight the cockpit areas depicted in Figures 14 and 15.

The azimuth and elevation angles of the sun are also of interest, because sun glare can affect a pilot's ability to see other aircraft. The azimuth (relative to true north) and altitude angles of the sun at the time and location of the accident were 108.39° and 23.59°, respectively.¹⁴ To compute the location (azimuth and elevation angles) of the sun in the Cessna and Sonex pilots' fields of view, the coordinates of the sun in earth coordinates were computed (using the sun angles and an assumed very large distance to the sun), and then transformed into the airplane body axis coordinates using the Euler angles shown in Figure 11. The azimuth and elevation angles of the sun were then computed from its body axis coordinates.

The results of these calculations indicate that the sun would have been behind the Sonex pilot's head and out of view. The azimuth and elevation angles of the sun from the Cessna are depicted in Figure 14 as the multicolored dashed line. Note that starting at about 08:52:35, the sun would have been visible in the Cessna windshield, and at the time of the collision was at about the same azimuth angle as the Sonex and about 25° of elevation above the Sonex. Hence, while sun glare would not have affected the Sonex pilot's ability to see the Cessna, it might have affected the Cessna pilots' ability to see the Sonex.

Figure 14a indicates that the Sonex would have been unobscured and visible through the Cessna's windshield from the Cessna's left seat throughout much of the minute before the collision, though it would have been obscured for about 4 seconds below the right side of the instrument panel starting at 08:52:17, and for about 15 seconds behind the whiskey compass starting at about 08:52:37. Figure 14b indicates that the Sonex would have been unobscured from the Cessna's right seat from 08:52:28 onwards (33 seconds before the collision). Before that time, the Sonex would have been mostly obscured from the right seat pilot by the right window post.

Figure 15 indicates that the Cessna would have been unobscured and visible through the Sonex's windshield throughout the minute before the collision (and before), except for the 10-second period between 08:52:41 and 08:52:51, when it would have been

¹⁴ As computed using <https://www.susdesign.com/sunangle/>.

obscured behind the canopy frame. The Cessna would have re-appeared from behind the frame about 10 seconds before the collision.

As noted above, the azimuth and elevation angles of the window and cockpit structures are sensitive to the position of the pilot's eyes in the cockpit. To determine how these angles change as the pilot's eye position changes (e.g., by leaning in different directions, or by a seat height adjustment), plots similar to Figures 14 and 15 were generated for the 27 different eye positions shown in Table 3. The positions are expressed as displacements from the nominal eye position along the three airplane body axes ($\{\Delta x_b, \Delta y_b, \Delta z_b\}$ ¹⁵).

Case name	Δx_b from nominal, in. (+ forward, - aft)	Δy_b from nominal, in. (+ right, - left)	Δz_b from nominal, in. (+ down, - up)
CCD	0	0	+1.5
FCD	+3	0	+1.5
ACD	-3	0	+1.5
FLD	+3	-3	+1.5
CLD	0	-3	+1.5
ALD	-3	-3	+1.5
FRD	+3	+3	+1.5
CRD	0	+3	+1.5
ARD	-3	+3	+1.5
CCC (nominal)	0	0	0
FCC	+3	0	0
ACC	-3	0	0
FLC	+3	-3	0
CLC	0	-3	0
ALC	-3	-3	0
FRC	+3	+3	0
CRC	0	+3	0
ARC	-3	+3	0
CCU	0	0	-1.5
FCU	+3	0	-1.5
ACU	-3	0	-1.5
FLU	+3	-3	-1.5
CLU	0	-3	-1.5
ALU	-3	-3	-1.5
FRU	+3	+3	-1.5
CRU	0	+3	-1.5
ARU	-3	+3	-1.5

Table 3. Matrix of eye positions for cockpit structure azimuth and elevation angle calculations.

The results of the calculations are presented in Figure 18 for the Cessna pilot's field of view, in Figure 19 for the Cessna copilot's field of view, and in Figure 20 for the Sonex pilot's field of view. The trajectory of each "target" airplane in these Figures is depicted

¹⁵ The body axis system is illustrated in Figure 12.

by the solid red line, and for simplicity is only shown for the last 42 seconds before the collision (from 08:52:19 to 08:53:01).

As shown in Figures 18-20, a variation in the pilot's eye position from the nominal position changes where the target airplane appears in the viewer's field of view, and how and when the target airplane might become obscured by the viewer airplane's structure. For example, Figure 18 shows that the duration of the period when the Sonex is obscured by the whiskey compass on the top of the Cessna's instrument panel is very sensitive to movements of the Cessna pilot's eye position. In contrast, Figures 20a and 2b show that even though the position of the Cessna in the Sonex's windshield changes with the Sonex pilot's eye position, at eye positions at least as high as nominal the Cessna remains unobscured in the Sonex windshield (except for the time it is behind the canopy frame) throughout the period studied. Figure 20c shows that when the pilot's eyes are 1.5 inches below the nominal position, the Cessna could be obscured by the Sonex's instrument panel for up to 2 seconds before the collision.

Figures 18-20 indicate that the visibility of one aircraft from the other can be very sensitive to the position of the pilots' eyes relative to the window structures. This observation underscores the fact that scanning for traffic visually can be more effective if pilots move their heads as well as redirect their eyes, since head movements may bring otherwise obscured aircraft into view.

D.3.4. Simulated views from the Cessna and Sonex cockpits

While Figures 14, 15, and 18-20 depict where the "target" airplanes could have appeared in the "viewer" airplanes' windows, they do not provide a sense of the background against which the targets would appear, and against which the pilot of each airplane would have to see the target. To provide a rough approximation of these backgrounds and of how the view from each cockpit evolved over time, the views from the cockpits were recreated in the *Microsoft Flight Simulator X (FSX)* simulation program, using airplane, sky, and terrain graphics inherent in *FSX*.

The cockpit structures at the nominal pilots' eye points (based on the laser scans) were constructed in *FSX* as semi-transparent panels that "mask" the view from each cockpit (see Appendix B); the cockpit geometries built into the airplane models in the simulation were not used. Airplane models were only used to represent the exterior "target" airplane geometry in the recreated views. The position (latitude, longitude, and altitude) and attitude (heading, pitch, and roll) of each airplane were recreated in *FSX* using the *FS Recorder* program developed by Matthias Neusinger,¹⁶ based on the position and attitude data used for the performance calculations for each airplane.

¹⁶ This program used to be available at <http://www.fs-recorder.net/>, but the website is no longer operational.

FSX contains inherent options to customize the time, date, and weather depiction in the simulation. The time and date were set to those of the accident (08:53 MDT on September 17, 2022), which results in the correct placement of the sun in the sky. The weather option was set to “clear skies” with “maximum visibility” and no clouds. This option was selected to compensate for the limited resolution of the computer display (for which the size of distant but theoretically visible objects can be smaller than a pixel), in order to display pixels representing the target airplanes as soon as possible. The resulting weather is generally consistent with the KLMO 08:55 METAR.

The view depicted by *FSX* depends on the program’s “camera” settings. In this *Study*, the *FSX* camera is equivalent to the pilot’s eyes: the view from the cockpit depends on the camera’s position, orientation (where it’s pointed), and its “field of view” (i.e., the range of azimuth and elevation angles that can be “seen” by the camera). The widest field of view available in *FSX* is 90° horizontally and about 62° vertically.¹⁷ Consequently, if the camera is pointed straight ahead (0° azimuth), then only azimuth angles between -45° and +45° will be visible in that view. If objects of interest (e.g., the target airplane) are beyond this range, then to “see” them the camera will have to be rotated away from 0° azimuth toward the object. However, in this case, a portion of the view straight-ahead will be lost, which may be unsatisfactory for the purpose of giving the viewer a good sense of the airplane’s direction of travel and general situation relative to the outside world.

To see objects beyond $\pm 45^\circ$ of azimuth while at the same time preserving a field of view of at least $\pm 45^\circ$ of azimuth about the direction of travel, the view from two co-located cameras can be joined side-by-side: the first camera pointed away from 0° azimuth to capture the object, and the second camera pointed in such a way that the boundaries of the fields of view of the cameras coincide at a particular azimuth angle. For example, if one camera is rotated to -45° azimuth, the left boundary of its field of view will be at $-45^\circ - 45^\circ = -90^\circ$, and the right boundary will be at $-45^\circ + 45^\circ = 0^\circ$. If the second camera is rotated to +45° azimuth, its left boundary will be at $+45^\circ - 45^\circ = 0^\circ$ (coinciding with the right boundary of the first camera), and its right boundary will be at $+45^\circ + 45^\circ = +90^\circ$. Setting the views from the cameras side-by-side, a continuous field of view from -90° to +90° is obtained.

However, discontinuities (kinks) in straight lines may appear at the boundary of these views when they are viewed side-by-side on a flat surface (such as a computer screen), because the viewer will be viewing both from the same angle, whereas the view on the left is intended to be viewed at an angle rotated 90° from that on the right. The discontinuities can be removed if each view is presented on a separate surface (monitor), and then the surfaces are joined at a 90° angle. However, this solution may be impractical (and is impossible for presenting screenshots of these views in a single document), and so the line discontinuities at the boundaries of the views may simply

¹⁷ These values are for an *FSX* window with an aspect ratio of 1.6, at a “zoom” setting of 0.3.

need to be tolerated. At non-zero roll angles, the slope of the horizon line is discontinuous at the boundary between the views, but there is no break in the horizon line itself.

As shown in Figure 14, in the last minute before the collision the Sonex appeared in the Cessna pilot's field of view between azimuth angles of -15° and 60° . Consequently, for this *Study* a single camera pointed along an azimuth angle of 20° is used to depict the view from the Cessna, covering azimuth angles between -25° and 65° . A single camera pointed along an azimuth angle of 10° is used to depict the view from the Sonex, covering azimuth angles between -35° and 55° .

Screenshots of the Cessna cockpit recreation are presented in Figures 21a-g, along with simulated Cockpit Display of Traffic Information (CDTI) screens depicting the traffic information that the ForeFlight application used by the Cessna pilots might have provided (the CDTI screens are discussed in section D.4.4). The times of the screenshots correspond to the events listed in Table 4. The locations of the Sonex in Figures 21a-g are highlighted by the yellow circles, though the airplane itself may be too small to be seen in some of the *FSX* images.

Screenshots of the Sonex cockpit recreation are presented in Figures 22a-g, along with simulated CDTI screens depicting the traffic information that the Garmin GNS430W device installed in the Sonex might have provided, had the ARINC 429 and RS-232 channels been configured to "On" instead of "Off." The locations of the Cessna in Figures 22a-g are highlighted by the yellow circles, though the airplane itself may be too small to be seen in some of the *FSX* images.

Time (MDT)	Letter ID in Figures 21 & 22	Time before collision (seconds)	Horizontal separation (nm)	Horizontal separation (ft)	Vertical separation (ft)	Closure rate (kt)
08:52:31.6	a	30	1.3233	8041	294	131
08:52:41.6	b	20	0.9206	5594	200	148
08:52:46.6	c	15	0.7145	4341	224	150
08:52:51.6	d	10	0.5037	3060	209	156
08:52:56.6	e	5	0.2685	1632	79	186
08:52:59.6	f	2	0.1085	659	9	194
08:53:01.0	g	0.6	0.0332	202	3	189

Table 4. Times corresponding to recreated cockpit views and CDTI displays in Figures 21 and 22.

A measure of the size of the "target" airplane in the field of view of the "viewer" is the difference in azimuth and elevation angles between different points on the "target." For this *Study*, the azimuth and elevation angles of the nose, tail, center, and left and right wingtips of the targets were computed (the angles plotted in Figures 13-15 correspond to the center of the targets). The difference in azimuth and elevation angles between the nose and the tail of the targets are presented as a function of time in

Figure 23 as the lines labeled " Δ azimuth, fuselage" and " Δ elevation, fuselage." The difference in angles between the left and right wingtips are presented as the lines labeled " Δ azimuth, wings" and " Δ elevation, wings." In these calculations, the nose, tail, and wingtips are assumed to lie in a plane, and so the airplanes in this representation have zero thickness. Hence, the information in Figure 23 does not represent the size of the area of the target presented to the viewer (which is what makes the target visible), but only the extent of a subset of dimensions that contribute to the area. Nonetheless, Figure 23 does provide a measure of the target size, and of the very sudden increase in size (called the "blossom" effect) within a few seconds of the collision. Reference 5 describes the minimum object size required for an object to be seen and recognized by a person:

Visual acuity is the ability to see high levels of detail in an image. Distant acuity is commonly measured using a Snellen eye chart containing static, high contrast letters positioned 20 feet from an observer [see Reference 6]. The ability to resolve a detail (a line or a space) as small as 1 minute of arc [0.0167°] is considered normal acuity. This permits a person to recognize a simple shape (such as a test letter such as "E") that subtends 5 minutes of arc (0.083 degrees).

However, the actual visual detection threshold depends on many factors, including viewer age, contrast, illumination, color, and the viewer's focus. Reference 5 notes that unfamiliar objects can be harder to recognize, and emphasizes the importance of visual contrast:

Research indicates that the minimum subtended angle required for recognizing an uncommon shape in a field of distractor items is 0.20 degrees [Reference 7].

...
Visual contrast is another consideration for estimating recognition time The minimum subtended angle for recognizing complex, low contrast targets is about 0.40 to 0.60 degrees [Reference 8].

Given these uncertainties, Figure 23 should not be used to determine a specific time at which the pilots "should" have been able to see the other airplane.

The yellow highlighted areas Figure 23 indicate the time periods during which, with the pilots' eyes at their nominal positions, the center of the "target" airplanes would have been obscured from the "viewer" pilots' views by airplane structure, consistent with Figures 14 and 15. At all other times, the target airplanes would not have been obscured from the viewer pilots' views.

During the minute prior to the collision (from 08:52:01 to 08:53:01), the Sonex would have traversed from the right half of Cessna's windshield (from an azimuth angle of about 53°) to the left half (to an azimuth of about -15°). Between 08:52:17 and 08:52:21, the Sonex would have been obscured by the right edge of the Cessna's instrument panel, and between 08:52:37 and 08:52:52 it would have been obscured behind the whiskey compass on top of the Cessna's instrument panel. As the Sonex traversed across the windshield, it would have appeared as a small object just below the horizon,

moving slowly against the background terrain. This complex background (compared to a sky background) might have made detecting the Sonex more difficult, particularly in the presence of sun glare.

During the same minute, the Cessna would have appeared in the Sonex's windshield as a small object moving slowly from left to right (from an azimuth angle of about -28° to an azimuth of about 14°). At times, the Cessna might have been below the horizon line presented by the Rocky Mountains, and at other times it would have appeared above this horizon against the background of the sky. In the final 3 seconds, as the Cessna descended to the collision altitude, it would have appeared below the horizon and against the terrain (see Figures 22f-g). Between 08:52:41 and 08:52:51, the Cessna would have been obscured the Sonex canopy frame.

D.4. Cockpit Display of Traffic Information (CDTI) study

D.4.1. Recreation and simulation of CDTI displays

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.2.1. 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. As noted in Section D.2.1, both the Cessna and the Sonex pilots had ADS-B In-based CDTI visual displays available to them, though it is likely that the CDTI on the Sonex would not have displayed any traffic information (or issued any traffic alerts) on the accident flight because its ARINC 429 and RS-232 channels were found to be selected “Off.” In fact, the FAA had not recorded ADS-B data from the Sonex for over nine weeks before the accident.

The Garmin avionics in the Sonex (when enabled) and the *ForeFlight* application used in the Cessna (run on a portable Apple iPad device¹⁸) implement similar but different traffic alerting criteria than those prescribed by the ATAS ADS-B In function described in AC 20-172B. For this investigation, simulated CDTI displays for both the Cessna and the Sonex were generated based on the recorded ADS-B and TIS-B information¹⁹ for the area and time of the accident, using the graphical conventions and alerting criteria for each aircraft – that is, the Garmin 430W conventions and criteria for the Sonex, and the *ForeFlight* conventions and criteria for the Cessna. The simulation of the Sonex CDTI is provided to depict the traffic information that *could* have been presented to the Sonex pilot, *if* the appropriate channels of the Garmin unit had been enabled.

¹⁸ See Reference 11 for details about how the iPad receives ADS-B data for presentation in *ForeFlight*.

¹⁹ As noted above, the FAA provided the NTSB with recorded ADS-B and TIS-B traffic data within a 25 nm radius of KLMO, and below 12,000 ft., from 14:30 UTC to 14:00 UTC (08:30 to 09:00 MDT). The data file provided by the FAA is included in the public docket for this accident.

The alerting criteria specified in DO-317B is also presented for comparison with the criteria used by Garmin and *ForeFlight*, though the traffic alerts that would have been generated using DO-317B criteria were not simulated. Given the rough similarities among the different alerting criteria, it is expected that the alerts generated using DO-317B criteria would not differ significantly from those generated by the Garmin 430W or by *ForeFlight*.

D.4.2. DO-317B graphical conventions and alert criteria

AC 20-172B describes the graphical conventions (symbol requirements) for the CDTI, which are more completely defined in RTCA document DO-317B. 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.
- If the directionality of the traffic target is known, the traffic symbol should be an arrowhead pointing in the direction of travel.
- Traffic symbols that are not proximate (i.e., not within 6 nm and $\pm 1,200$ ft. of the ownship) should be cyan-colored or white and open (not filled).
- Traffic symbols that are proximate should be cyan or white and filled.
- Traffic that generates an ATAS alert should be displayed with yellow symbols enclosed in a 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 tendency²⁰ (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 penetrate a smaller, "collision airspace zone" (CAZ) around the target.²¹

²⁰ The vertical tendency will only be annunciated when the computed rate of climb or descent is at least 500 ft./min.

²¹ 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 ± 200 ft.

D.4.3. Sonex equipment: Garmin 430W symbology and alert criteria

As noted above, the Sonex was equipped with a panel-mounted GNSS receiver for displaying ADS-B traffic information, but the receiver's ARINC 429 and RS-232 channels were configured "Off," and so the airplane could not broadcast ADS-B Out information and would likely not have displayed any ADS-B In traffic information, either. Nonetheless, the traffic information that *could* have been presented on the Garmin 430W screen, had the communication channels been configured correctly, will be considered here (the resulting images are shown in Figure 22).

The Garmin *400W/500W Series Garmin Optional Displays Pilot's Guide Addendum* (Reference 9) defines the graphical conventions for traffic information displayed on the 430W receiver. Under the heading of "TIS Symbology,"²² Reference 9 states:

TIS traffic is displayed on the 400W/500W Series unit according to TCAS [Traffic Collision Avoidance System] symbology, graphically displayed on a dedicated graphical page ... and on the moving Map Page. A Traffic Advisory (TA) symbol appears as a solid yellow circle (or half circle on the outer range ring if the traffic is outside the range of the dedicated Traffic Page). Proximity Advisories (PA) are displayed as a solid diamond, and other traffic is displayed as an open diamond. PA and other traffic is normally displayed in white, or it may be alternatively configured for display in cyan. When configured for cyan, the traffic page range rings and markings are displayed in white. Altitude deviation from own aircraft altitude is displayed above the target symbol if traffic is above own aircraft altitude, and below the symbol if they are below own aircraft altitude. Altitude trend is displayed as an up arrow (> +500 ft/min), down arrow (< - 500 ft/min), or no symbol if less than 500 ft/min rate in either direction.

Reference 9 notes that "traffic ground track is indicated on the 400W/500W display by a 'target track vector,' a short line displayed in 45-degree increments. This vector shows the flight direction of the traffic."

The conditions required for a traffic target to be classified as a PA or TA are defined in the Garmin *400/500 Series GTS 8XX Interface: Pilot's Guide Addendum* (Reference 10). Section 1.2 of Reference 10, titled "Traffic Symbology," states:

A TA (Traffic Advisory) is generated when the GTS 8XX predicts that an intruder aircraft may pose a collision threat. A solid yellow circle represents an intruder aircraft that meets the TA criteria as described in the TA Alerting Conditions section. A TA consists of the traffic symbol and an aural alert (e.g., "traffic, 12 o'clock, high, 3 miles").

...

PAs are defined as traffic within the 6.0-nm range, within ± 1200 ft. of altitude separation, and are not a traffic advisory (TA).

²² A description of the GNS430W on Garmin's website (<https://www.garmin.com/en-CA/p/301>) notes that "with a GDL 88 Datalink, the GNS 430W can display ADS-B traffic targets using TIS-A symbology." The symbology described in Reference 9 is for TIS traffic, but also applies to ADS-B traffic.

Section 1.3 of Reference 10, titled "TA Alerting Conditions," states:

The GTS 8XX automatically adjusts its TA sensitivity level ... to reduce the likelihood of nuisance TA alerting during flight phases likely to be near airports. Level A (less sensitivity) TA sensitivity is used when the aircraft's radar altimeter (if equipped) indicates own altitude is less than 2000 feet AGL. If no radar altimeter is present, Sensitivity Level A is active when the landing gear is extended. Level A is also active when groundspeed is less than 120 knots with no radar altimeter present in a fixed gear aircraft. In all other conditions, Level B (greater sensitivity) TA sensitivity is used to assess TA threats.

The accident aircraft are fixed-gear airplanes with no radar altimeter, and the ground speeds of both airplanes remained below 120 knots during the time period considered in this *Study*; hence, "Level A" TA sensitivity level was used to simulate the alerts the Garmin 430W could have provided to the Sonex pilot (had the appropriate channels been turned on). Reference 10 defines the TA alerting conditions for "Level A" sensitivity as follows, when the "intruder" (traffic target) altitude is available:

Intruder closing rate provides less than 20 seconds of vertical and horizontal separation.

Or:

Intruder range is within 0.2 nm and vertical separation is within 600 feet.

Section 1.3 of Reference 10, titled "Aural Alerts," states:

A TA consists of a displayed traffic symbol (solid yellow circle) and an aural alert. The aural alert announces "traffic", followed by the intruder aircraft's position, altitude relative to own aircraft ("high", "low", or "same altitude"), and distance from own aircraft; e.g. "traffic, 12 o'clock, high, 3 miles".

Reference 9 states that an aural alert will accompany a TA alert under the following conditions:

The TIS audio alert is generated from the GTX 3xx whenever the number of Traffic Advisories on the 400W/500W display increases from one scan to the next. Limiting Traffic Advisories only reduces the "nuisance" alerting due to proximate aircraft. For example, when the first Traffic Advisories appears on the TIS display, the user is alerted audibly. So long as a single aircraft remains on the TIS display, no further audio alert is generated.

If a second (or more) aircraft appears on the display, a new audio alert is sounded. If the number of Traffic Advisories on the TIS display decreases and then increases, a new audio alert is sounded. ...

The symbology and alerting criteria for the Garmin 430W described above were simulated using the ADS-B and TIS-B data for the time and area of the accident. Images of the resulting traffic displays are shown in Figure 22. Note that the actual scale and map background of the display are selectable by the pilot; for clarity, the simulated images use a simple black background with the outer range ring set to 5 nm. The actual settings used on the accident flight are unknown. Table 5 lists the aural traffic alerts

generated by the simulation in the minute before the collision. An alert associated with the Cessna is generated at 08:52:20, about 41 seconds before the collision.

Time (MDT)	Seconds before collision	Traffic Advisory content
08:52:01	60.6	traffic 11 o'clock low 1 mile
08:52:20	41.6	traffic 11 o'clock same altitude 1 mile descending

Table 5. Aural alerts generated by Garmin 430W simulation. The alert generated at 08:52:20 concerns Cessna N2117Y; the alert at 08:52:01 concerns a different aircraft.

Figure 25 depicts the Garmin simulation traffic density within 10 nm of the collision, at the time of the collision. In the five minutes preceding the collision, the simulation generates 21 Proximity Advisories (in which the target symbols change from open white diamonds to closed white diamonds, but no aural alert is generated) and 2 Traffic Advisories (in which the target symbols change from closed white diamonds to closed yellow circles, and an aural alert is generated). One of these TA's concerned Cessna N2117Y (see Table 5).

D.4.4. Cessna equipment: *ForeFlight* symbology and alert criteria

As noted above, the Cessna pilots were using the *ForeFlight Mobile* application (*ForeFlight*) running on a portable (not permanently installed) Apple iPad device. ADS-B In traffic information (including TIS-B traffic) was received and transmitted to the iPad using an Appareo Stratus 3i portable receiver.

The *ForeFlight* website²³ describes the *ForeFlight Mobile* application as follows: "Designed by pilots for pilots, *ForeFlight* delivers personal aviators an all-in-one solution for flight planning, checklists, charts, weather, airport information, flight logging, document management, hazard awareness, and more." The functionality of the application of most interest in this *Study* is the depiction of traffic (including aural and visual alerts) relative to the ownship on a moving map background, similar to the functionality provided by the Garmin 430W display on the Sonex, and the CDTI displays envisioned in the RTCA DO-317B MOPS.

The *ForeFlight* application is documented thoroughly in the *ForeFlight Mobile Pilot's Guide* (Reference 11). Section 24.7 of Reference 11 describes the application's ADS-B Traffic function. The traffic symbols and alerting algorithms used in *ForeFlight* are described as follows (emphasis in original):

A traffic target's color and symbol depend on its location, proximity, and movement.

²³ See <https://foreflight.com/solutions/personal/> (accessed on February 1, 2024).

- **Moving targets** are displayed as arrowheads pointing in their direction of travel. A TrafficTrend™ vector is displayed in front of the arrowhead to indicate the target's expected position in the next 60 seconds (longer vector = faster speed).

- **Stationary targets** and targets with no direction or speed information are depicted as diamonds.

- **Airborne targets** are **cyan**.

- **Surface targets** are **brown**.

...

Relative Altitude Symbols

A traffic target's relative altitude is depicted with a plus **[+]** (height above you) or minus **[-]** symbol (height below you). Relative altitude is given in hundreds of feet. ...

Up and down arrows next to a traffic target indicate that the traffic is climbing or descending greater than 500 feet per minute (relative to your altitude).

...

Traffic Cautions and Warnings

Cautions and warnings are issued for traffic targets that pose a risk. Multiple cautions and warnings can be issued simultaneously. Your groundspeed and the groundspeed of the traffic target must be greater than 40 knots for a caution or warning to be issued.

Traffic Cautions are issued for targets that are less than 45 seconds from being within 2.0 nm and +/- 1,200' of your position. When a caution is issued, the target's icon is highlighted **YELLOW**.

Traffic Warnings are issued for targets that are less than 25 seconds from being within 1.3 nm and +/- 1,200' of your position. When a warning is issued, the target's icon is highlighted **RED**, and a **Traffic Alert** is activated if the setting is enabled.

Traffic targets remain highlighted for 15 seconds after they no longer exceed the thresholds.

... Traffic Alerts

Traffic alerts are enabled by default and appear regardless of the selected view. Tap **More > Settings > Alerts** to disable traffic alerts.

A simultaneous audible alert is issued if the **Speak All Alerts** setting is enabled. Alerts include the target's relative (clock) direction, distance, and altitude.

Traffic alerts are activated when:

- You and the traffic target have a groundspeed greater than 40 knots.
- The traffic target is less than 25 seconds from the warning range (closer than 1.3 nm and +/- 1,200').

Figure 24 reproduces the example traffic alert "popup" depicted in Reference 11. *ForeFlight* aural alerts can be transmitted to the pilot's headset via Bluetooth, if the headset is so equipped (the Cessna instructor pilot's headset was Bluetooth capable).

Note that to depict traffic, the *ForeFlight* "traffic layer" must be enabled. Also note that *ForeFlight* depicts all traffic targets as filled cyan arrowheads, unless they are in "caution" or "warning" status, in which case they are depicted as filled yellow or red

arrowheads. Open symbols, used by DO-317B compliant systems and by the Garmin 430W to depict traffic targets beyond a defined horizontal and / or vertical distance from the ownship, are not used in *ForeFlight*.

The settings of the *ForeFlight* application on the Cessna at the time of the accident are unknown. Hence, it is not known whether the “traffic layer,” “traffic alerts,” and / or “Speak All Alerts” options were enabled or disabled (though the alerts are automatically enabled with each power cycle).

The symbology and alerting criteria for the *ForeFlight* application were simulated using the ADS-B and TIS-B data for the time and area of the accident. Images of the resulting traffic displays are shown in Figure 21. Note that the actual scale and map background of the display are selectable by the pilot; for clarity, the simulated images use a simple black background with the outer range ring set to 5 nm. The actual settings used on the accident flight are unknown. The NTSB *ForeFlight* simulation does not generate traffic alert popups such as that shown in Figure 24, but does generate the aural alerts that accompany the popups. Table 6 lists the aural traffic alerts generated by the *ForeFlight* simulation in the minute before the collision.

Time (MDT)	Seconds before collision	Traffic Alert content
8:52:05	56.6	Traffic 2 o'clock low 2 miles
8:52:55	6.6	Traffic 2 o'clock low 1 mile
8:52:56	5.6	Traffic 3 o'clock high 1 mile

Table 6. Aural alerts generated by the *ForeFlight* simulation. The alert generated at 08:52:05 concerns Sonex N255BF; the others concern different aircraft.

Figure 26 depicts the *ForeFlight* simulation traffic density within 10 nm of the collision, at the time of the collision. In the five minutes preceding the collision, the simulation generates 16 Traffic Cautions (in which the target symbols change from cyan arrowheads to yellow arrowheads, but no traffic or aural alert is generated) and 11 Traffic Warnings (in which the target symbols change from yellow arrowheads to red arrowheads, and a Traffic Alert and aural alert are generated). One of these warnings concerned the Sonex (see Table 6).

E. CONCLUSIONS

The circumstances of this accident underscore the difficulty in seeing airborne traffic (the foundation of the “see and avoid” concept in visual meteorological conditions), even when pilots might be alerted to traffic in the vicinity by equipment such as CDTI. While CDTI with aural alerts can help to make pilots aware of surrounding traffic, and prompt them to look in the right direction for conflicting traffic, in this accident the benefits of CDTI might have been defeated by (1) the likelihood that the Sonex pilot did not receive any traffic information on his CDTI because the ARINC 429 and RS-232 channels on his Garmin 430W receiver were configured “Off,” and (2) the traffic density

in the area of the collision and the consequent number of alerts that might have made it difficult for the Cessna pilots to recognize the collision threat posed by the Sonex. In the 10 seconds before the collision, an NTSB simulation of the *ForeFlight* application used on the Cessna generates two “Traffic Warnings” (and accompanying aural alerts) that concern two aircraft that are *not* the Sonex. The simulation generates a Traffic Warning concerning the Sonex about 57 seconds before the collision.

It should be noted that the configuration of the *ForeFlight* application used on the Cessna is not known, and therefore it is not known whether the “traffic layer” in the application was enabled, or if the traffic and / or aural alerts in the application were enabled (though the alerts are automatically enabled with each power cycle). If these settings were not enabled, then the traffic information provided by the application would have been limited. Furthermore, it cannot be determined conclusively whether the Cessna in fact received TIS-B traffic messages concerning the Sonex.

Regarding the pilots’ opportunities to see the other airplane through the cockpit windows, Section D.3 presents the results of using the recorded surveillance data to estimate the location of each airplane in the other airplane’s windows during the minute prior to the collision. The results are shown in Figures 13-15 and 18-23.

The visibility of one airplane from another is sensitive to the position of the pilot’s eyes relative to the cockpit windows. This sensitivity is illustrated in Figures 18 and 19, which underscore the fact that looking for traffic can be more effective if pilots move their heads as well as redirect their eyes, since head movements may bring otherwise obscured aircraft into view. The descriptions of visibility that follow correspond to the pilots’ eyes in their nominal positions, with the understanding that the views out the windows change if the pilots move their heads.

During the minute prior to the collision (from 08:52:01 to 08:53:01), the Sonex would have traversed from the right half of Cessna’s windshield to the left half, and would have been obscured by the right edge of the Cessna’s instrument panel for 4 seconds and by the Cessna’s whiskey compass for 15 seconds. As the Sonex traversed across the windshield, it would have appeared as a small object just below the horizon, moving slowly against the background terrain. This complex background (compared to a sky background) might have made detecting the Sonex more difficult, particularly in the presence of sun glare; as shown in Figures 14 and 21, the azimuth angles from the Cessna to the sun and to the Sonex were similar at the time of the collision.

During the same minute, the Cessna would have appeared in the Sonex’s windshield as a small object moving slowly from left to right, and would have been obscured by the Sonex canopy frame for about 10 seconds. At times, the Cessna might have been below the horizon line presented by the Rocky Mountains, and at other times it would have appeared above the horizon against the background of the sky. In the final 3

seconds, as the Cessna descended to the collision altitude, it would have appeared below the horizon and against the terrain (see Figures 22f-g).

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F. REFERENCES

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11. ForeFlight, *ForeFlight Mobile Pilot's Guide*, version 13.0, January 2021.

G. GLOSSARY

G.1. Acronyms

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-R	Automatic Dependent Surveillance - Rebroadcast
AFM	Airplane Flight Manual
AGL	Above ground level
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance Radar
ATAS	ADS-B Traffic Advisory System
ATC	Air Traffic Control
AWOS	Automated Weather Observing Station
CDTI	Cockpit Display of Traffic Information
CFR	Code of Federal Regulations
CG	Center of Gravity
EFB	Electronic Flight Bag
FAA	Federal Aviation Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HRRR	High Resolution - Rapid Refresh atmospheric model for winds
IIC	Investigator In Charge
MAC	Mean Aerodynamic Chord
MDT	Mountain Daylight Time
METAR	Meteorological Terminal Air Report (Aviation Routine Weather Report)
MRMS	Multi-Radar Multi-Sensor
MSL	Mean Sea Level
NAS	National Airspace System
NOAA	National Oceanographic and Atmospheric Administration
KBJC	Rocky Mountain Municipal Airport, Denver, Colorado
KLMO	Vance Brand Airport, Longmont, Colorado
NTSB	National Transportation Safety Board
PA	Proximity Advisory (Garmin 430W system)
POH	Pilot's Operating Handbook
TA	Traffic Advisory (Garmin 430W system)
TCAS	Traffic Collision Avoidance System
TIS-B	Traffic Information Service - Broadcast
UTC	Universal Coordinated Time
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

G.2. English symbols

C_L	Lift coefficient
ϵ_V	Error in ground speed computed from surveillance data
ϵ_x	Position error in surveillance data
Δt	Time interval between surveillance data samples

G.3. Greek symbols

α	Angle of attack
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FIGURES



Figure 1. Pre-accident photograph of Cessna 172S N2117Y (photo credit: Jaiden Batts).

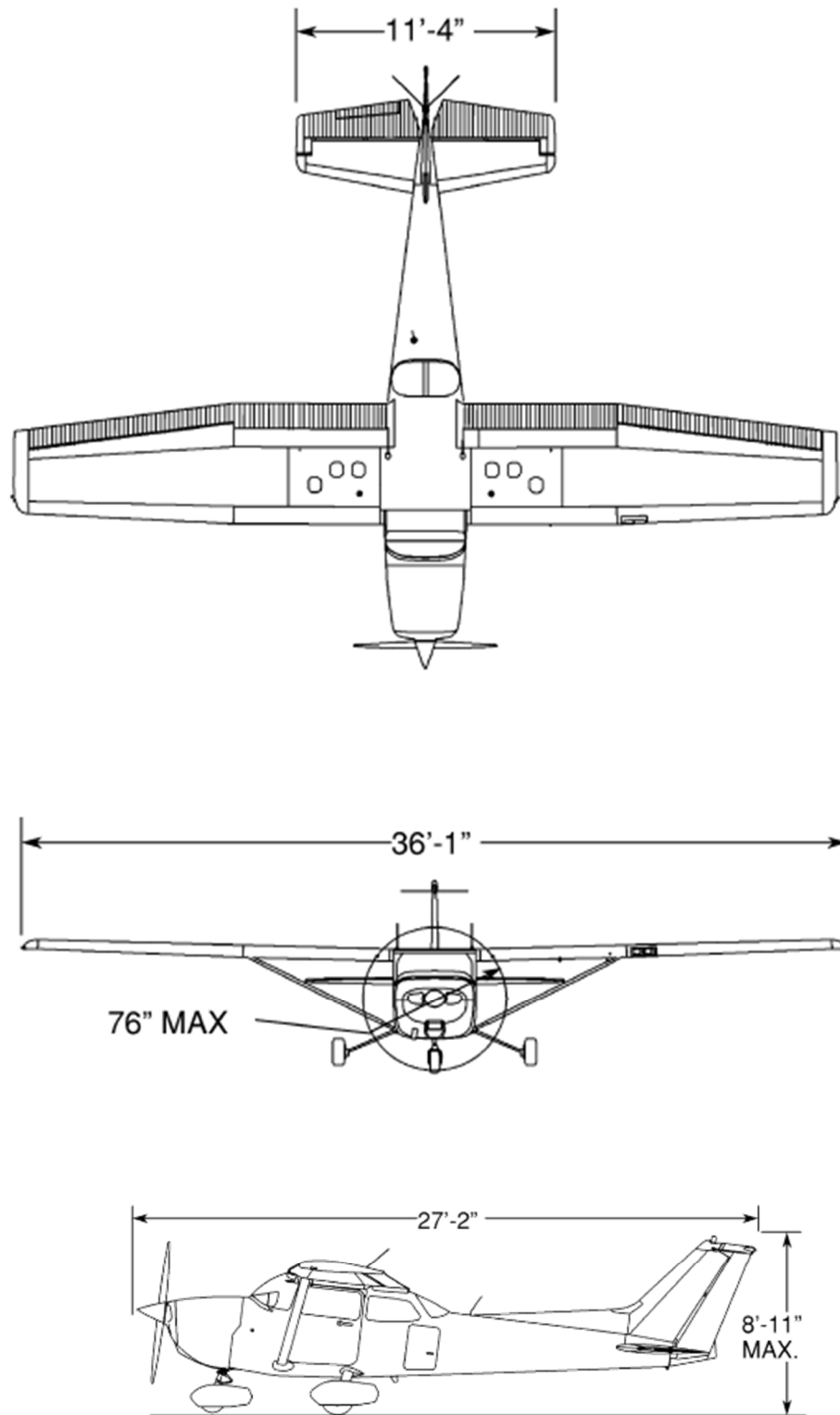


Figure 2. 3-view of the Cessna 172 Skyhawk, from Reference1.



Figure 3. Photograph of exemplar Sonex Xenos-B motorglider. N255BF was painted white with red and black trim (photo credit: Sonex Aircraft).

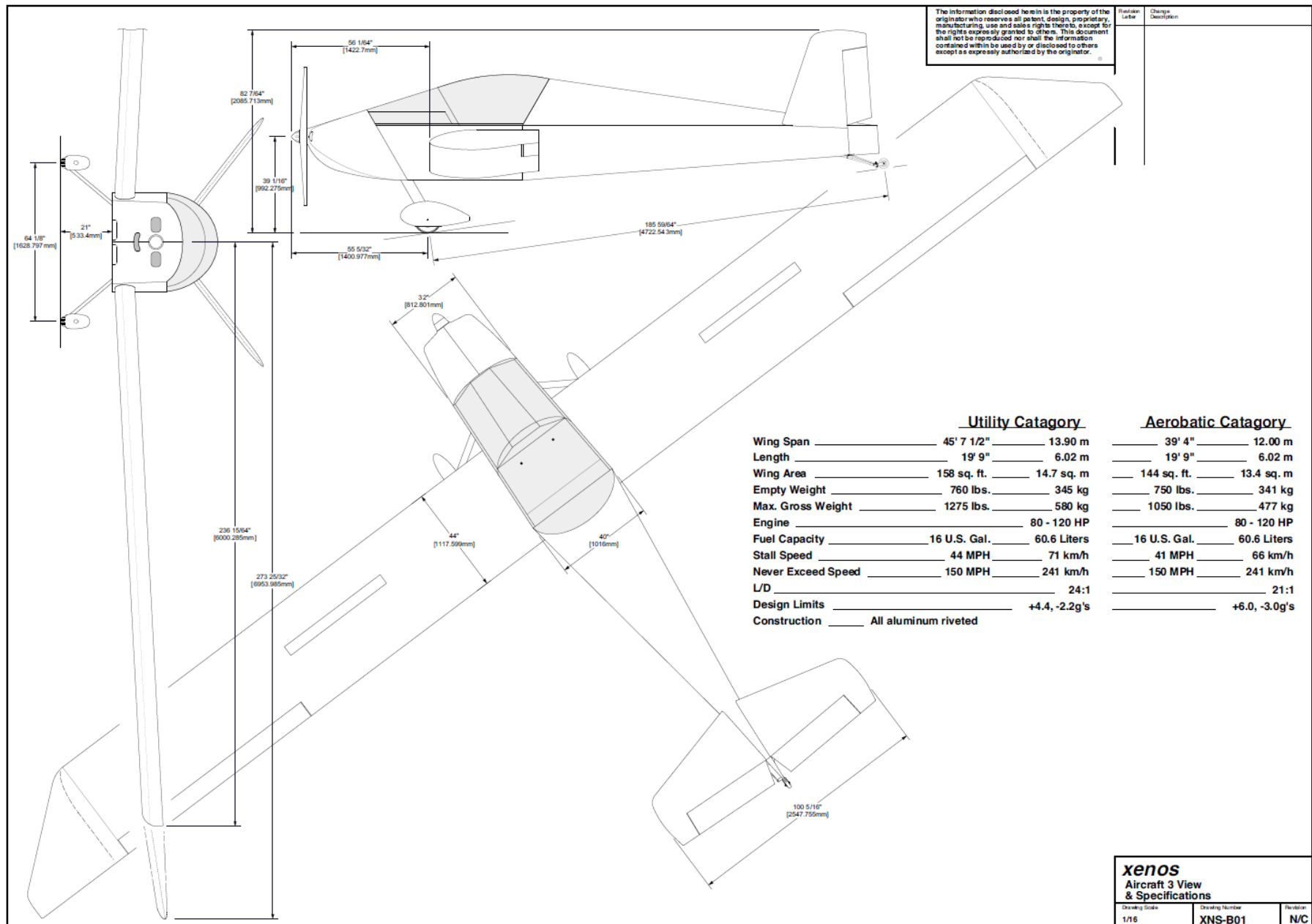
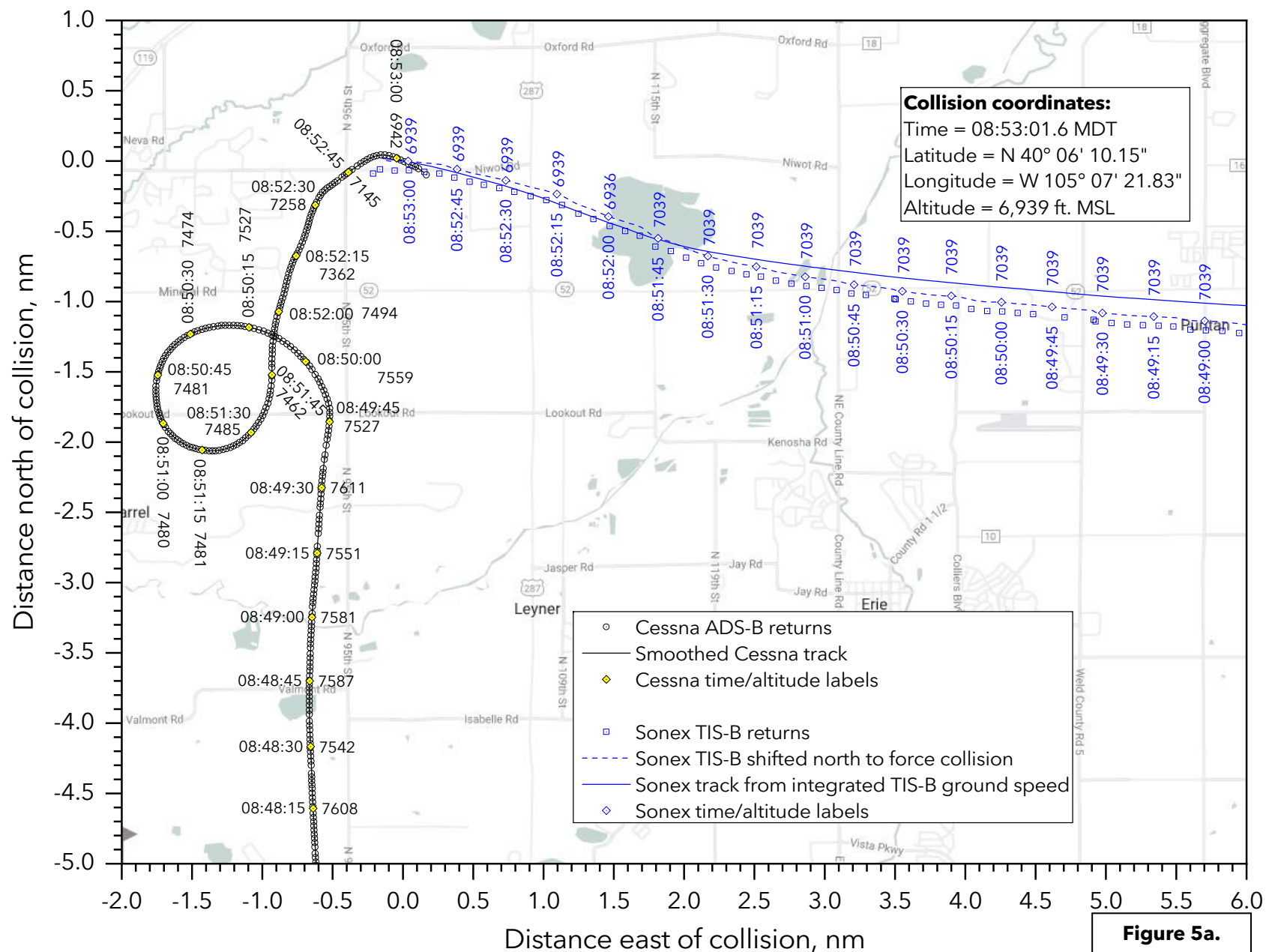


Figure 4. 3-view of the Sonex Xenos-B motorglider, provided by Sonex Aircraft.

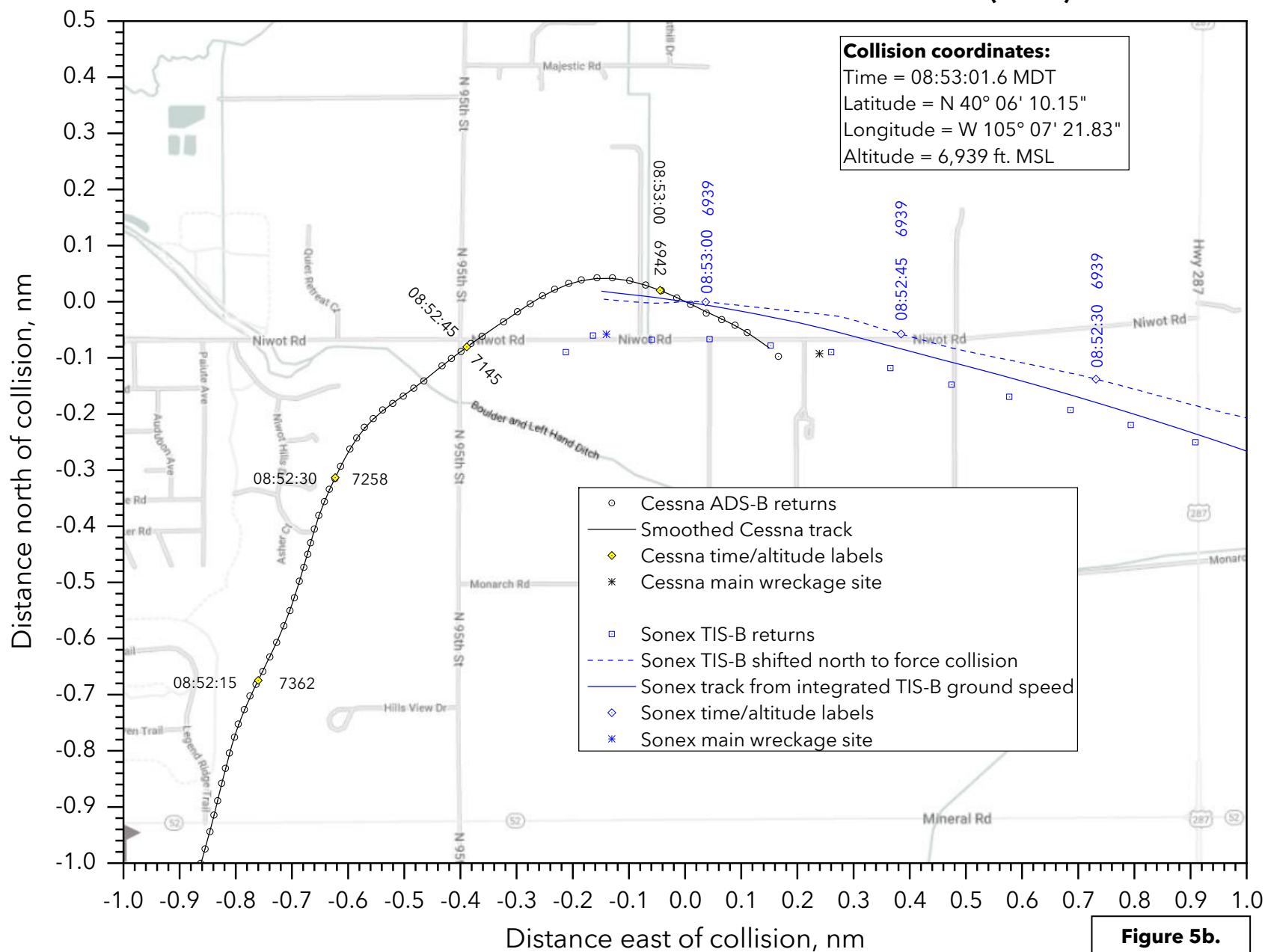
CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Plan view of ADS-B data for Cessna and TIS-B data for Sonex



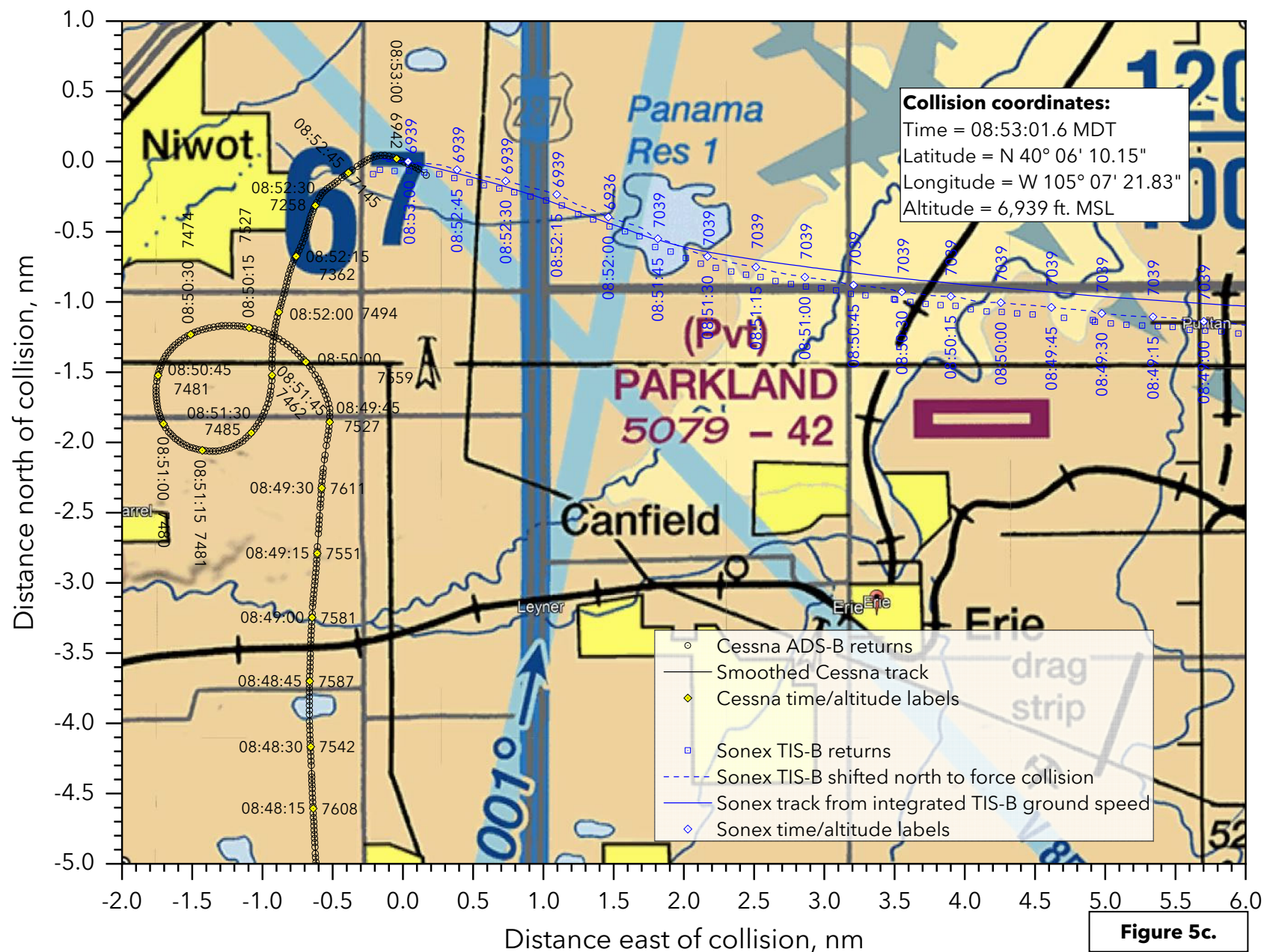
CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Plan view of ADS-B data for Cessna and TIS-B data for Sonex (detail)



CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Plan view of ADS-B data for Cessna and TIS-B data for Sonex



CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF

Longmont, CO, 9/17/2022

Cessna and Sonex north and east coordinates vs. time

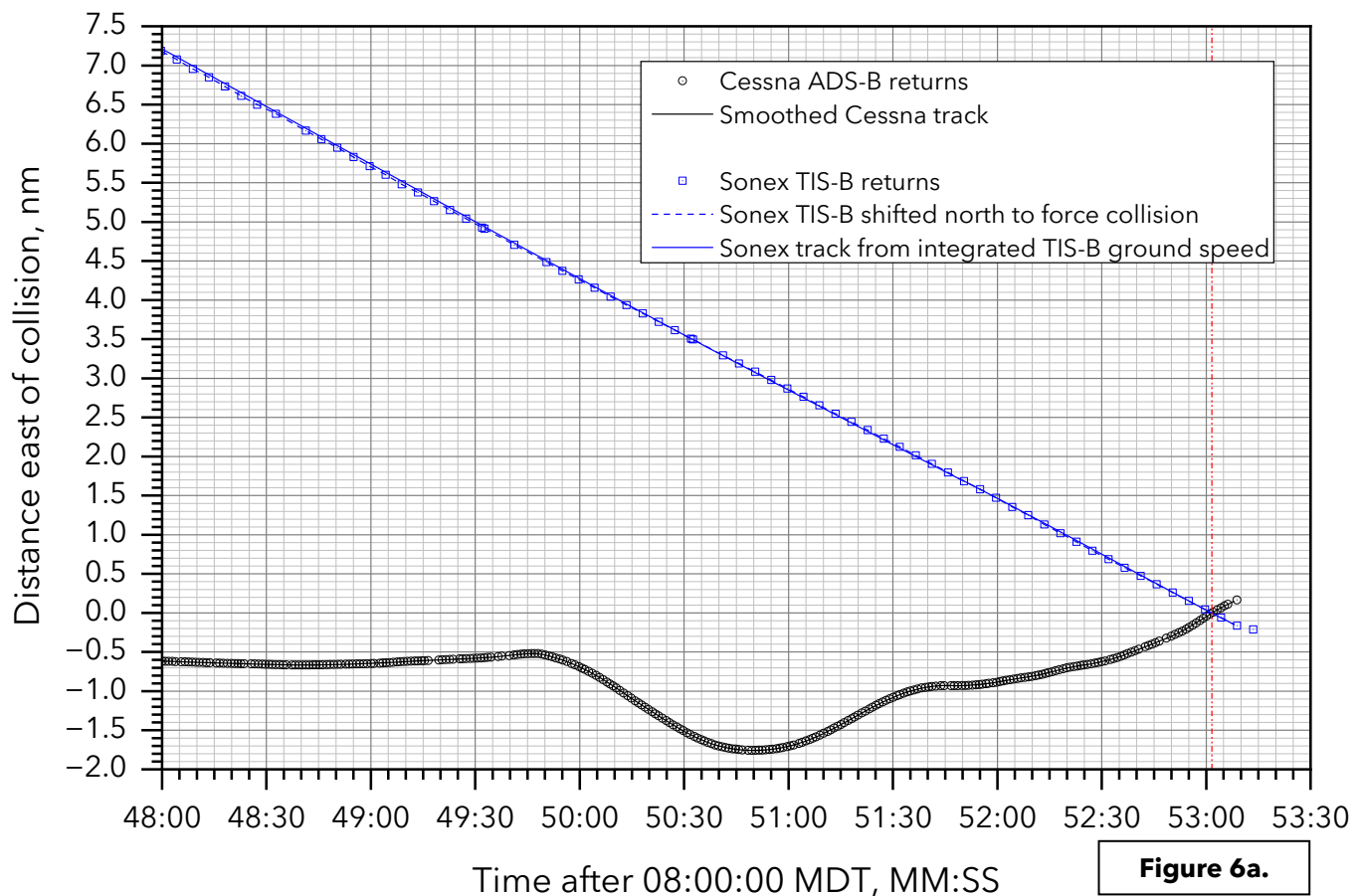
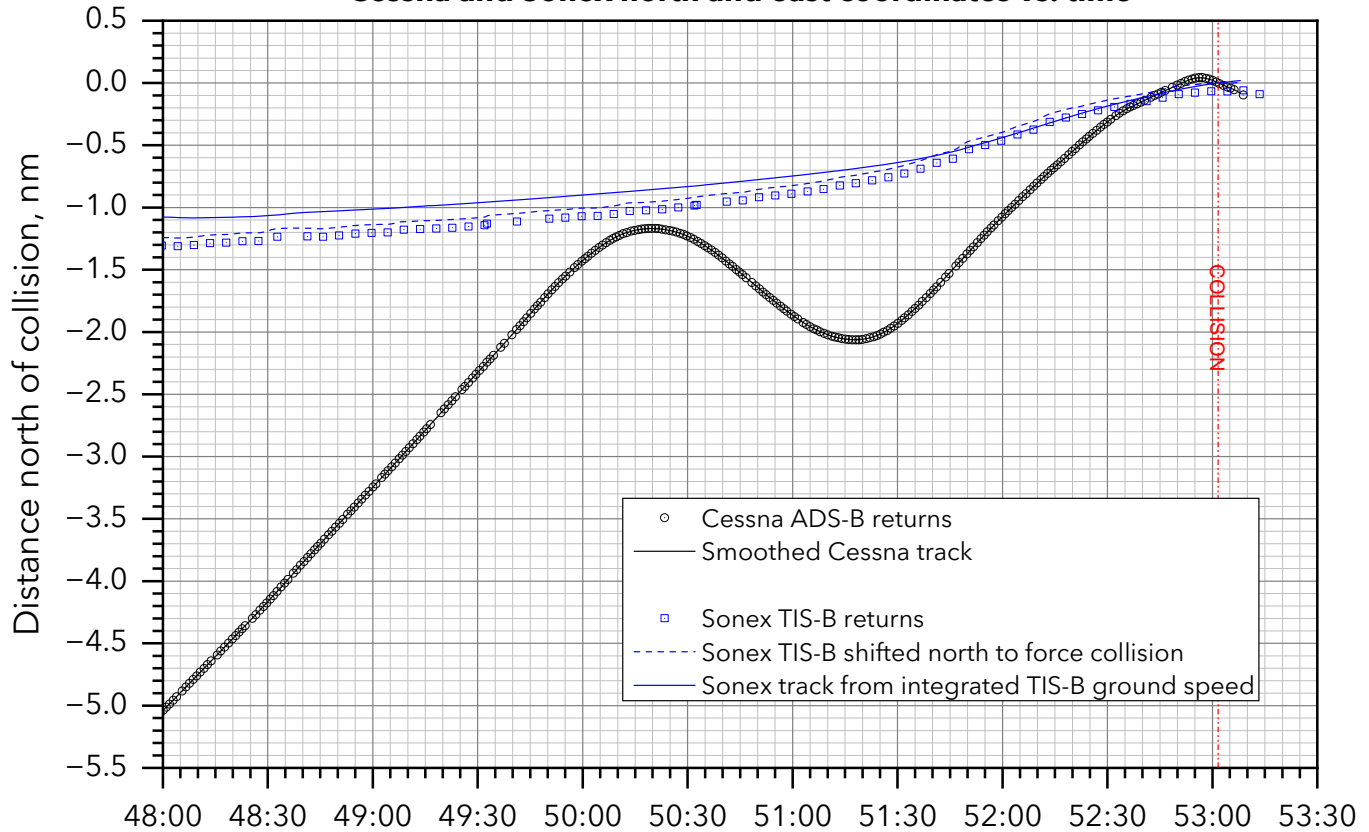
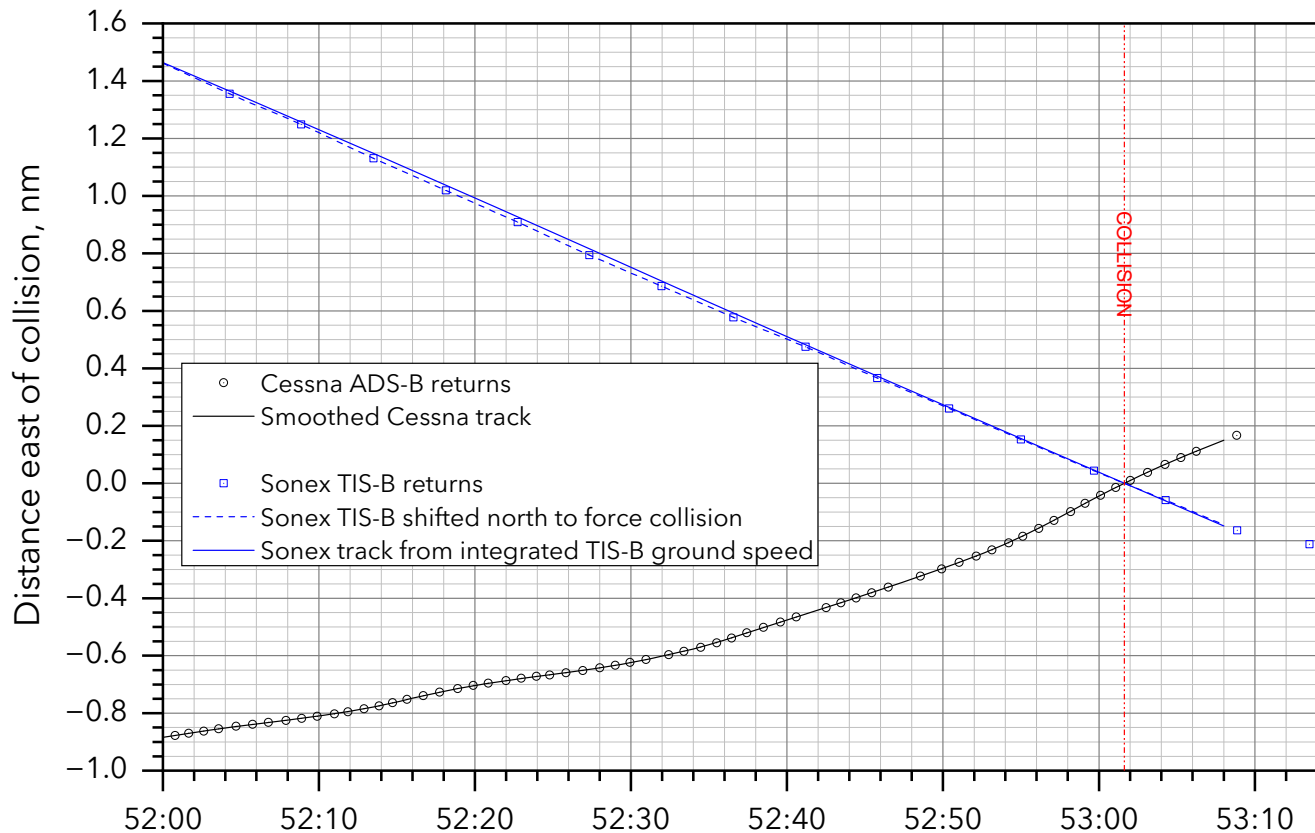
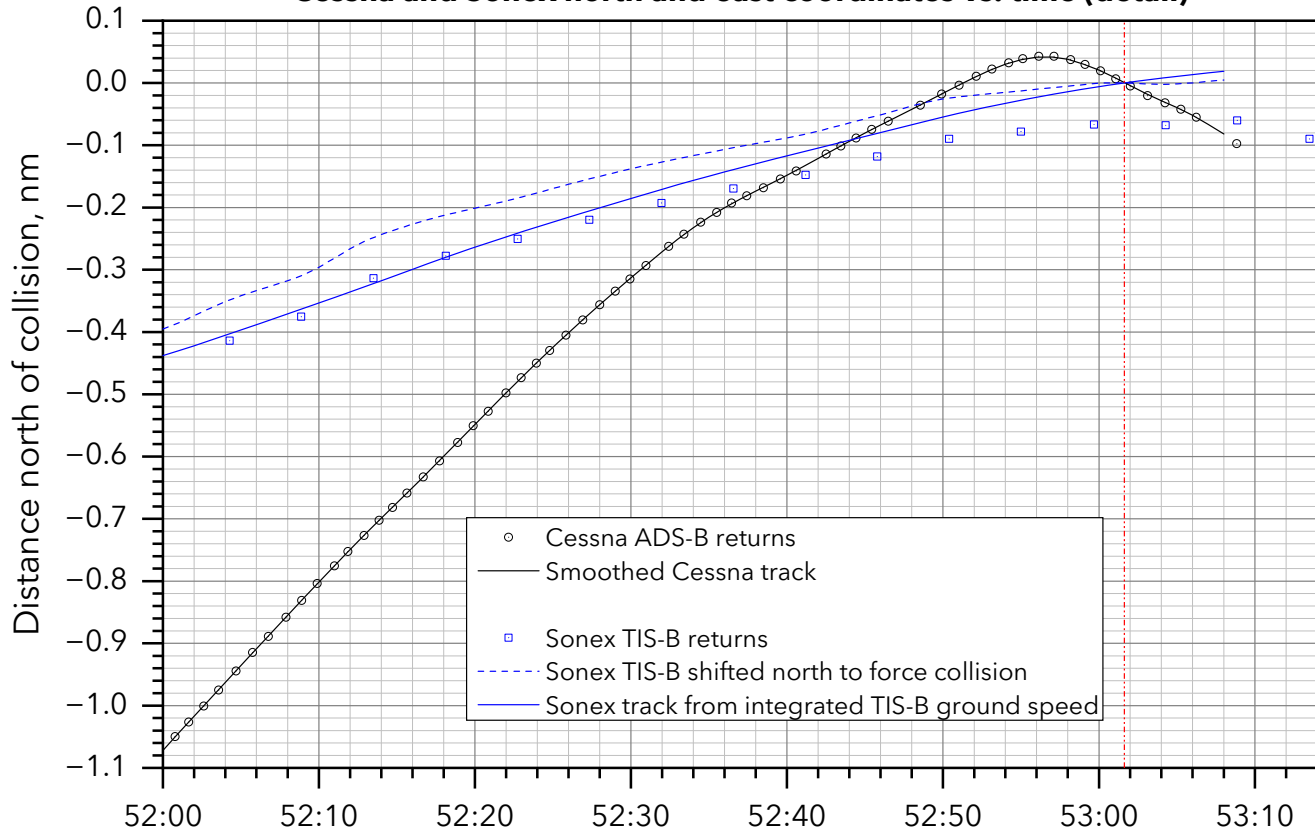


Figure 6a.

**CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022**

Cessna and Sonex north and east coordinates vs. time (detail)



Time after 08:00:00 MDT, MM:SS

Figure 6b.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Cessna and Sonex altitude data vs. time

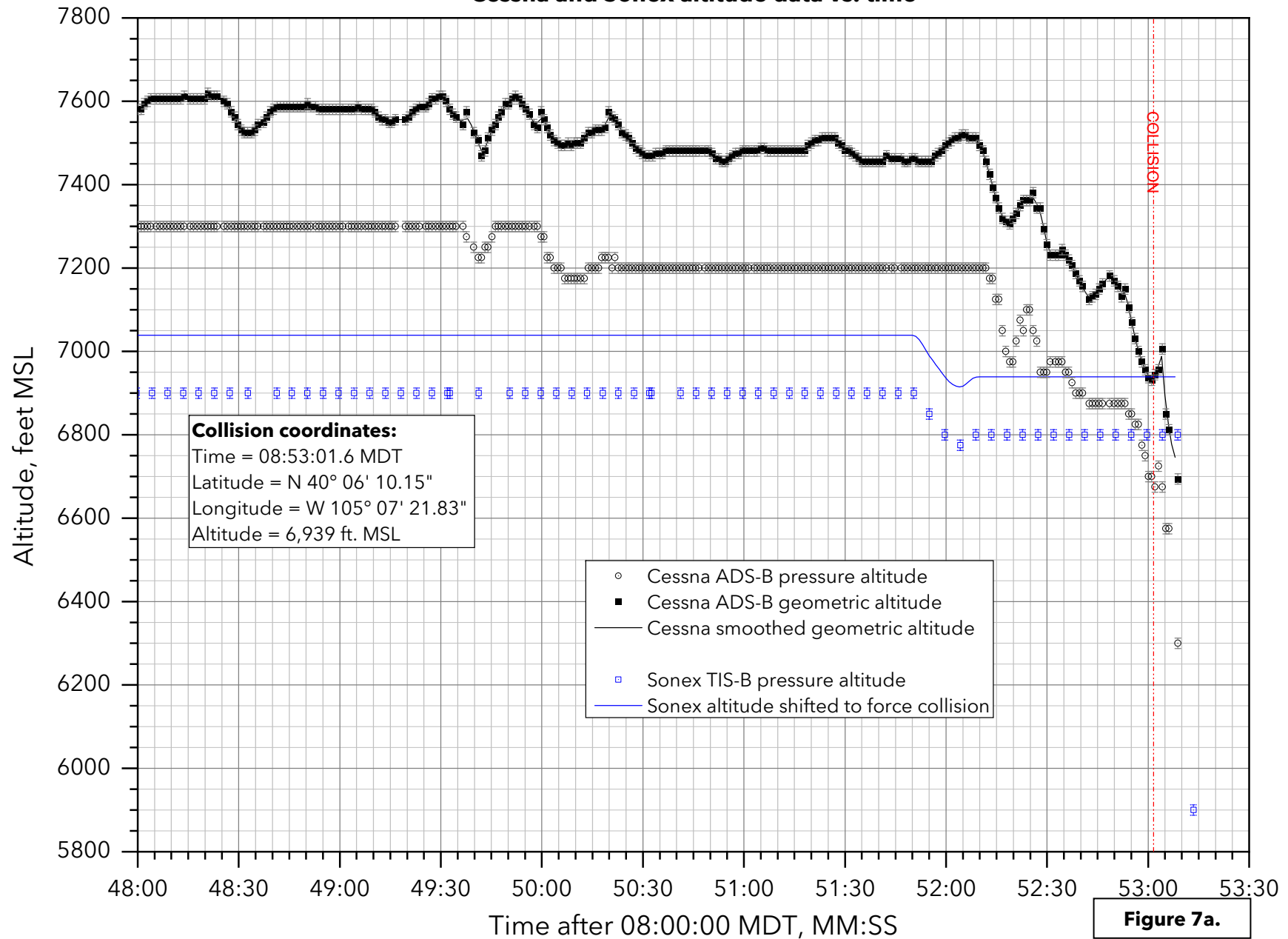
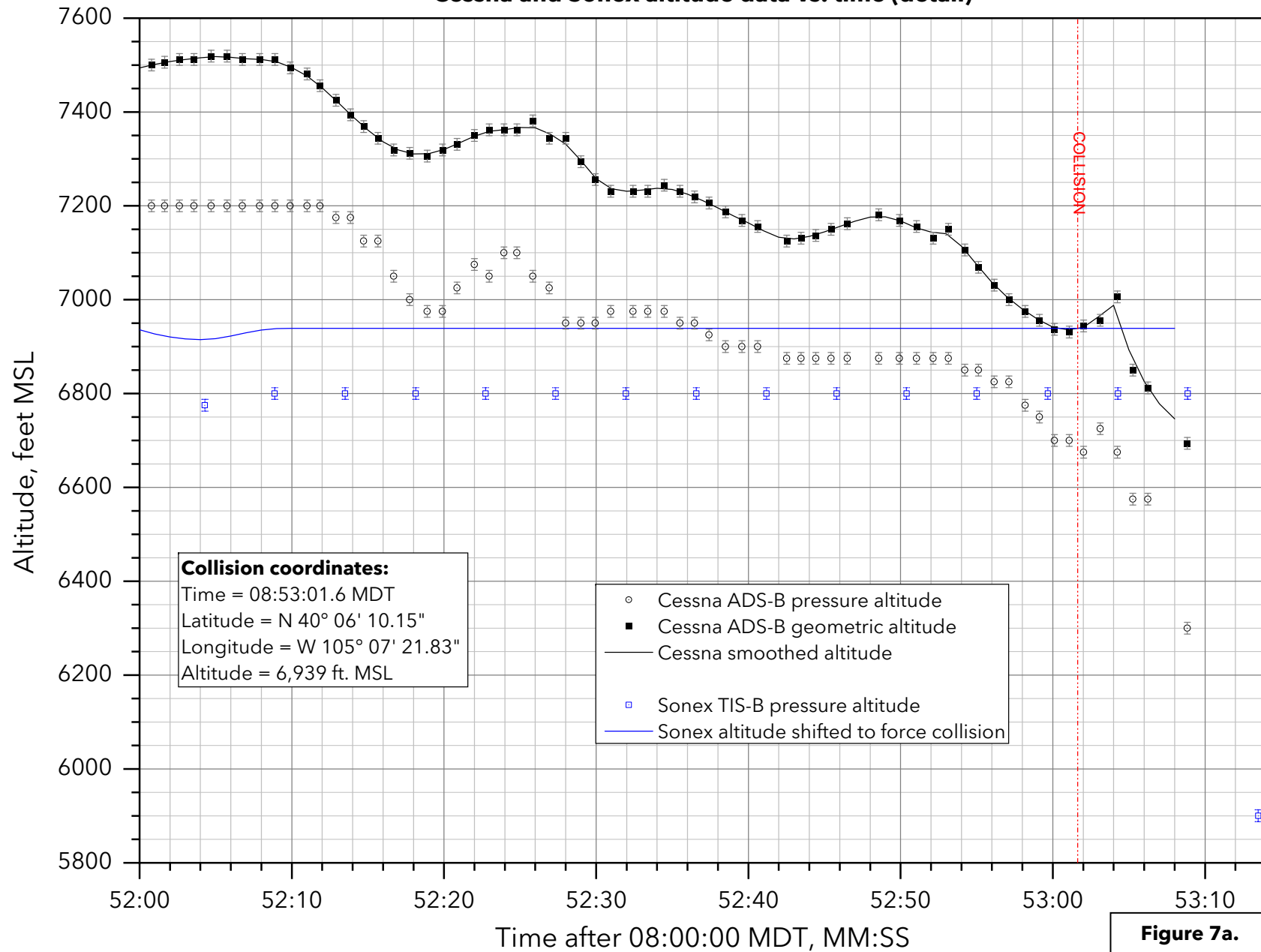


Figure 7a.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Cessna and Sonex altitude data vs. time (detail)



Winds aloft from 15:00 UTC (09:00 MDT) HRRR model sounding

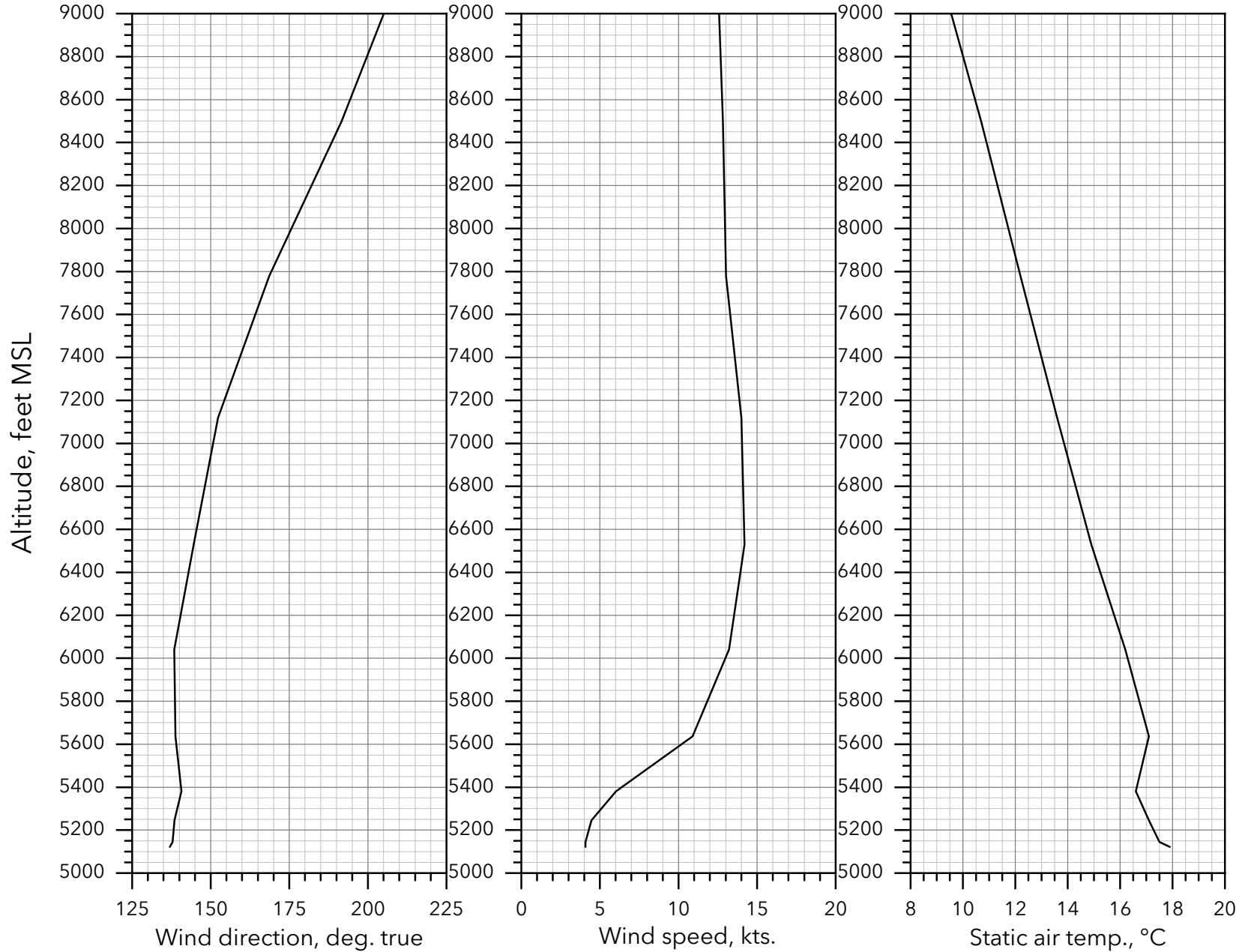
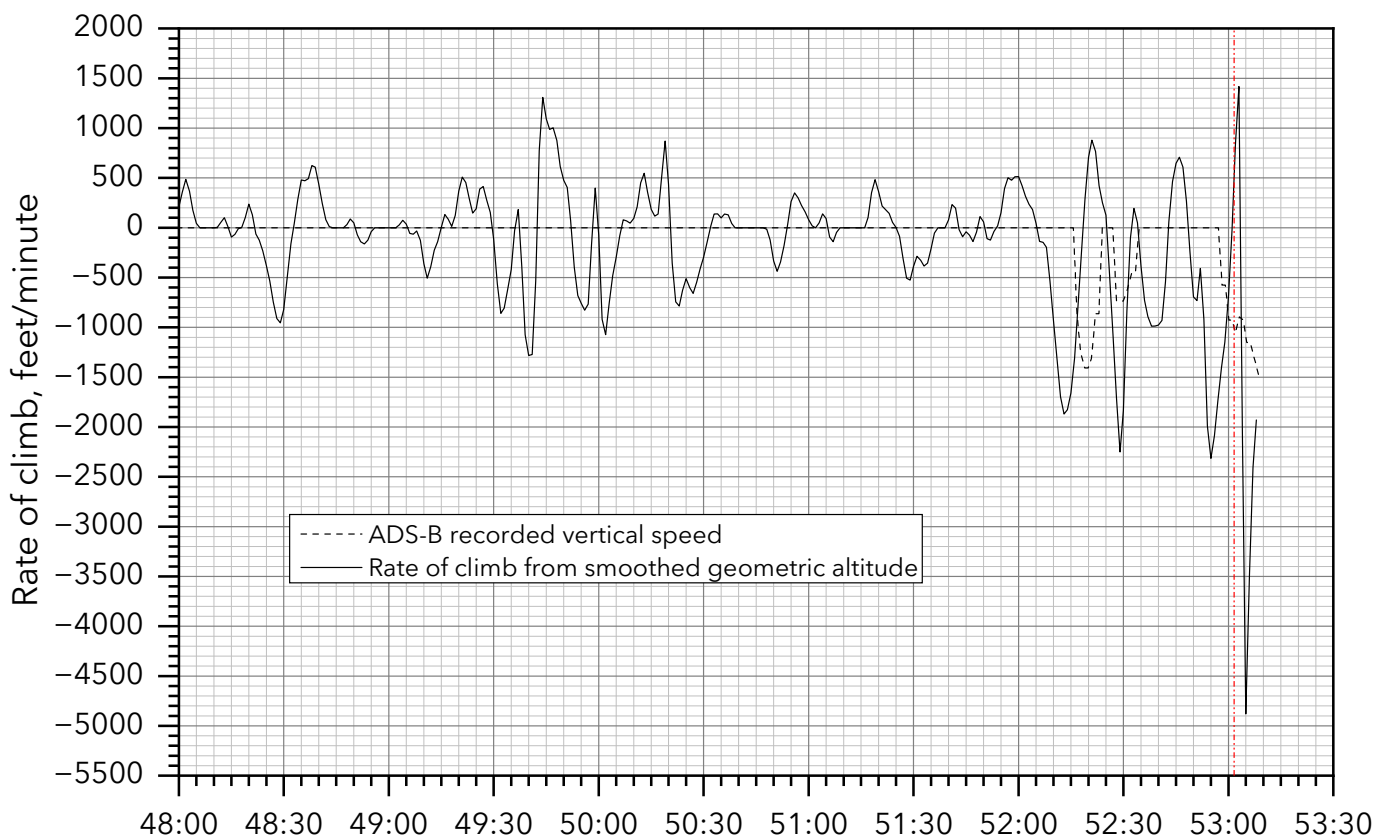
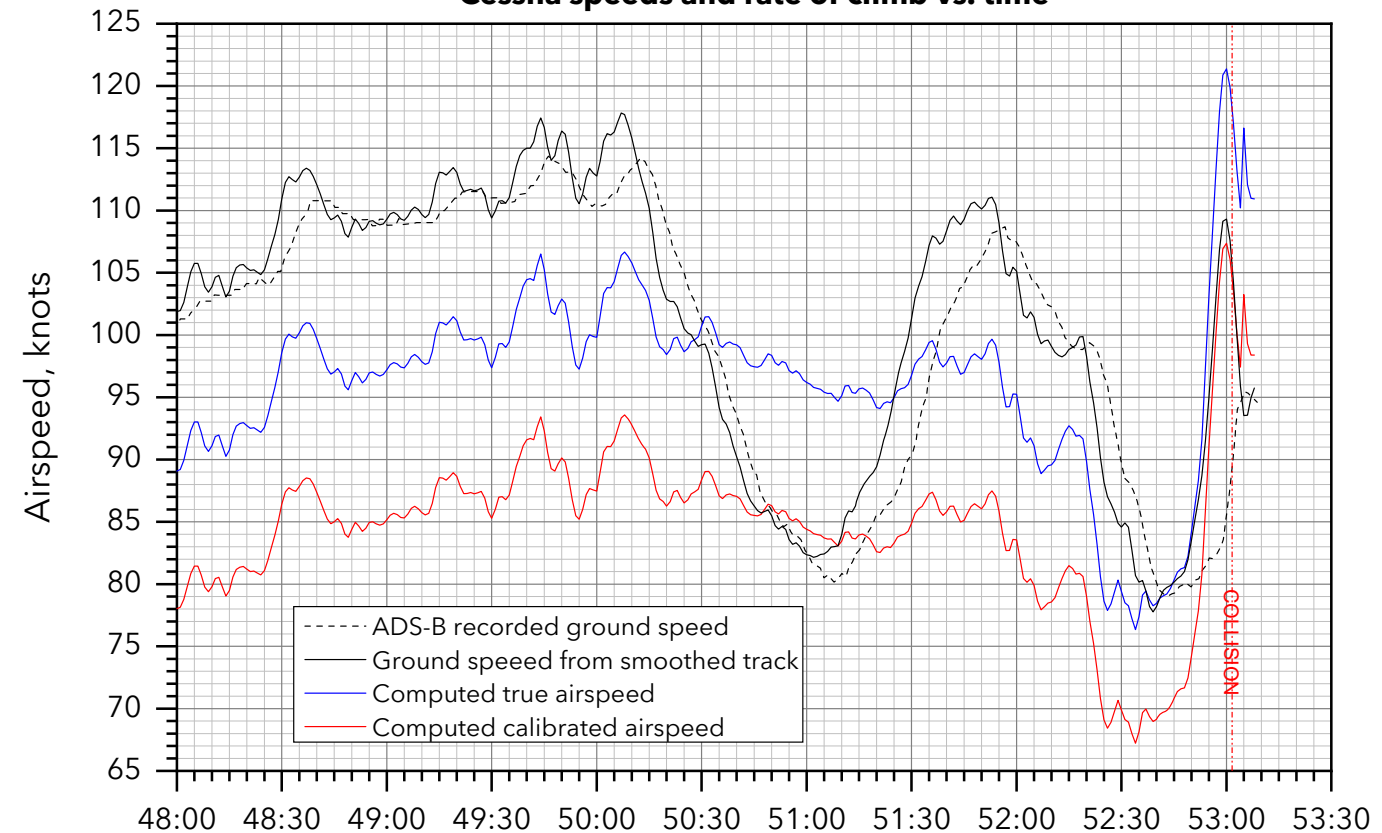


Figure 8.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022

Cessna speeds and rate of climb vs. time

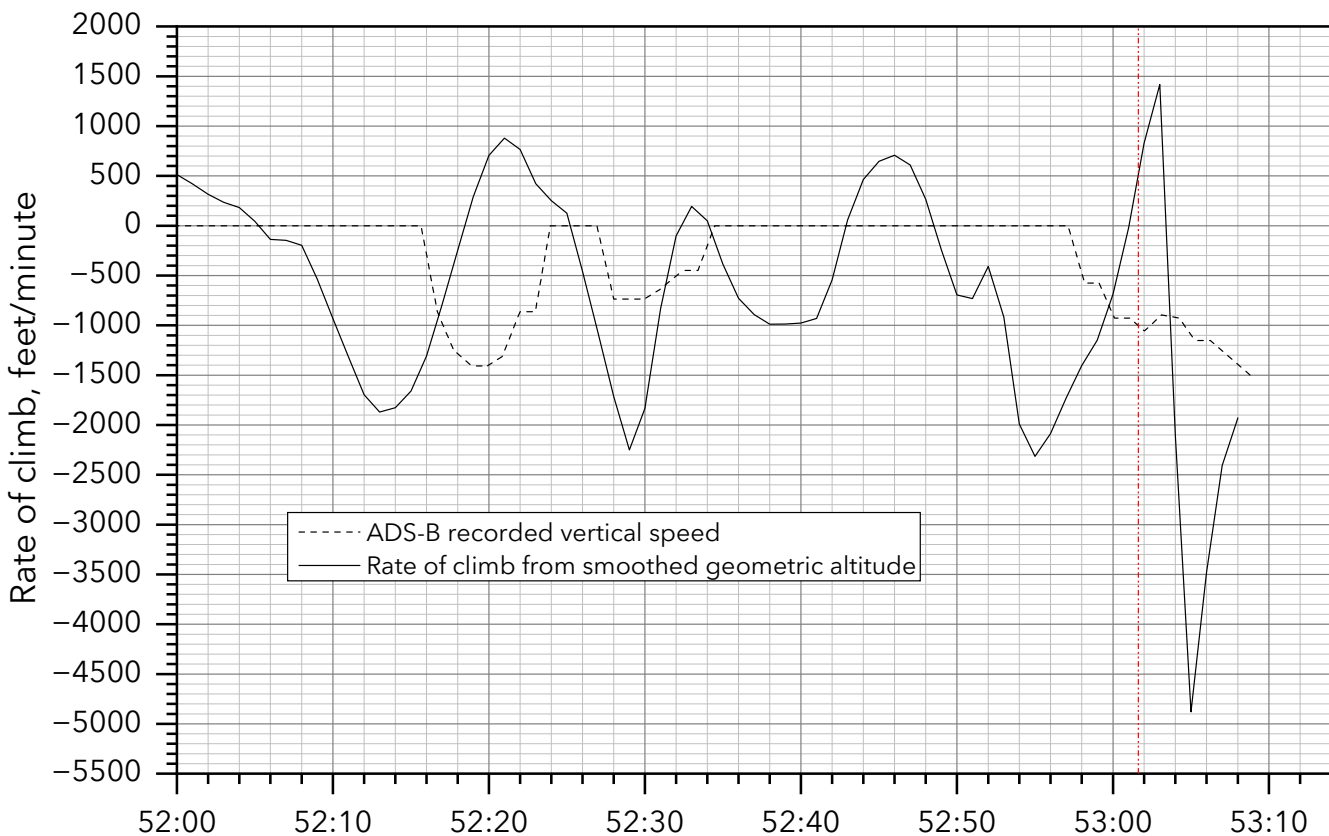
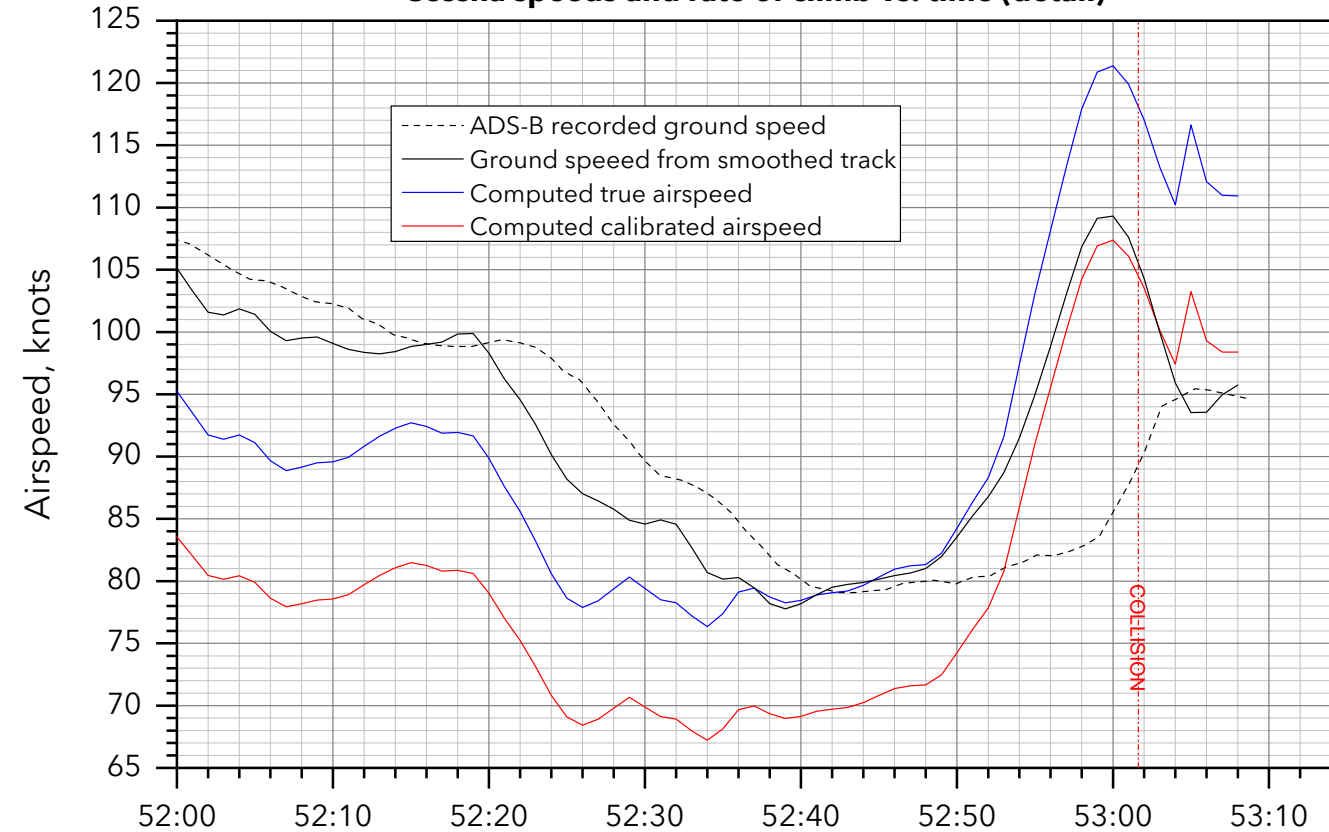


Time after 08:00:00 MDT, MM:SS

Figure 9a.

**CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022**

Cessna speeds and rate of climb vs. time (detail)



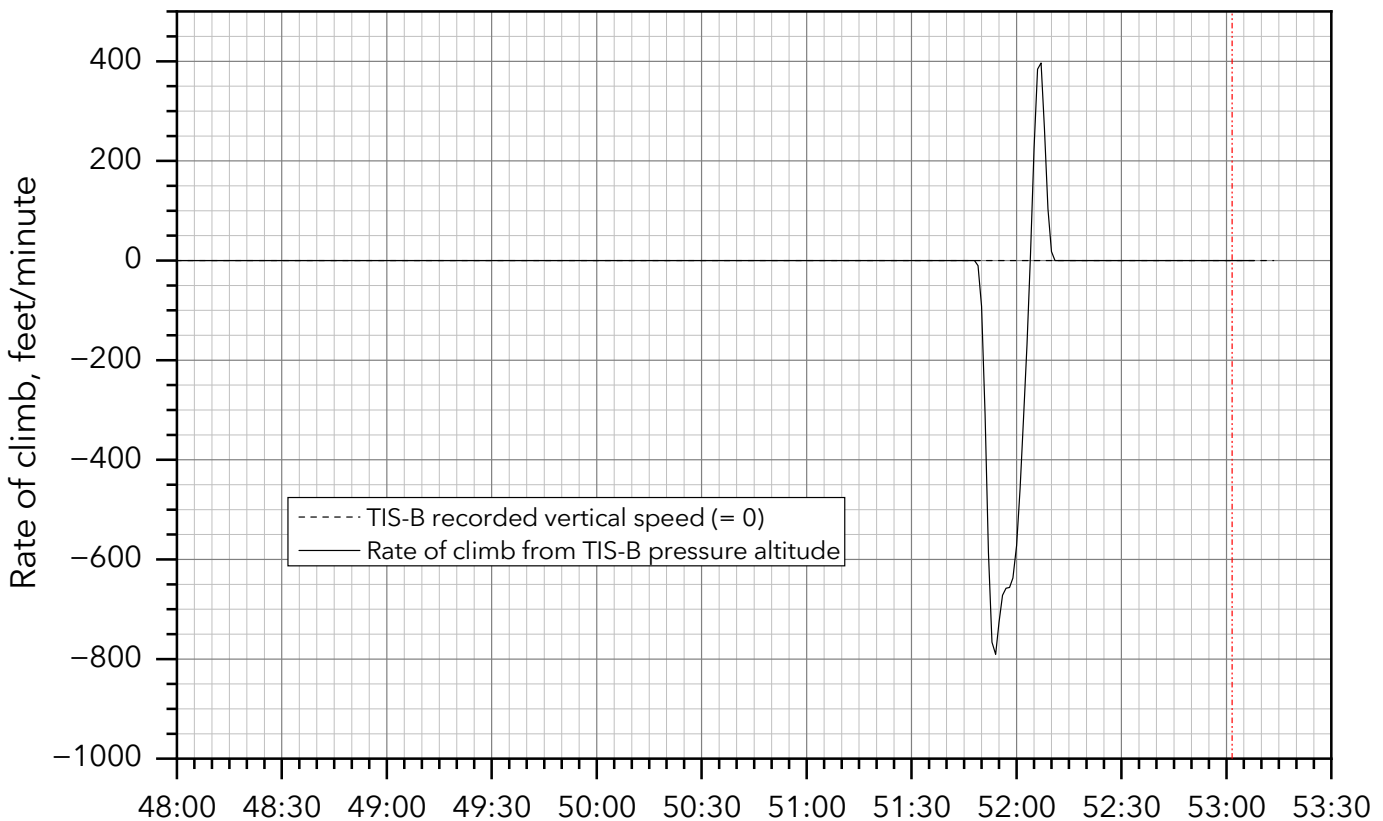
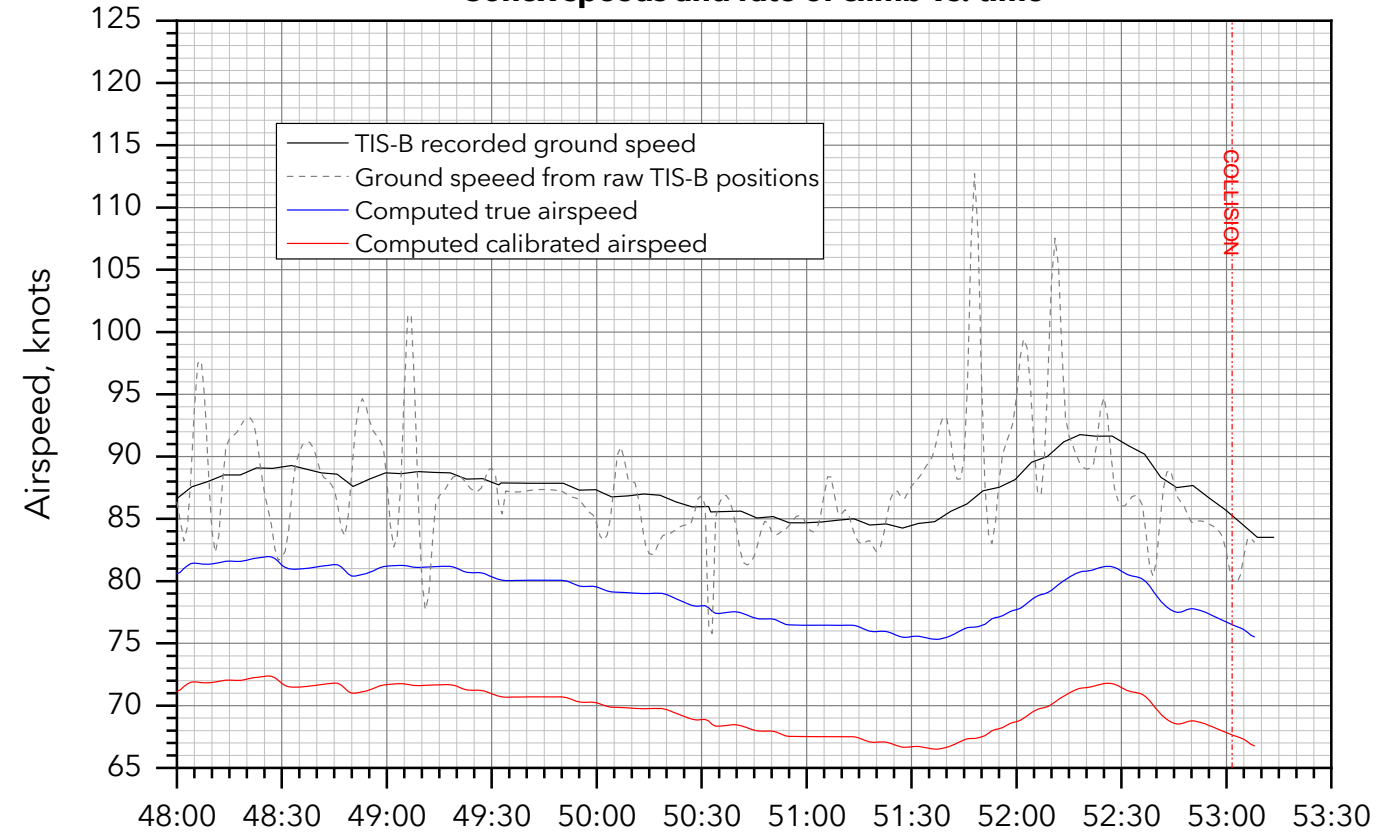
Time after 08:00:00 MDT, MM:SS

Figure 9b.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF

Longmont, CO, 9/17/2022

Sonex speeds and rate of climb vs. time

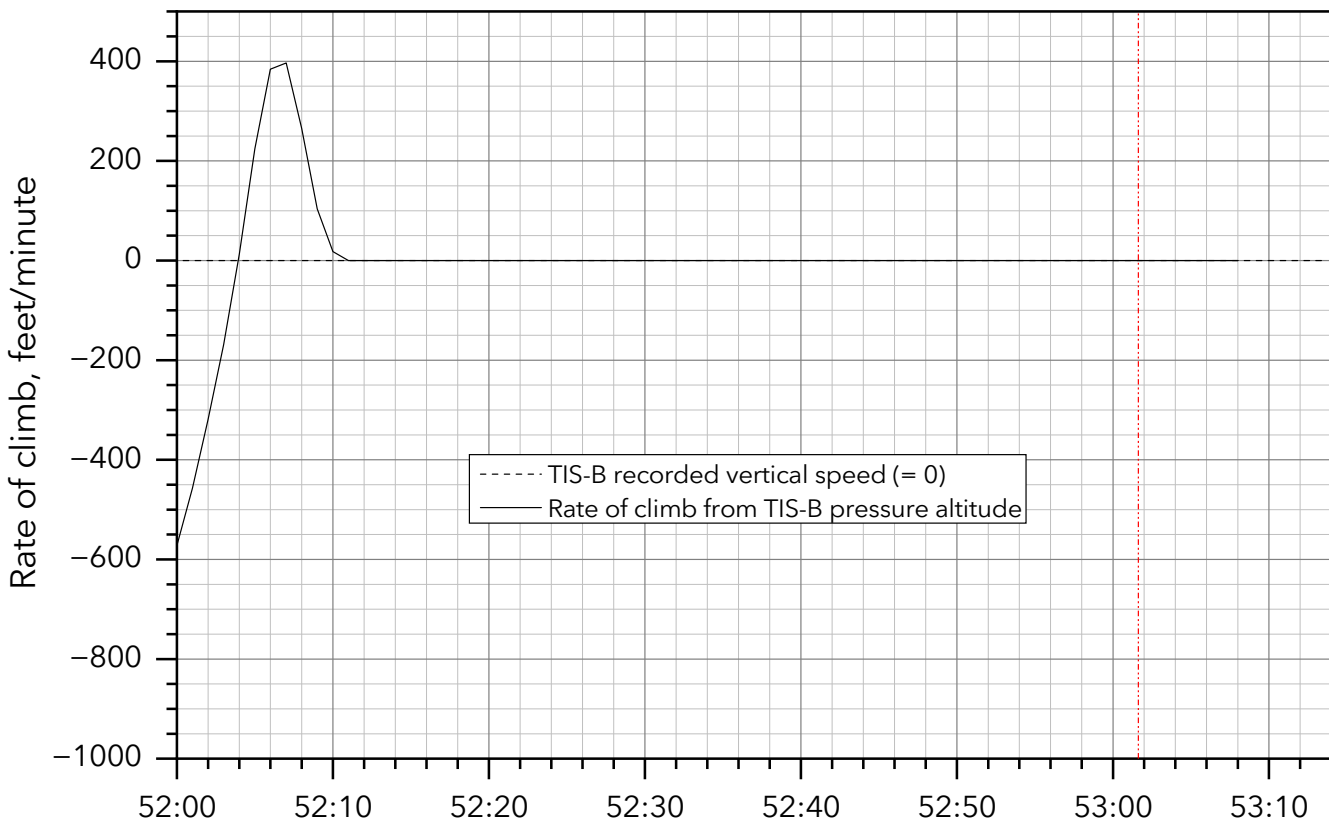
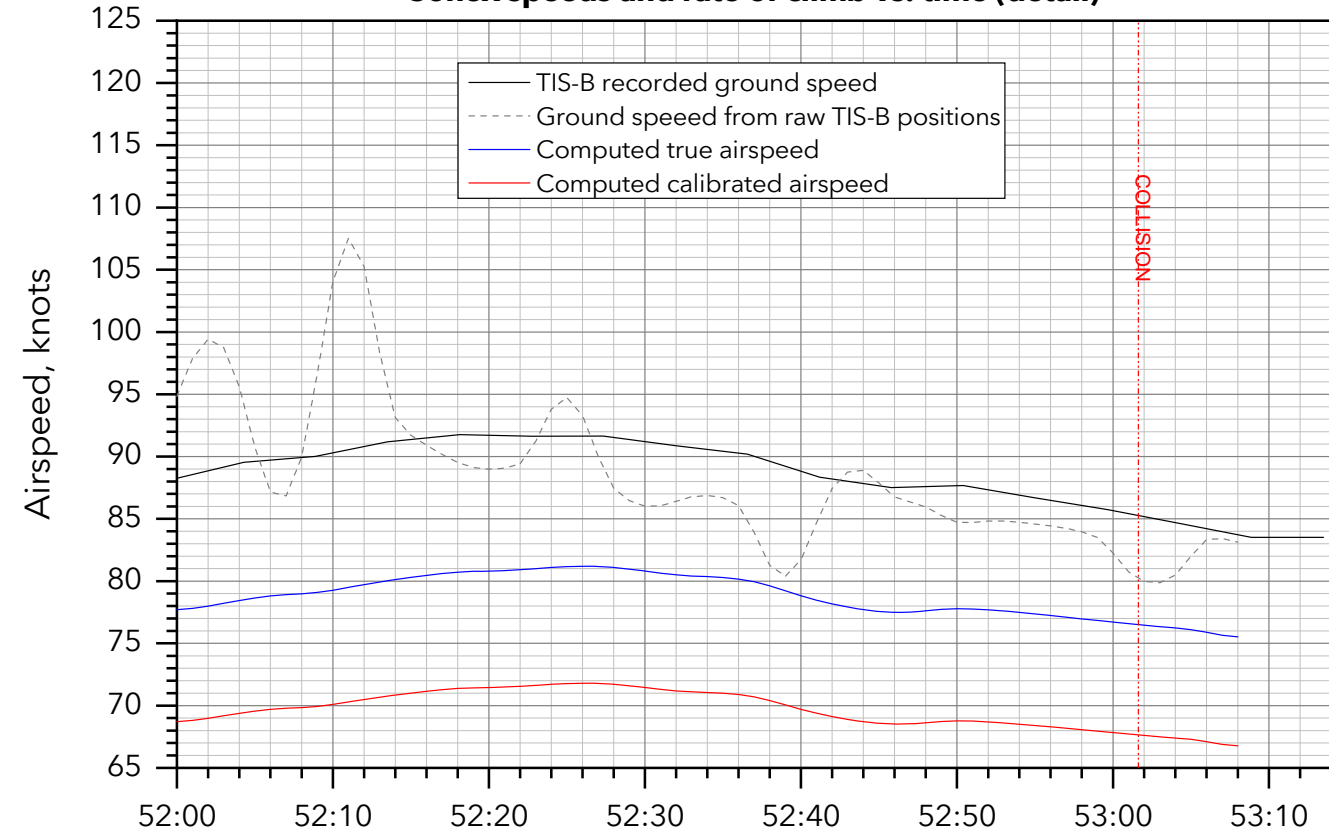


Time after 08:00:00 MDT, MM:SS

Figure 9c.

Longmont, CO, 9/17/2022

Sonex speeds and rate of climb vs. time (detail)



Time after 08:00:00 MDT, MM:SS

Figure 9d.

**CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022**

Cessna and Sonex separation and closure rate

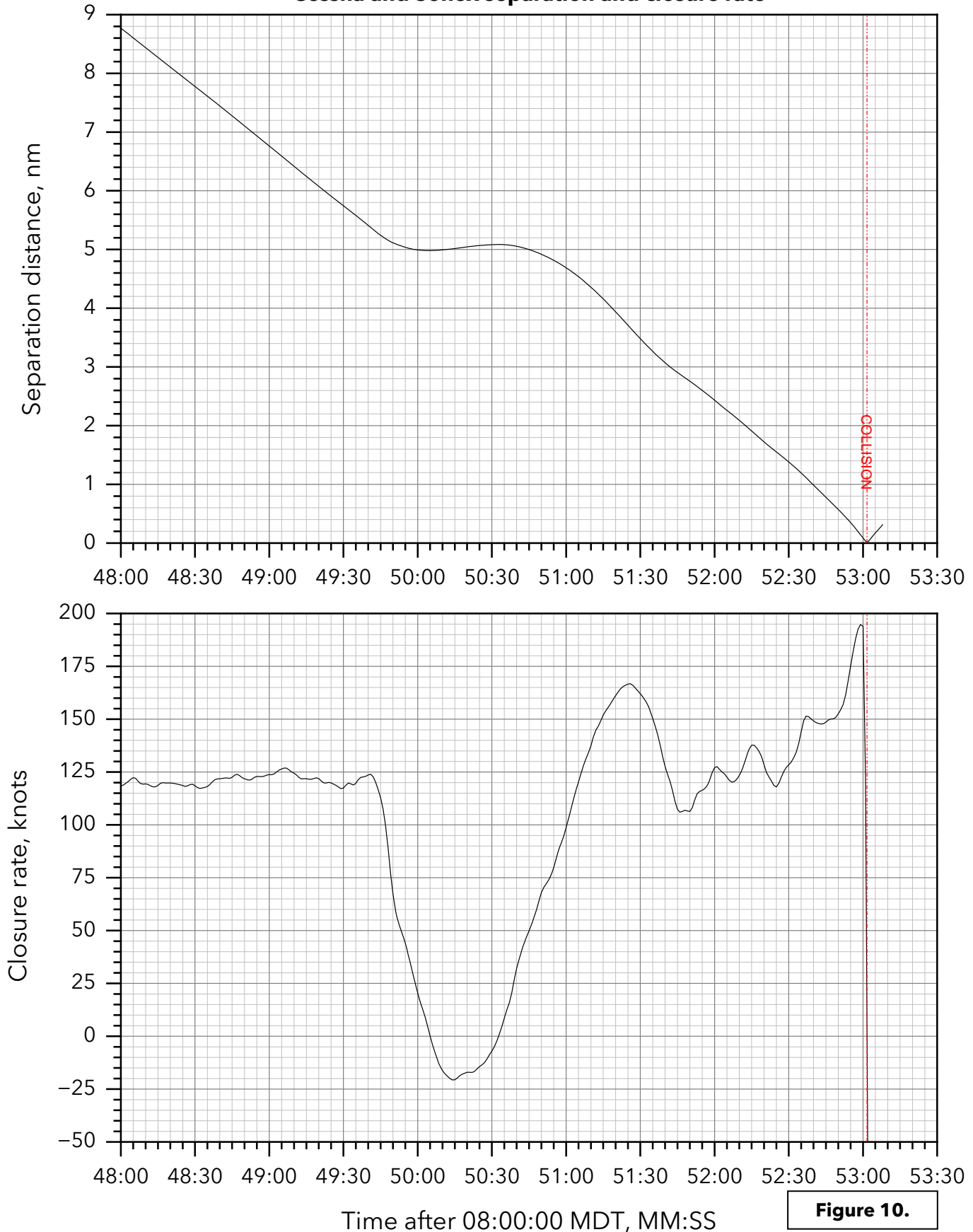


Figure 10.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022

Cessna and Sonex Euler angles

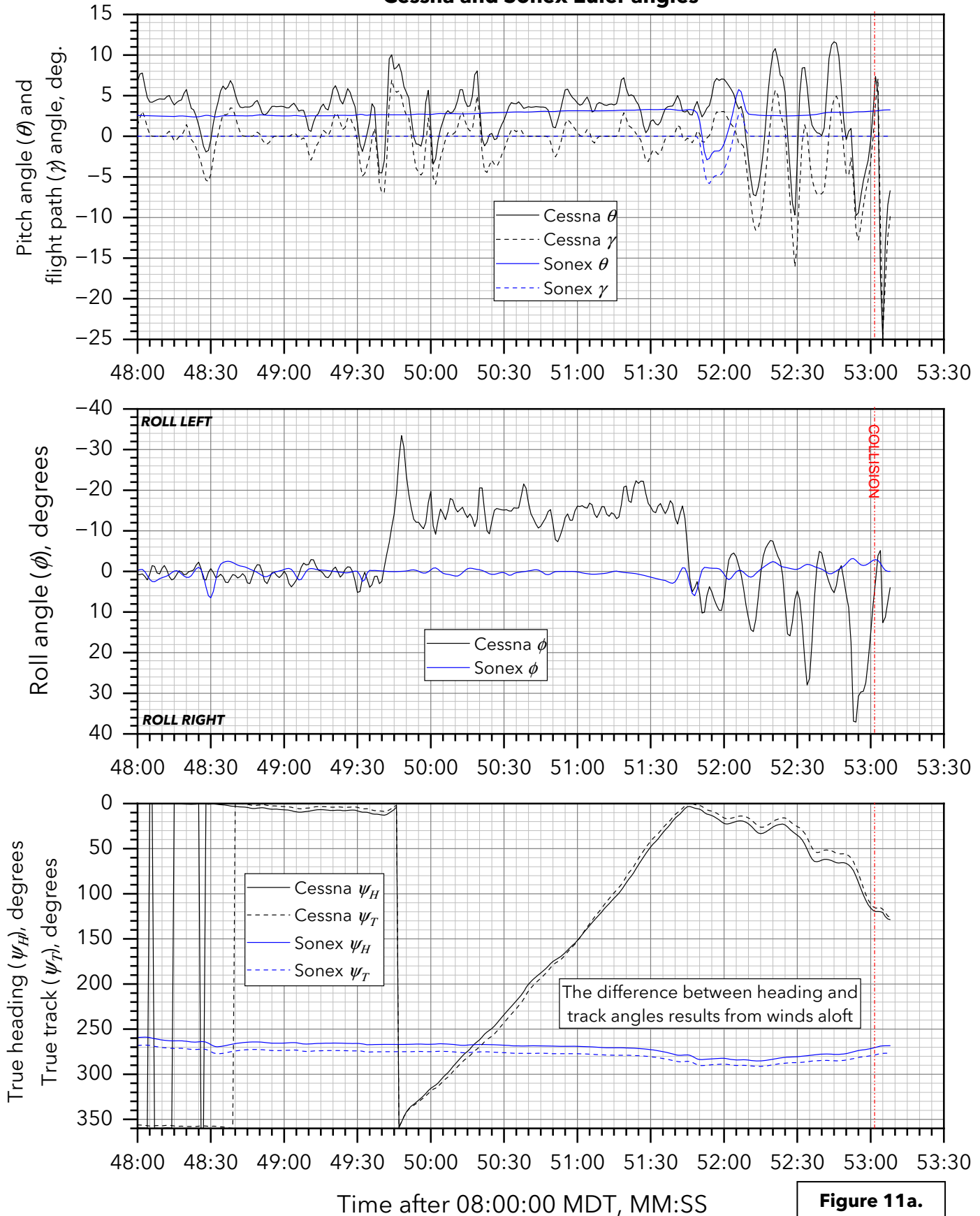


Figure 11a.

**CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022**

Cessna and Sonex Euler angles (detail)

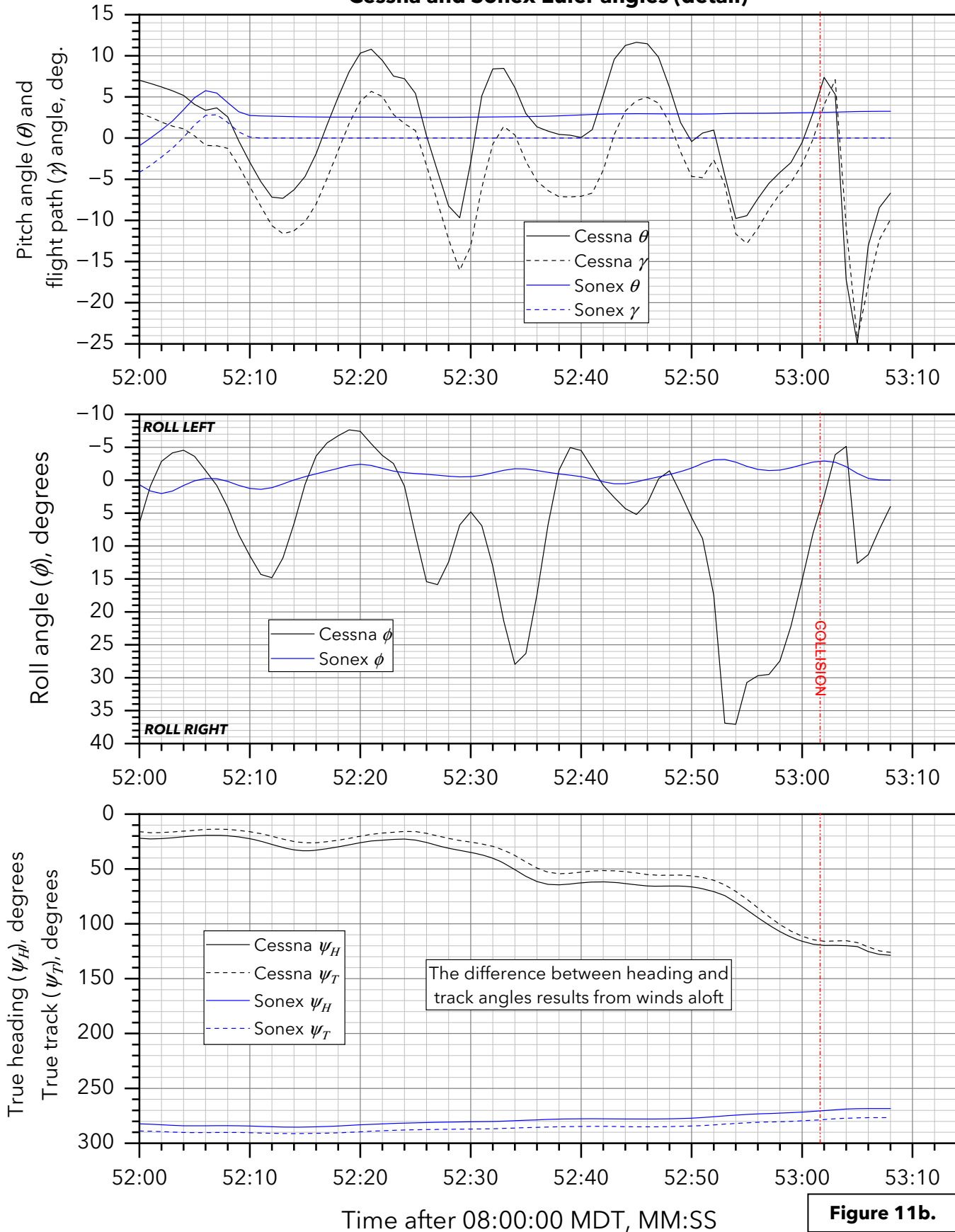


Figure 11b.

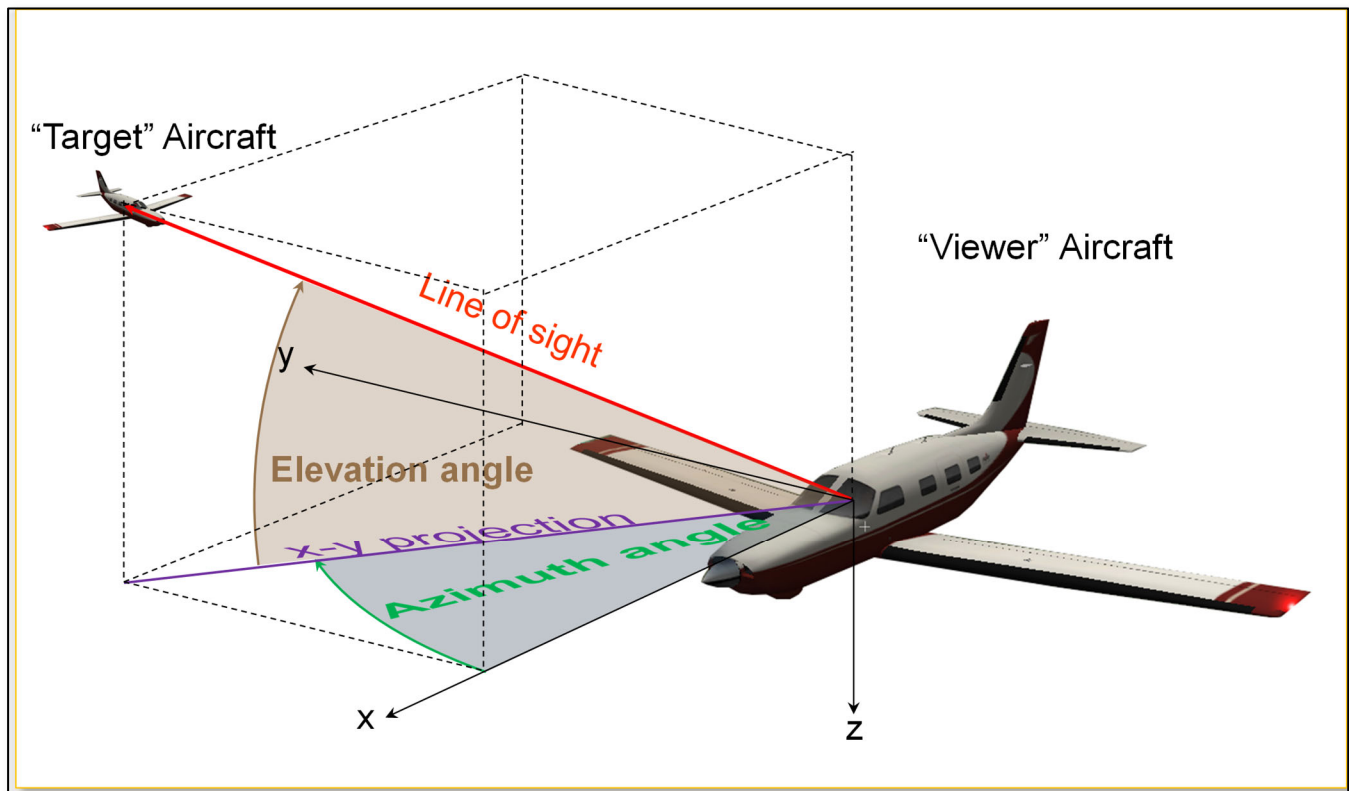
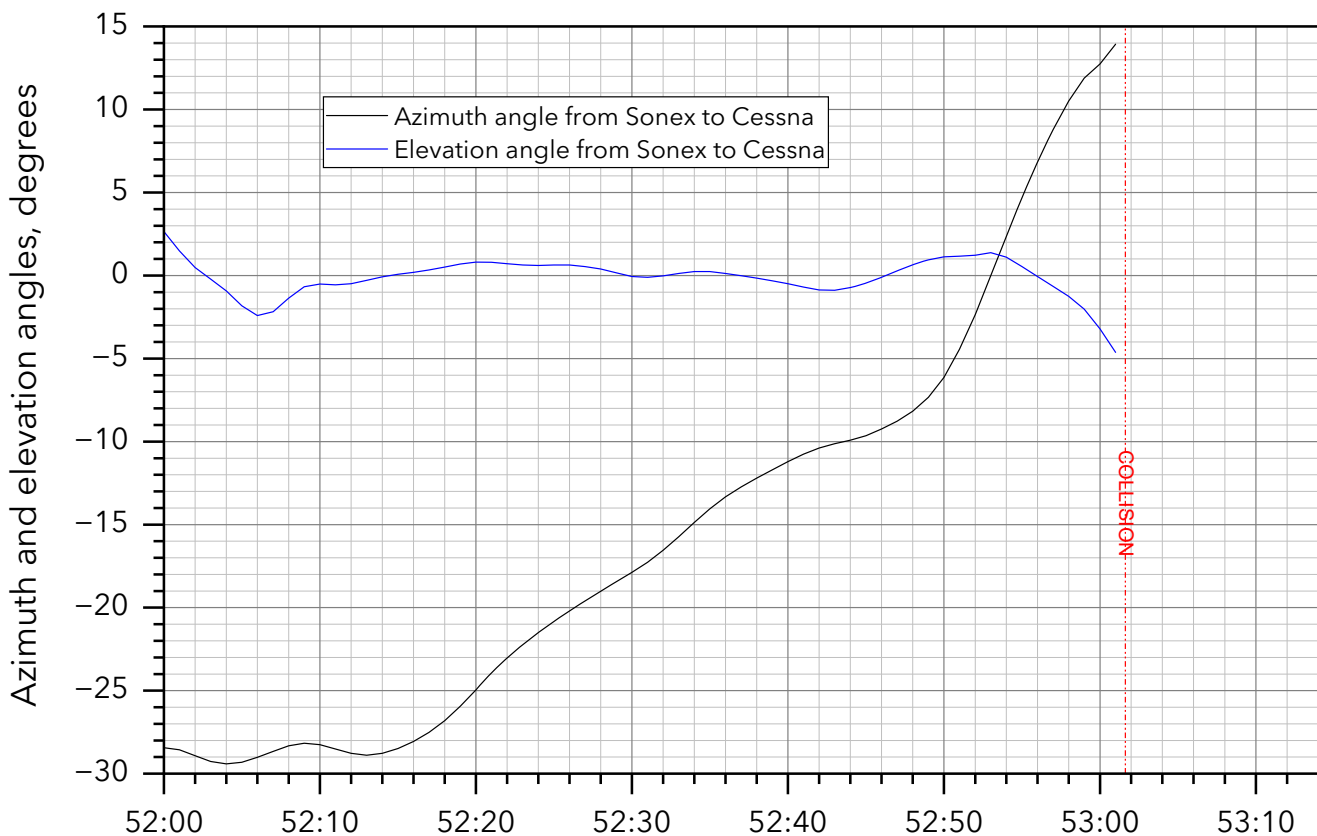
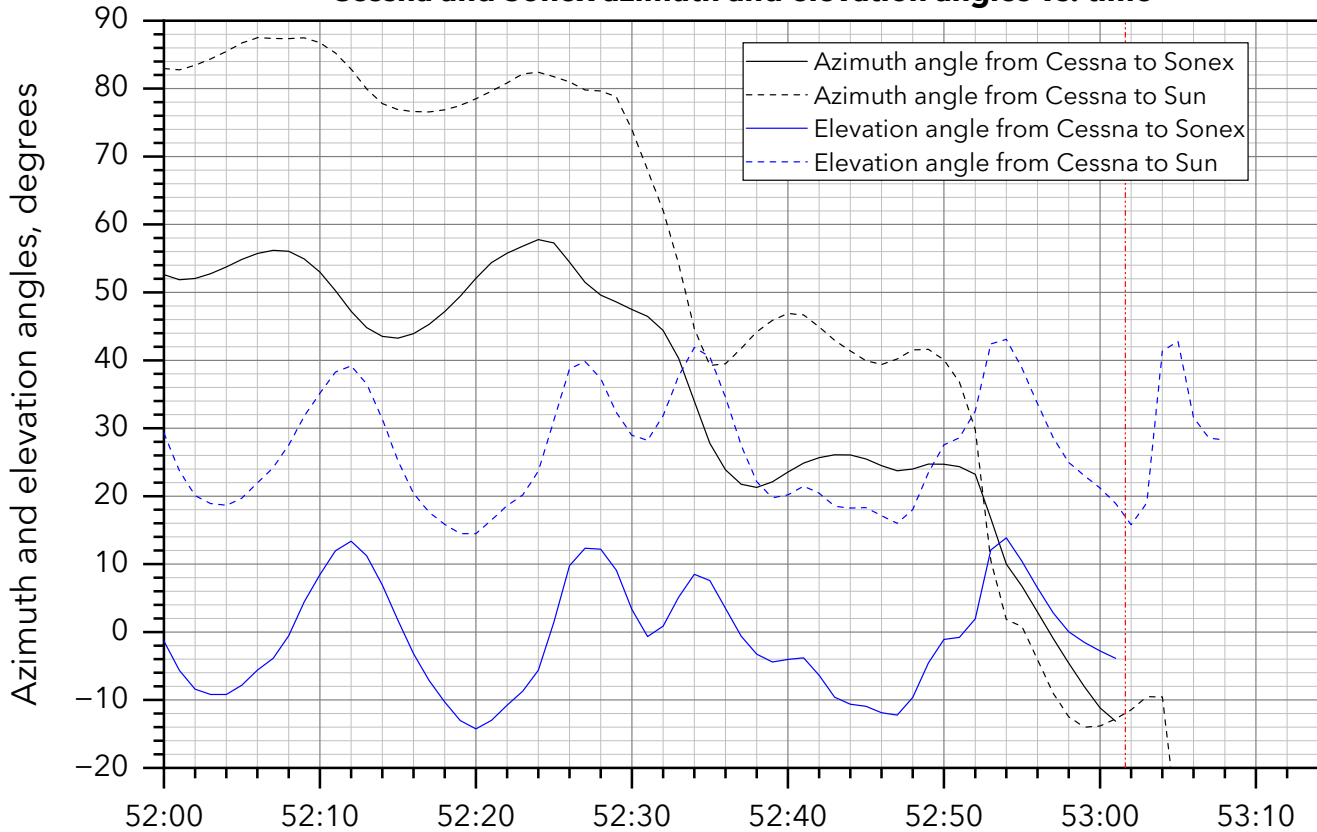


Figure 12. Azimuth and elevation angles from “viewer” airplane to “target” airplane.

**CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF
Longmont, CO, 9/17/2022**

Cessna and Sonex azimuth and elevation angles vs. time



Time after 08:00:00 MDT, MM:SS

Figure 13.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Elevation vs. azimuth viewing angles from pilot seat of Cessna to Sonex and to Sun

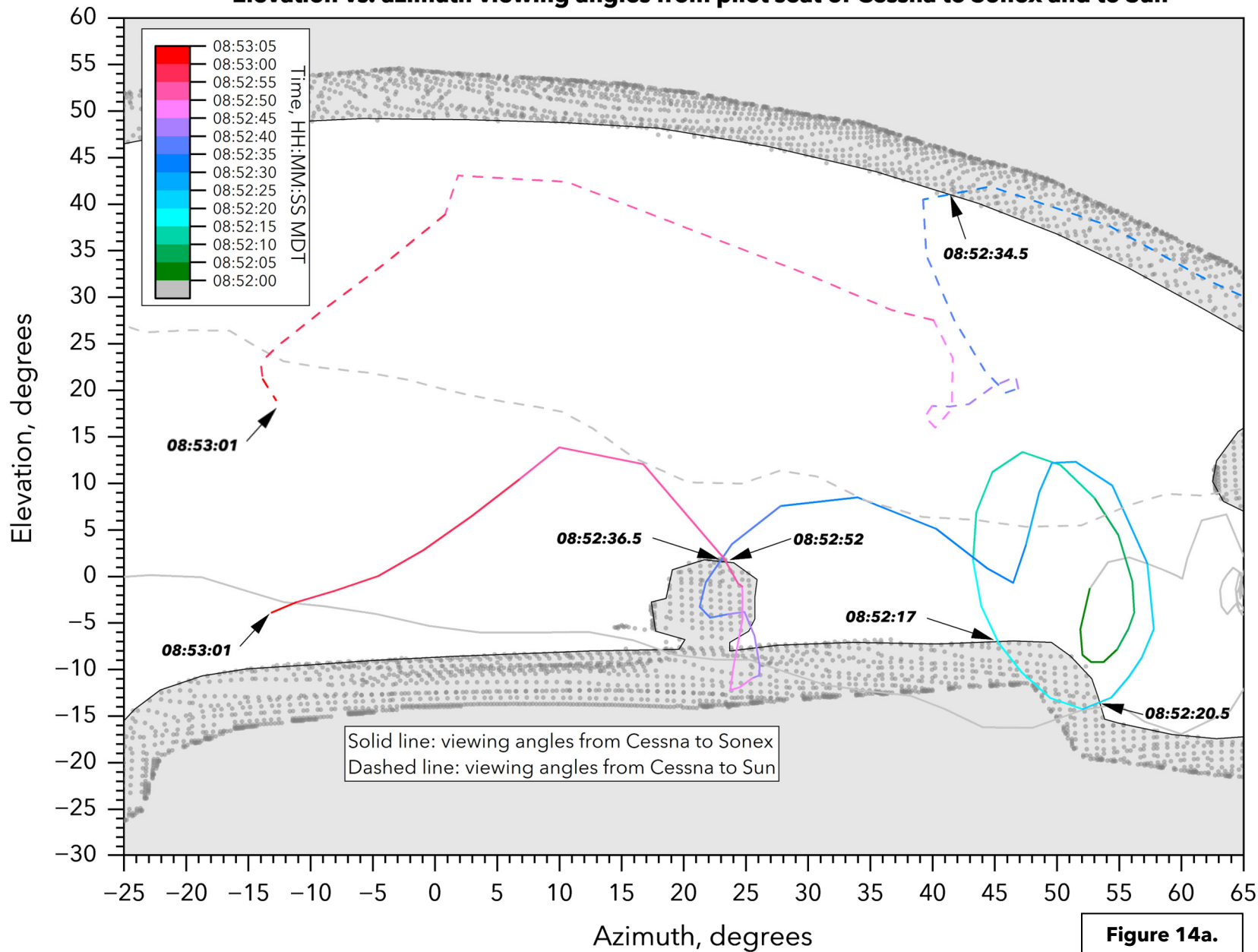


Figure 14a.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Elevation vs. azimuth viewing angles from copilot seat of Cessna to Sonex and to Sun

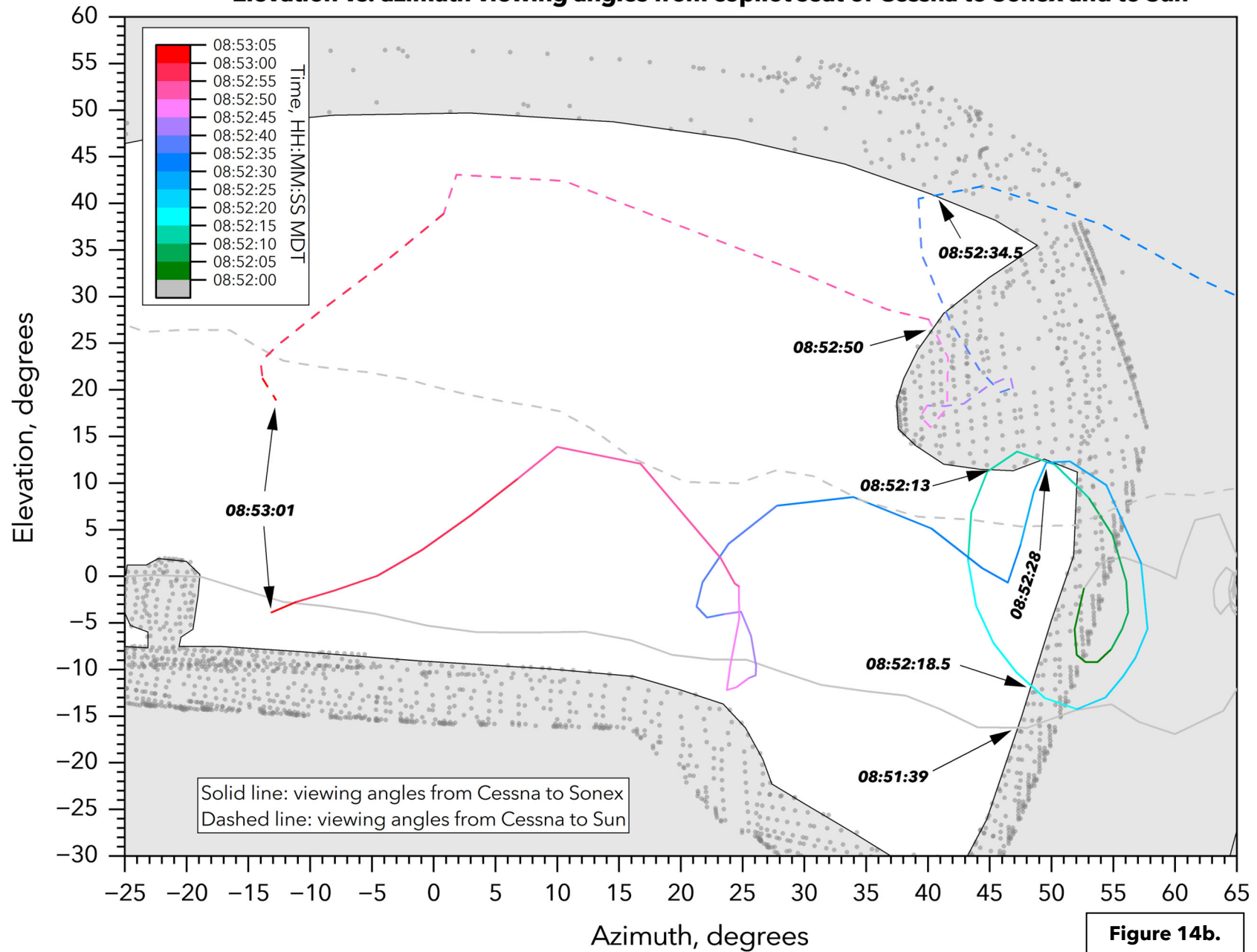


Figure 14b.

CEN22FA424: Midair collision, Cessna 172S N2117Y / Sonex Xenos-B N255BF, Longmont, CO, 9/17/2022

Elevation vs. azimuth viewing angles from pilot seat of Sonex to Cessna

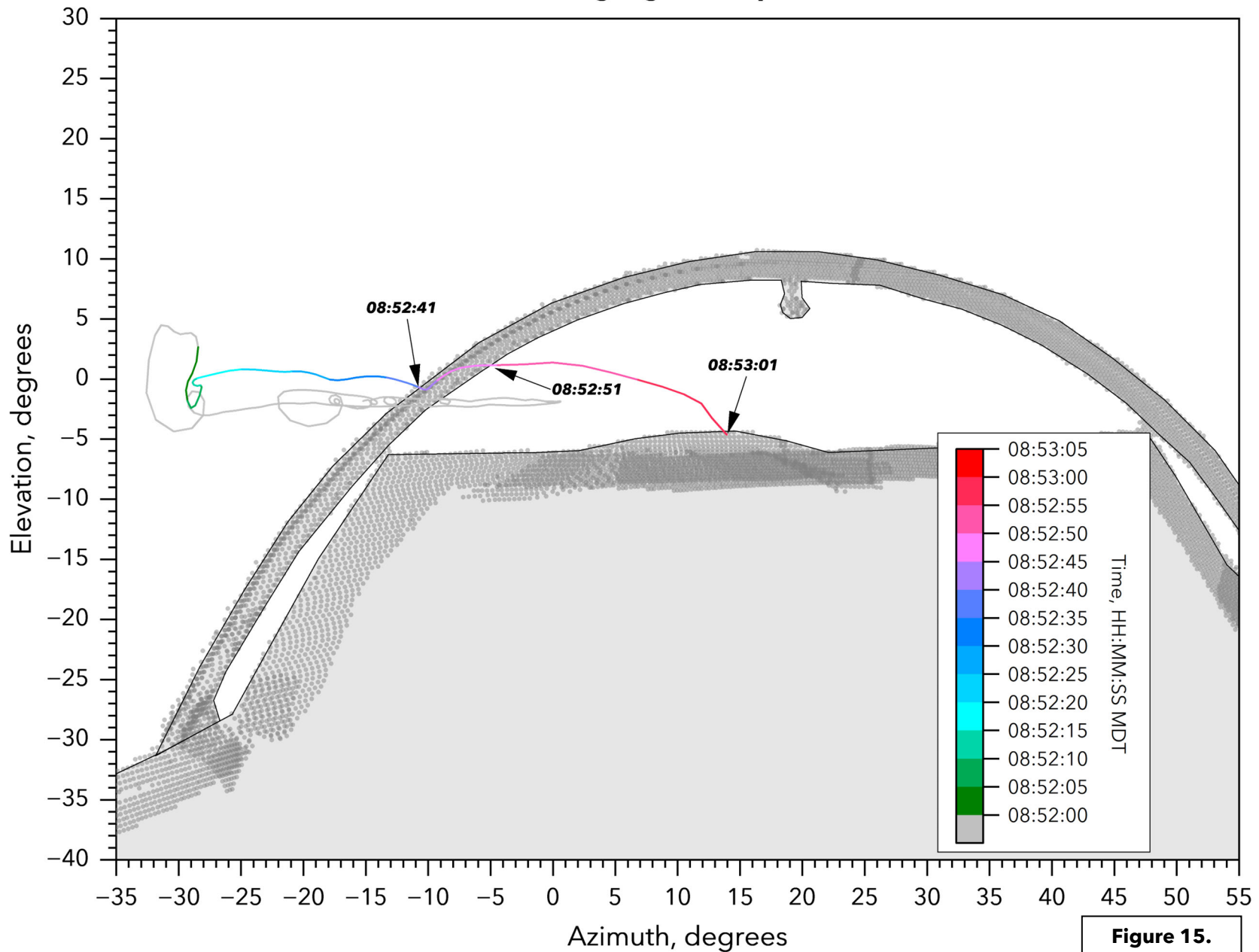


Figure 15.



Figure 16a. Color image of the 360° laser scan from the left seat of the exemplar Cessna172. The yellow box highlights the area depicted in Figure 14a.

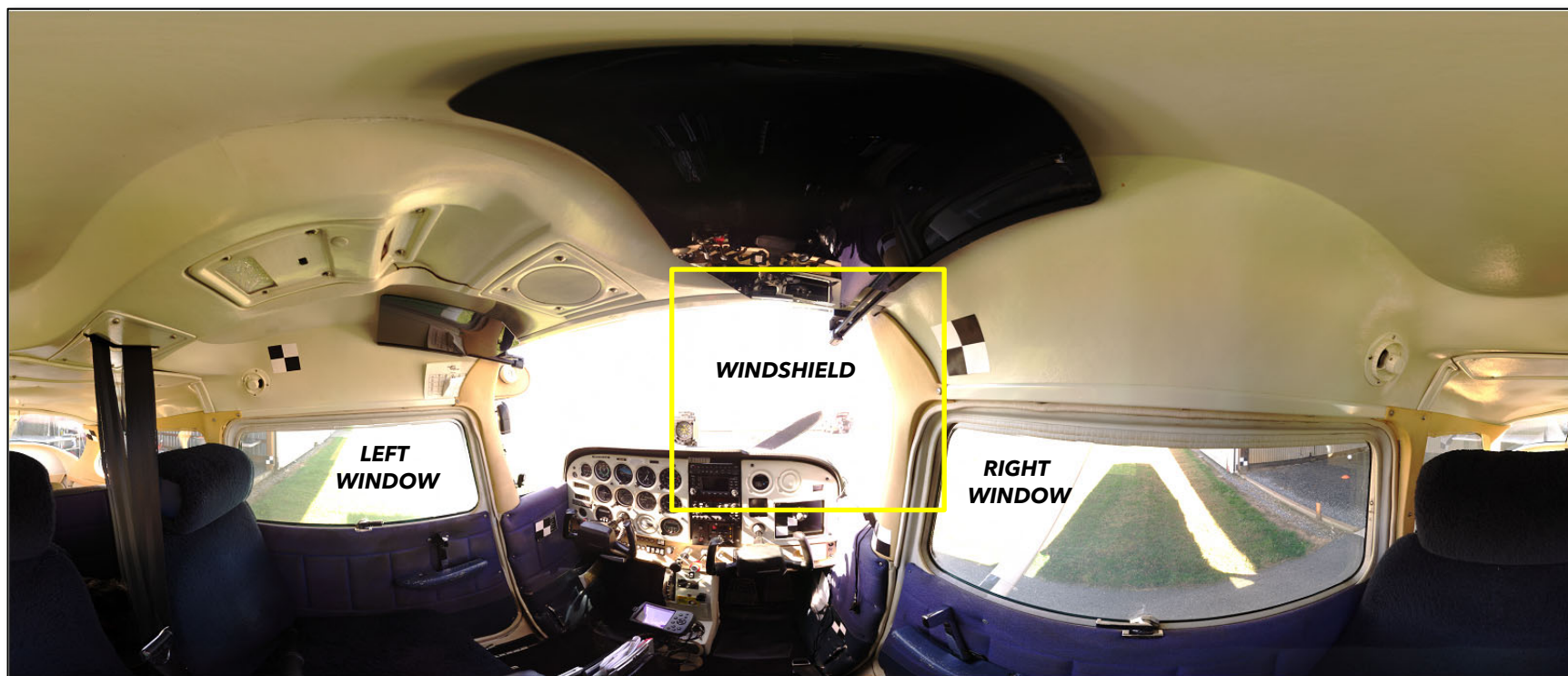


Figure 16b. Color image of the 360° laser scan from the right seat of the exemplar Cessna 172. The yellow box highlights the area depicted in Figure 14b.

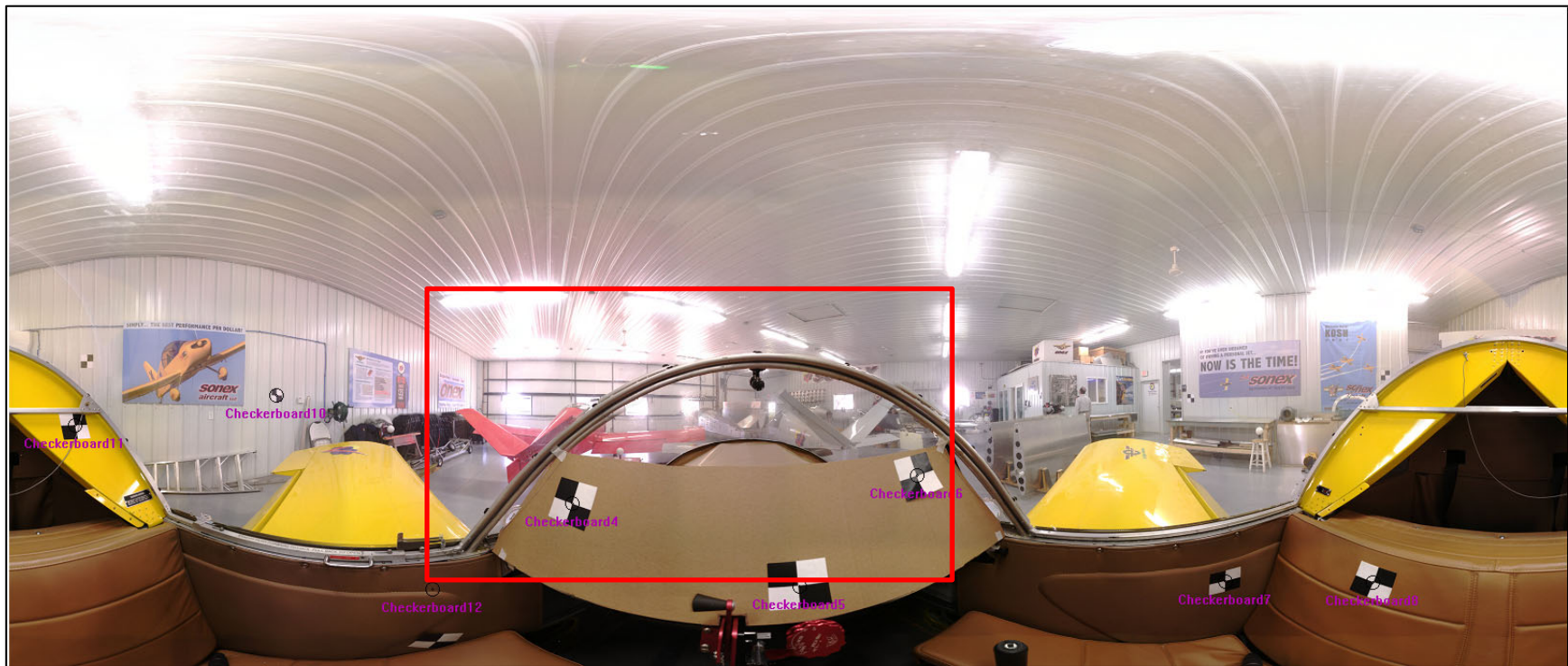


Figure 17a. Color image of the 360° laser scan from the right seat of the exemplar Sonex, including a cardboard template used to represent the wide instrument panel installed in N255BF. The red box highlights the area depicted in Figure 15.



Figure 17b. Color image of the 360° laser scan from the right seat of the exemplar Sonex, with the cardboard template removed, depicting the original exemplar airplane configuration.

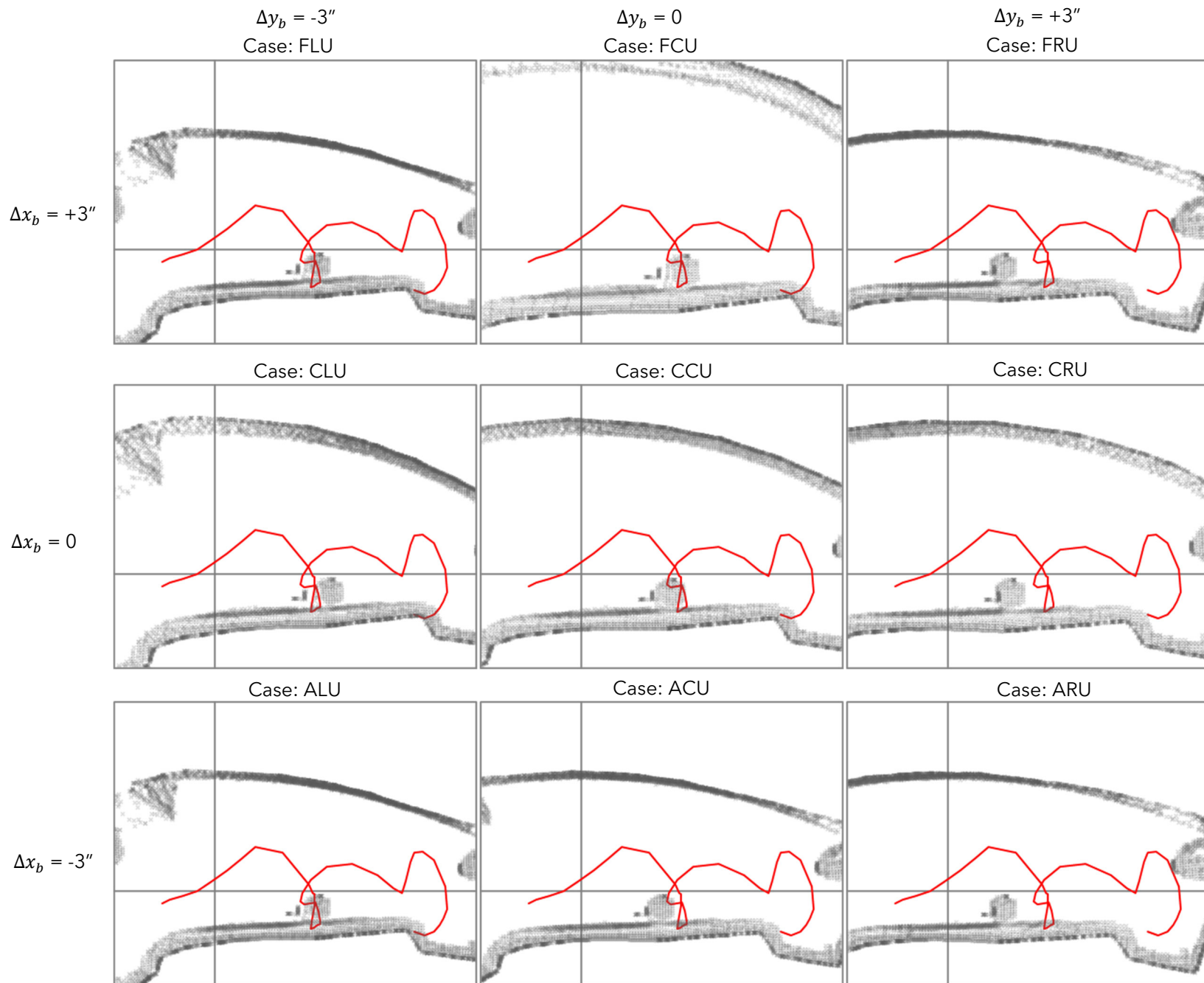


Figure 18a. Viewing angles for the Cessna pilot seat at $\Delta z_b = -1.5''$ (i.e., up). Plots are elevation angle vs. azimuth angle.

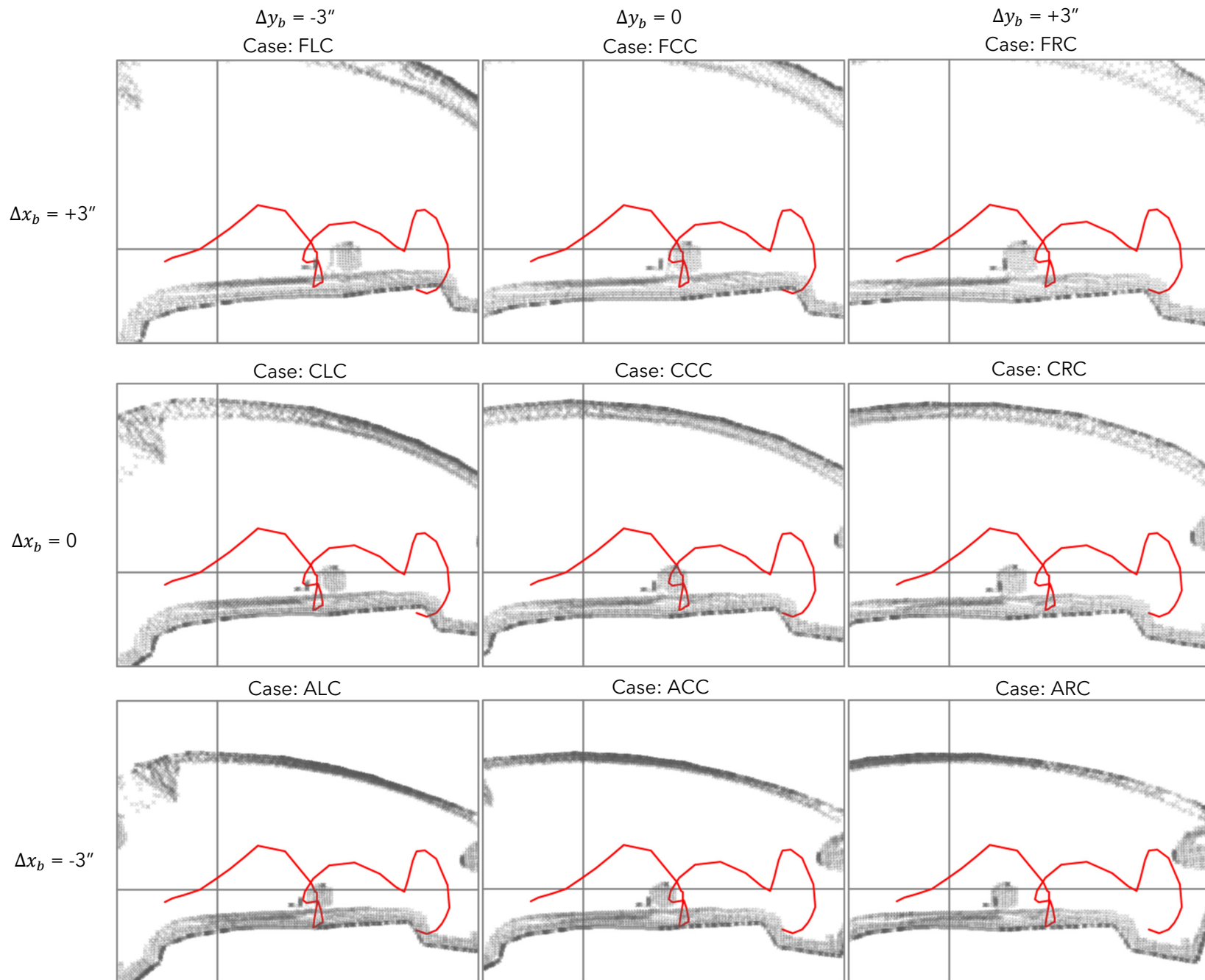


Figure 18b. Viewing angles for the Cessna pilot seat at $\Delta z_b = 0$. Plots are elevation angle vs. azimuth angle.

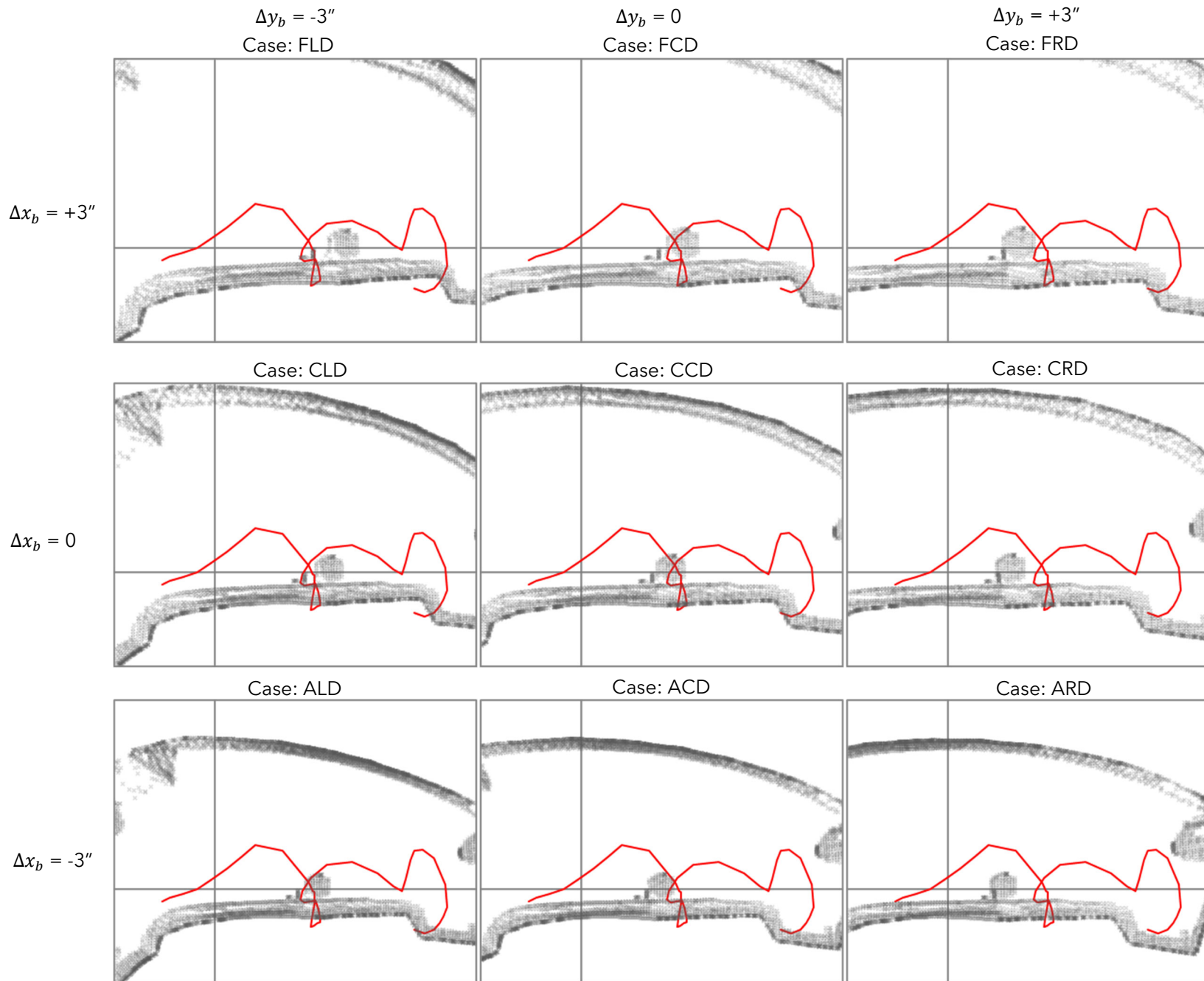


Figure 18c. Viewing angles for the Cessna pilot seat at $\Delta z_b = +1.5''$ (i.e., down). Plots are elevation angle vs. azimuth angle.

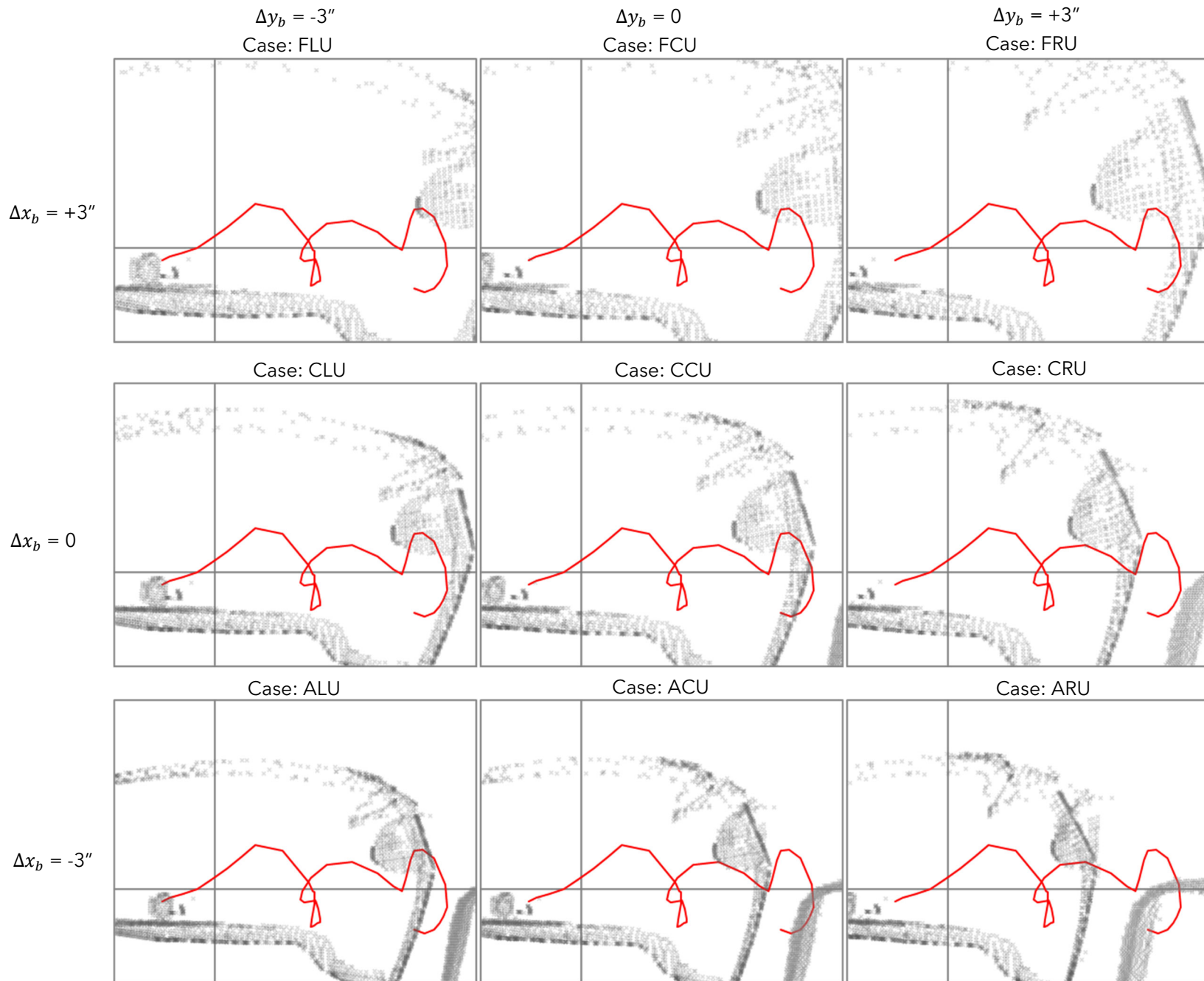


Figure 19a. Viewing angles for the Cessna copilot seat at $\Delta z_b = -1.5''$ (i.e., up). Plots are elevation angle vs. azimuth angle.

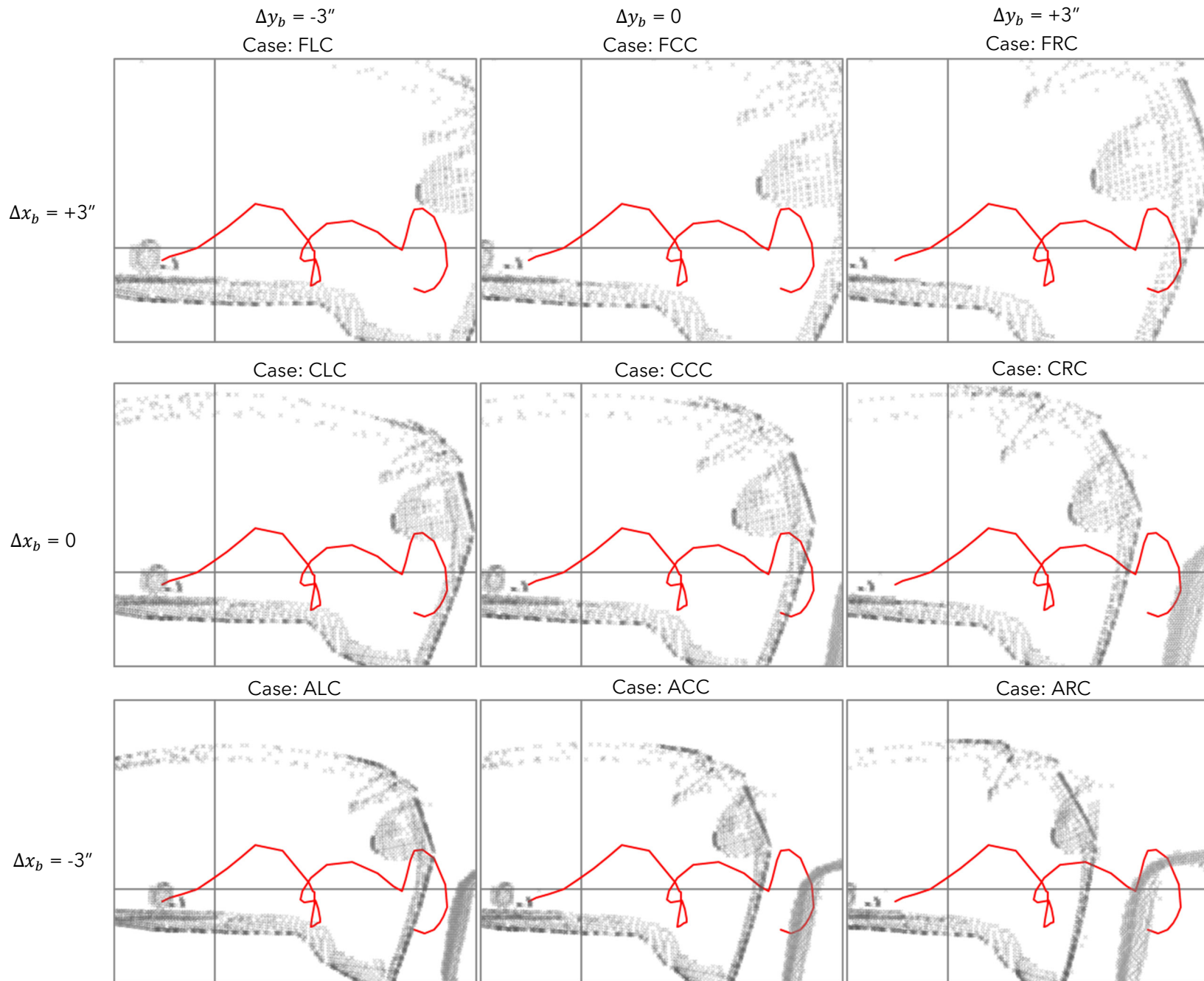


Figure 19b. Viewing angles for the Cessna copilot seat at $\Delta z_b = 0$. Plots are elevation angle vs. azimuth angle.

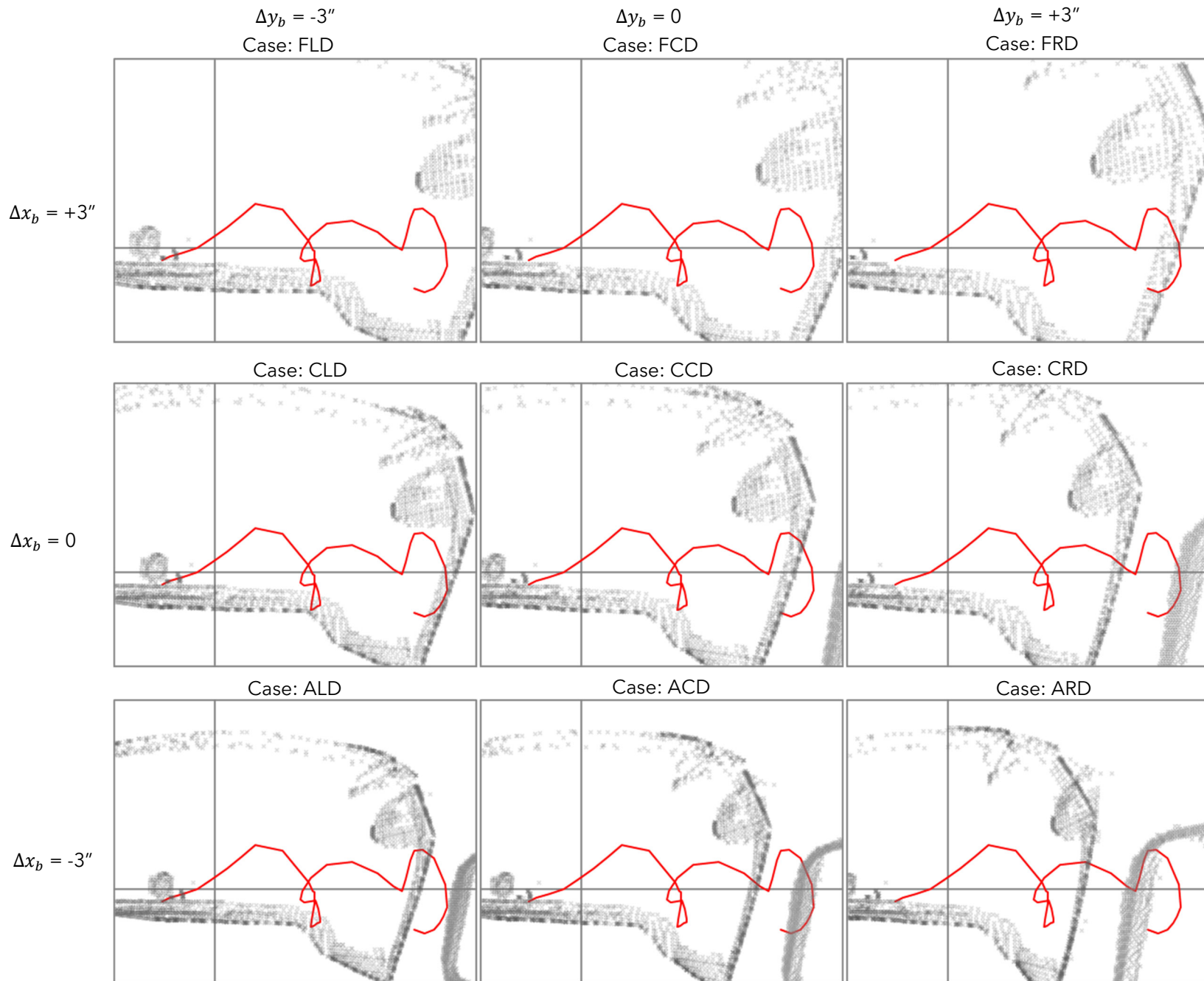


Figure 19c. Viewing angles for the Cessna copilot seat at $\Delta z_b = +1.5''$ (i.e., down). Plots are elevation angle vs. azimuth angle.

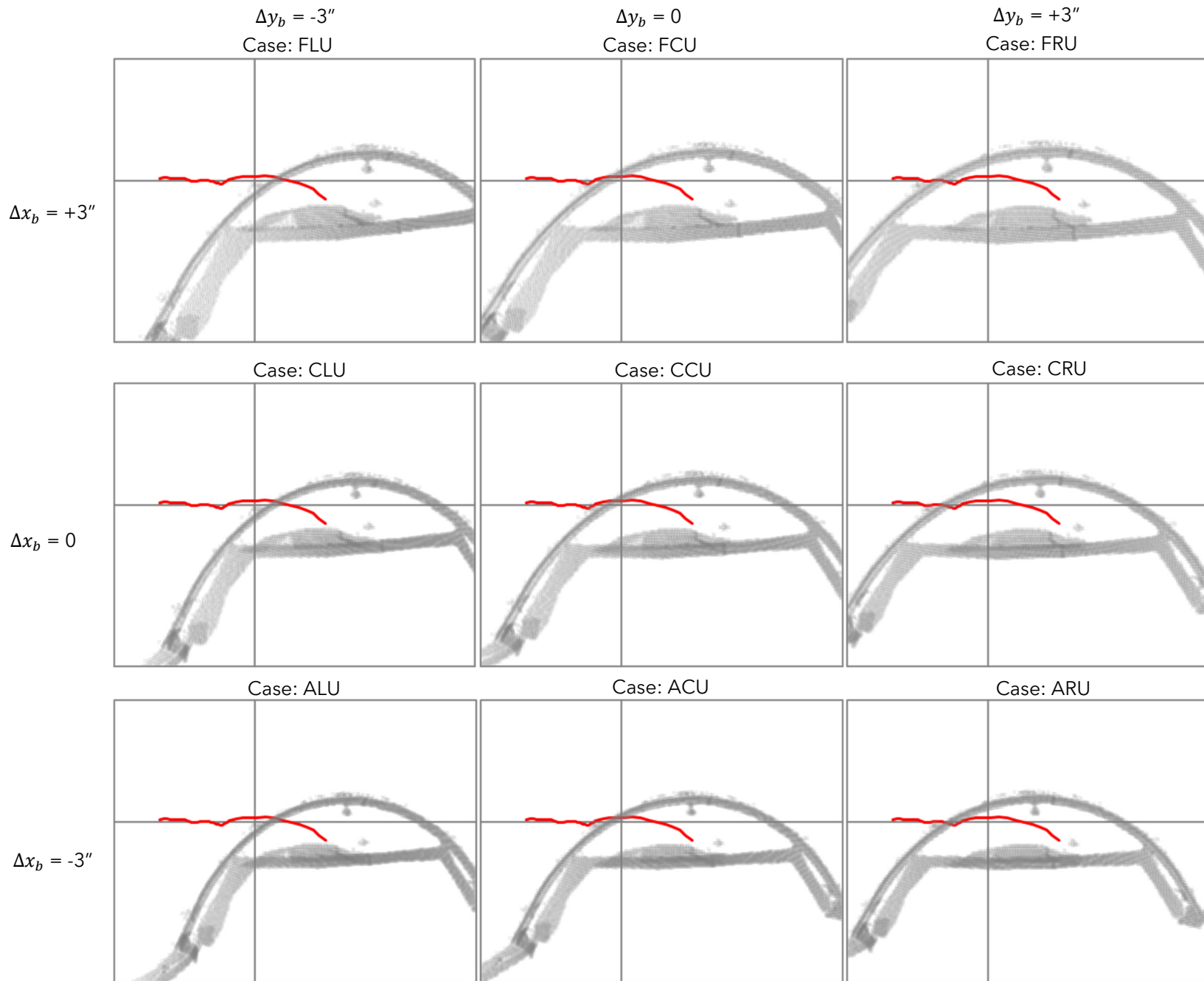


Figure 220a. Viewing angles for the Sonex pilot seat at $\Delta z_b = -1.5''$ (i.e., up). Plots are elevation angle vs. azimuth angle.

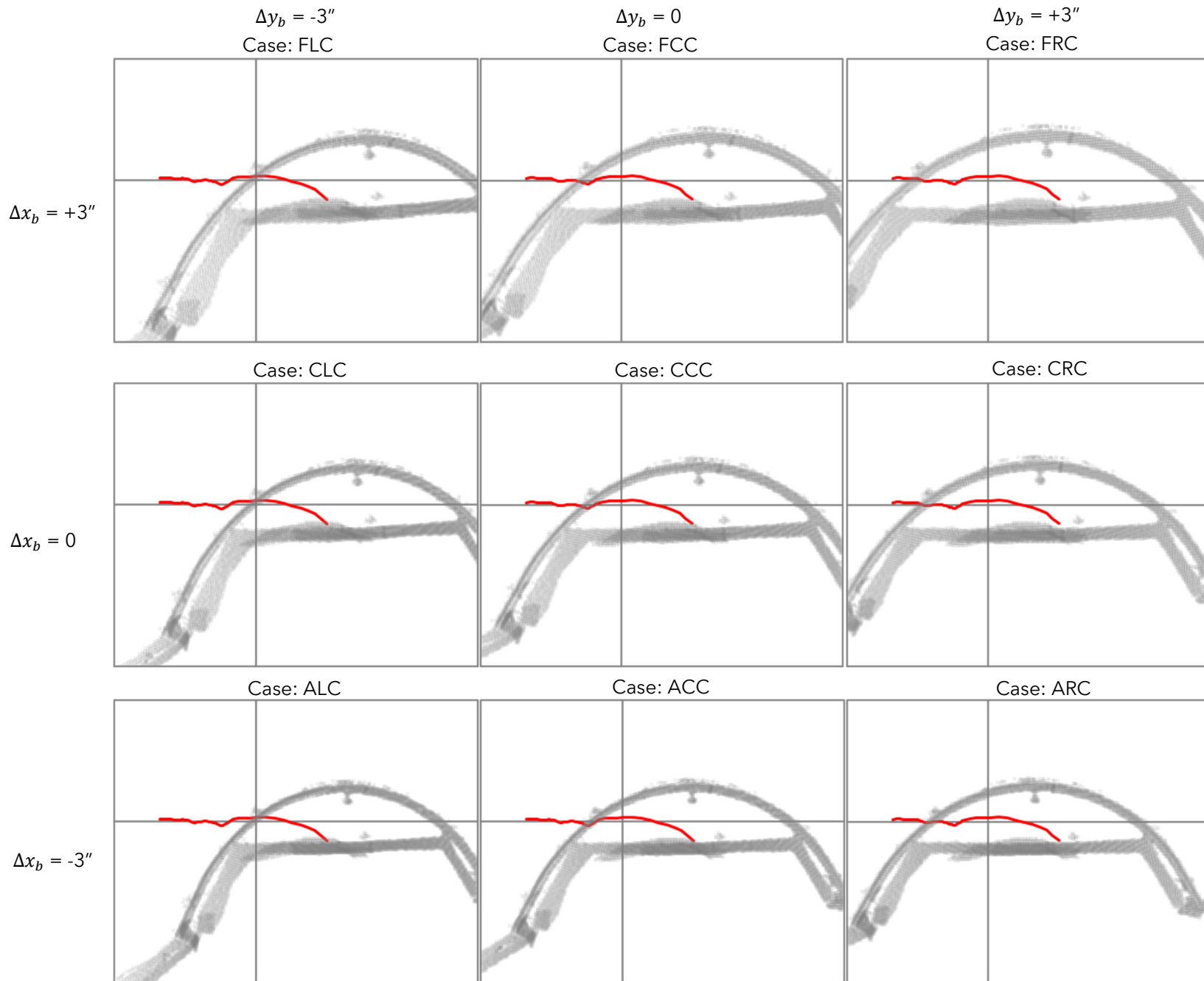


Figure 20b. Viewing angles for the Sonex pilot seat at $\Delta z_b = 0$. Plots are elevation angle vs. azimuth angle.

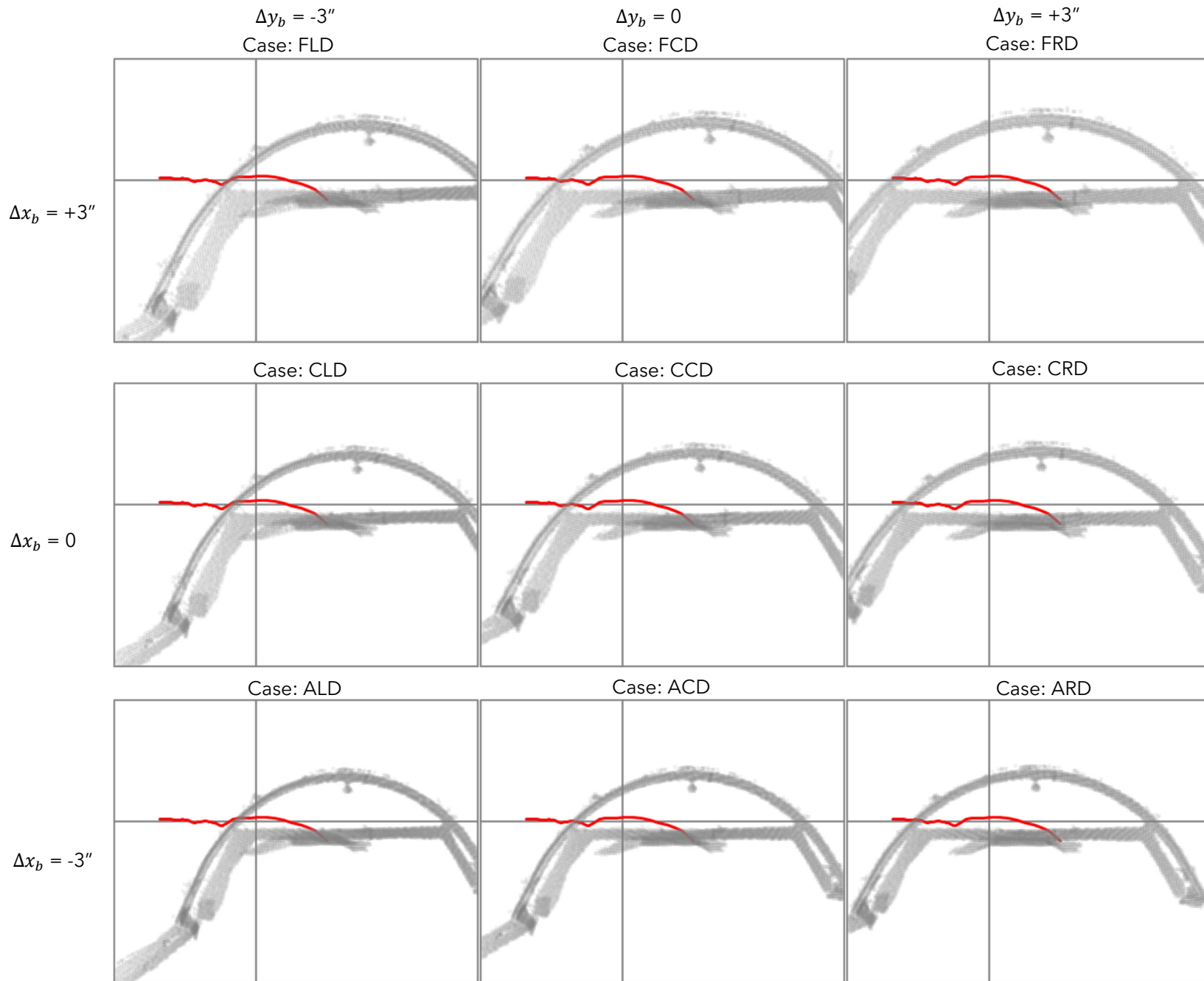


Figure 20c. Viewing angles for the Sonex pilot seat at $\Delta z_b = +1.5''$ (i.e., down). Plots are elevation angle vs. azimuth angle.

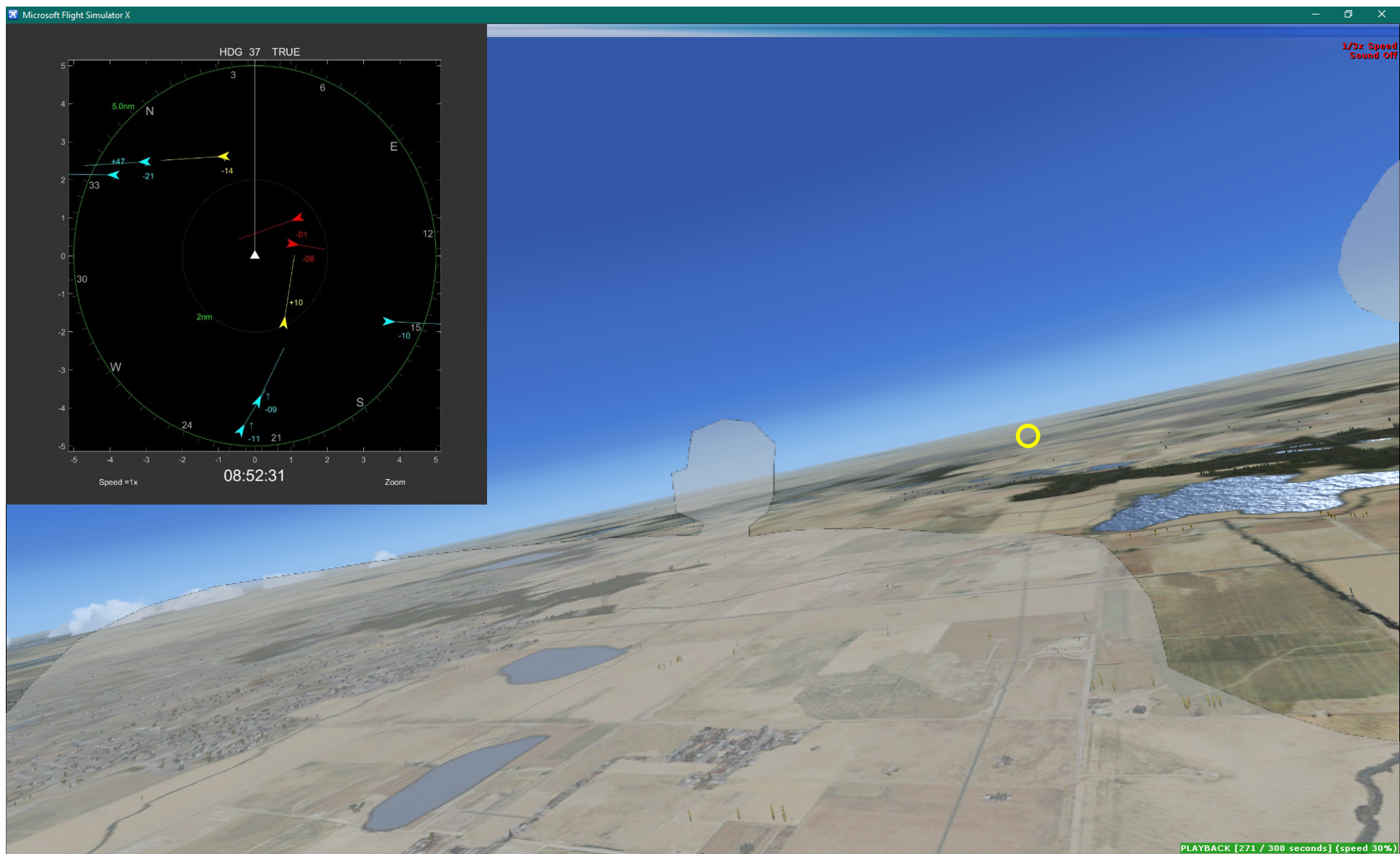


Figure 21a. Simulated view from the Cessna pilot seat at 08:52:31.6 (30 seconds before the collision). The Sonex is located in the yellow circle.

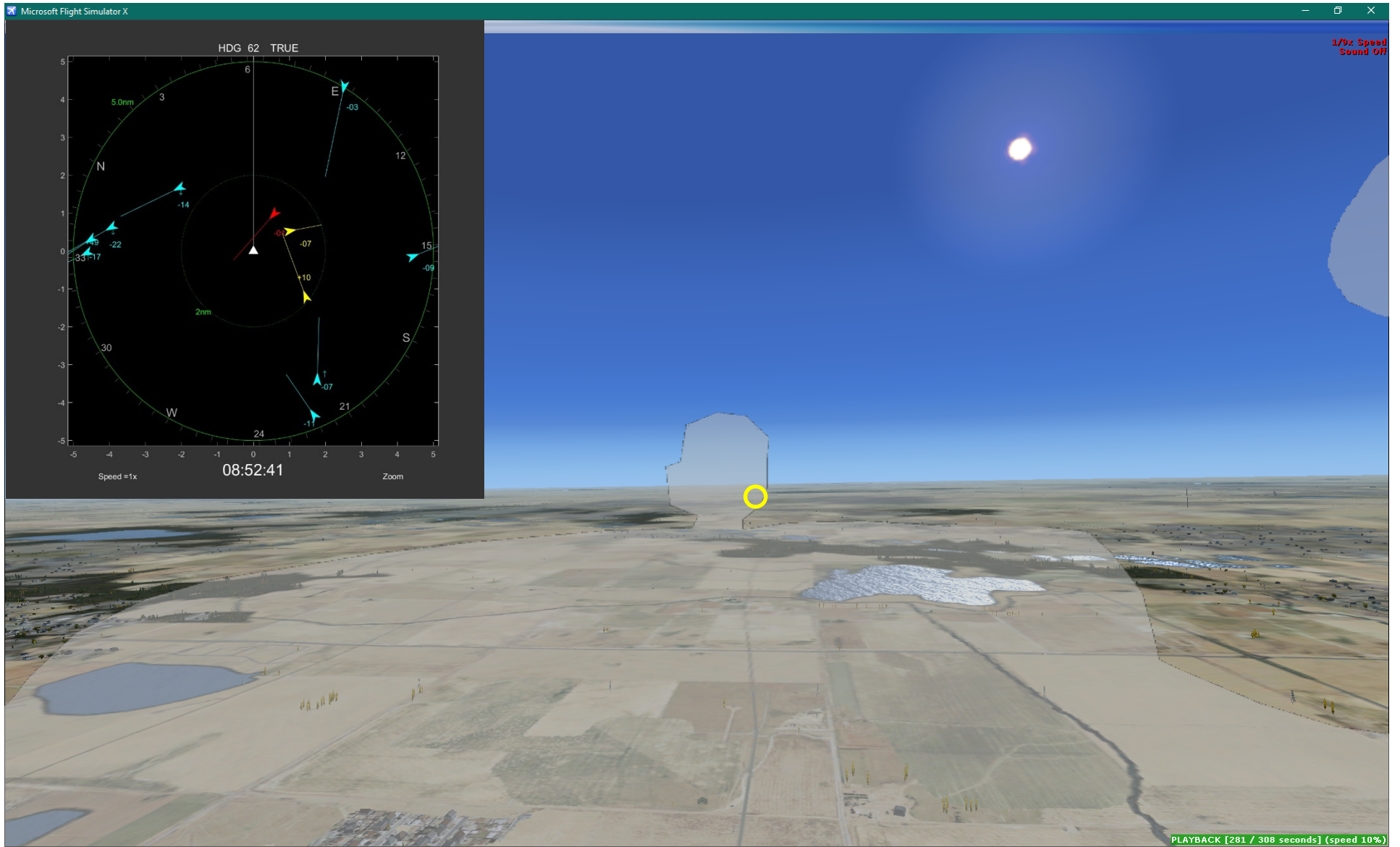


Figure 21b. Simulated view from the Cessna pilot seat at 08:52:41.6 (20 seconds before the collision). The Sonex is located in the yellow circle.

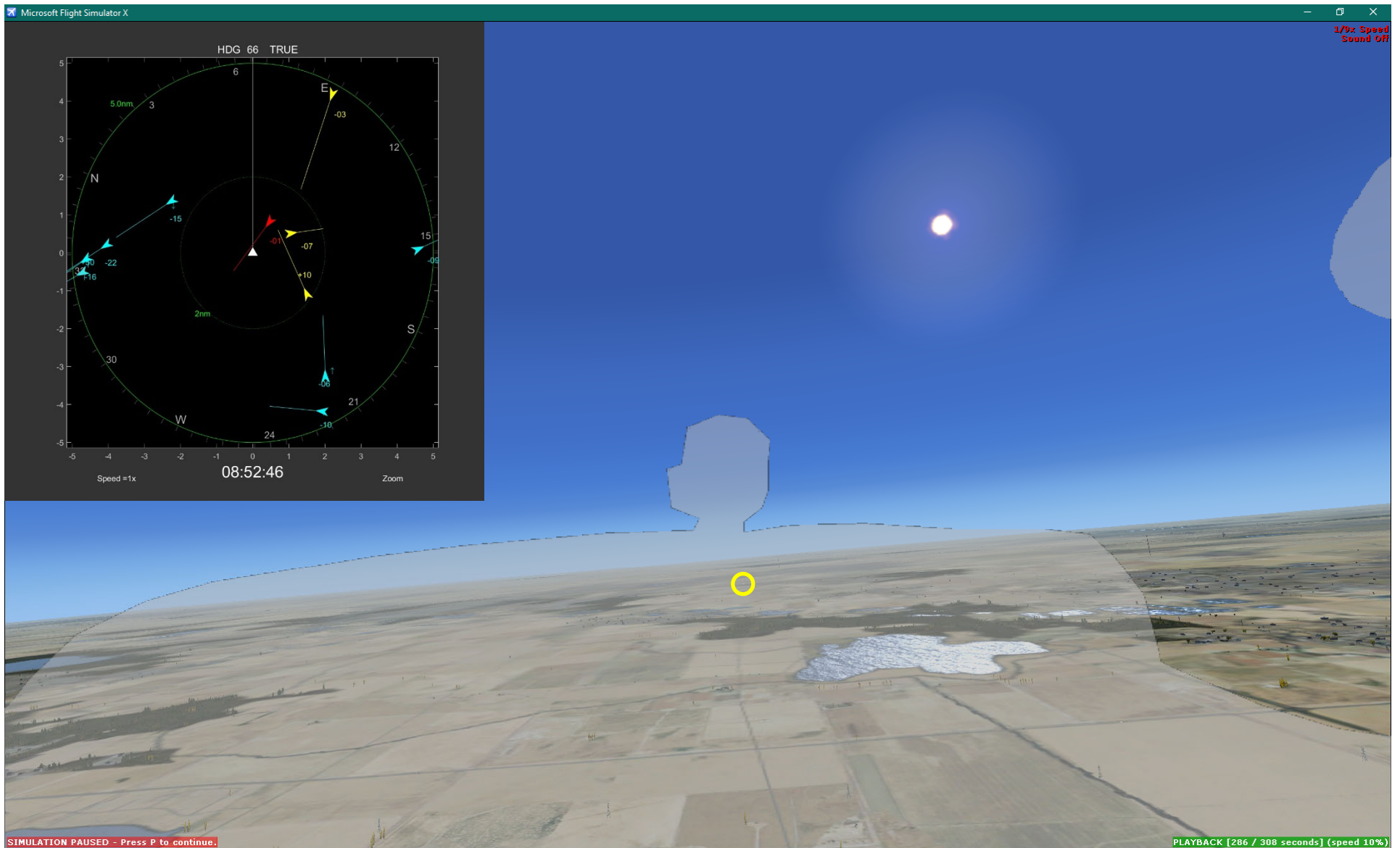


Figure 21c. Simulated view from the Cessna pilot seat at 08:52:46.6 (15 seconds before the collision). The Sonex is located in the yellow circle.

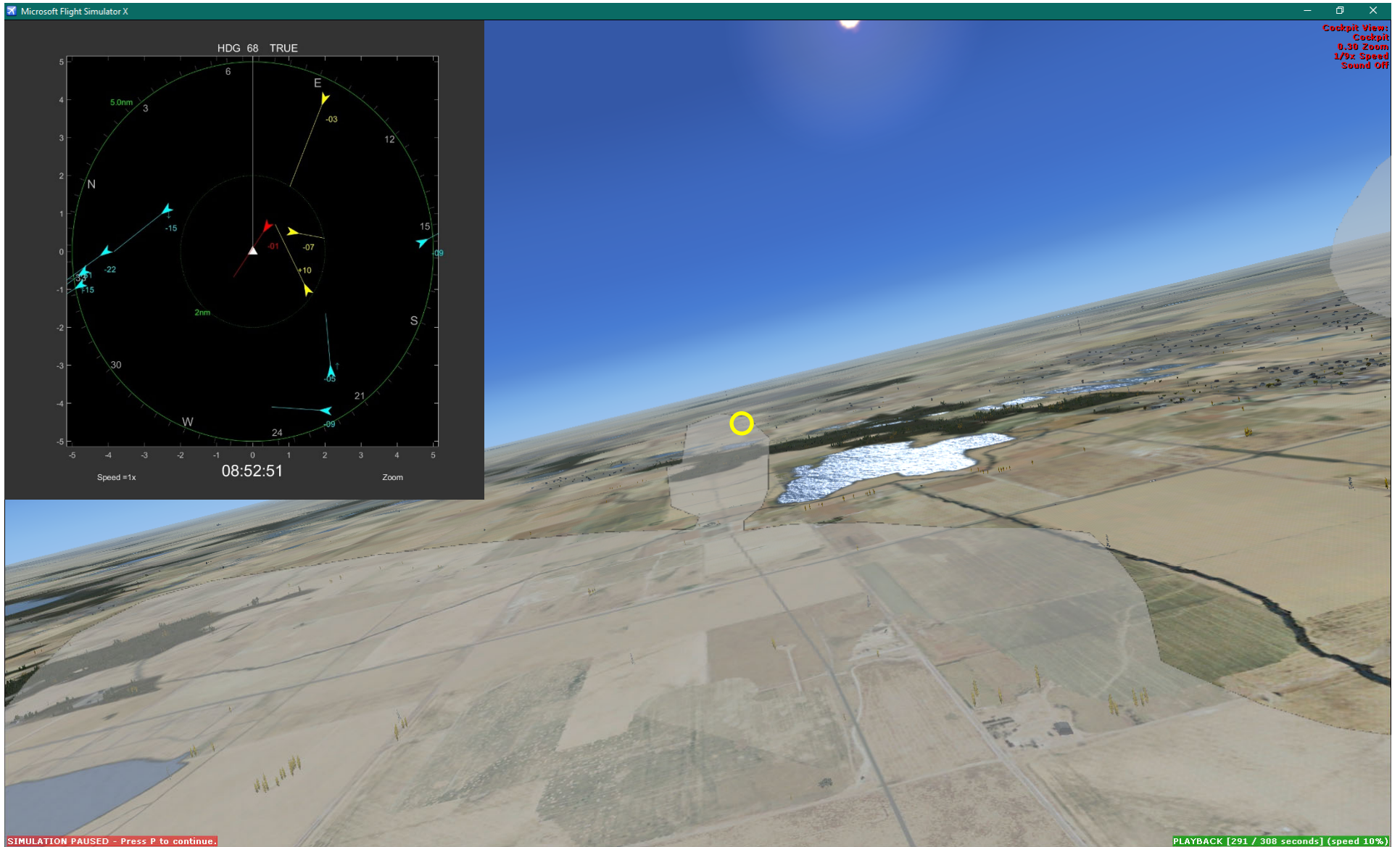


Figure 21d. Simulated view from the Cessna pilot seat at 08:52:51.6 (10 seconds before the collision). The Sonex is located in the yellow circle.

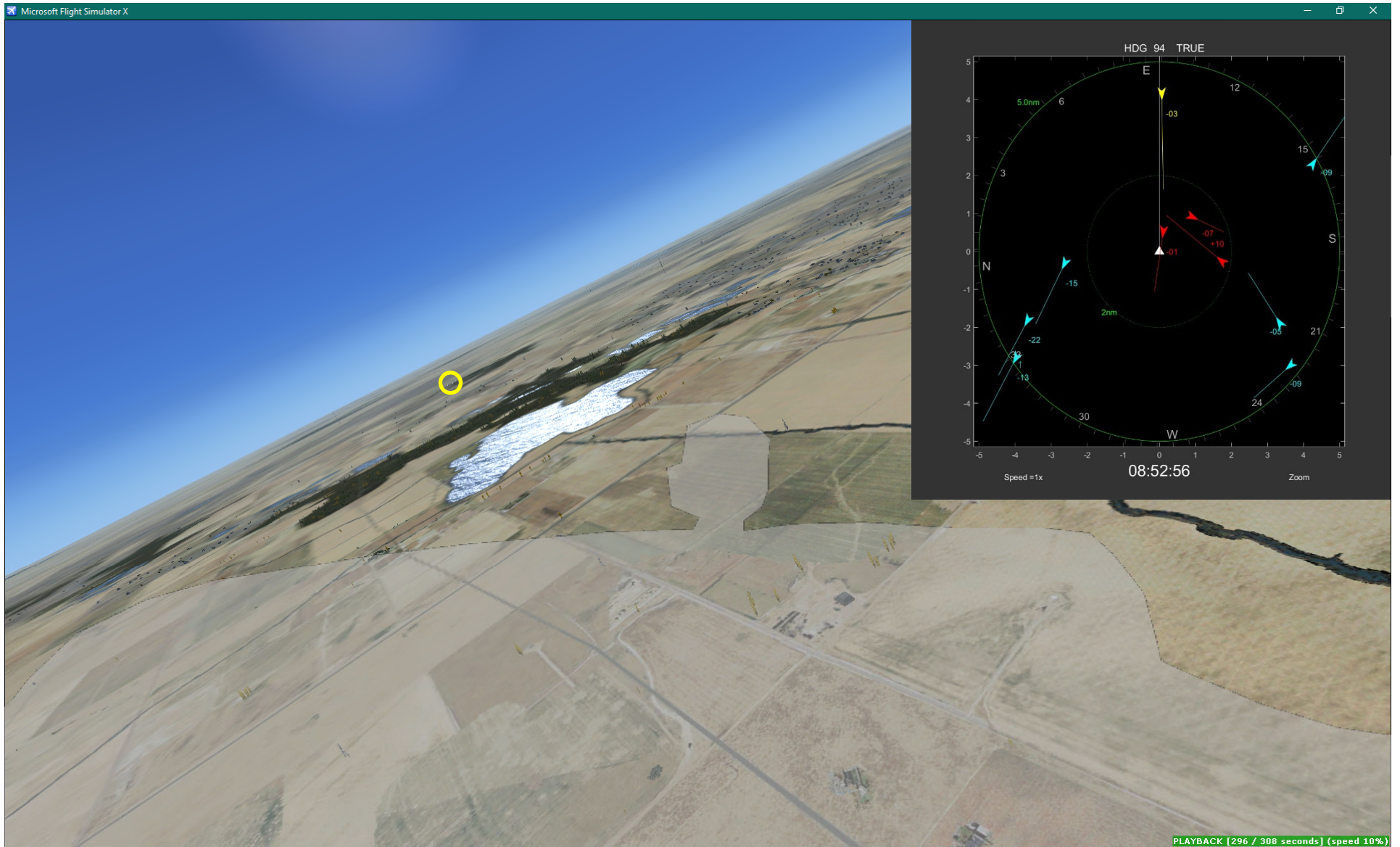


Figure 21e. Simulated view from the Cessna pilot seat at 08:52:56.6 (5 seconds before the collision). The Sonex is located in the yellow circle.

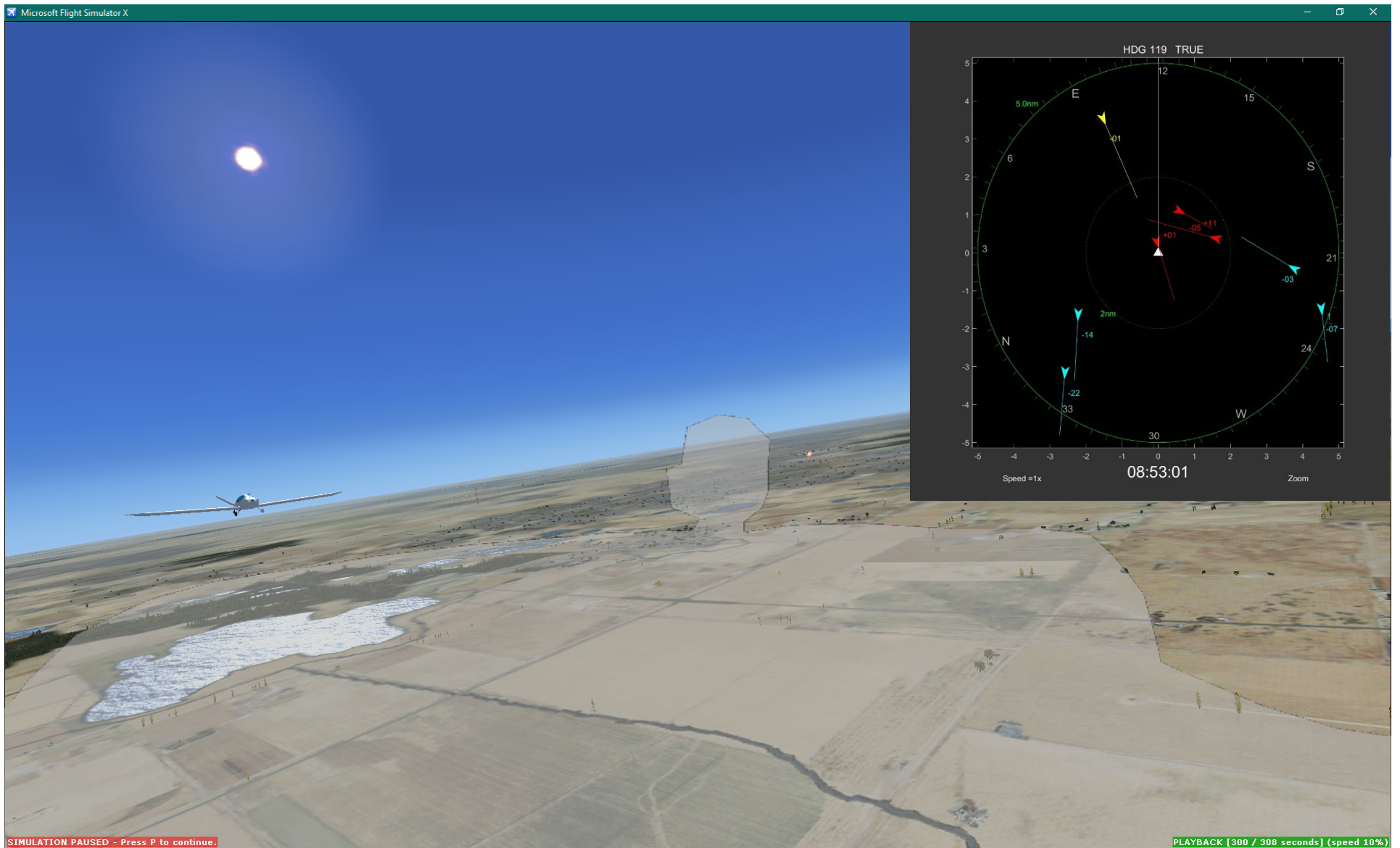


Figure 21g. Simulated view from the Cessna pilot seat at 08:53:01.0 (0.6 seconds before the collision).

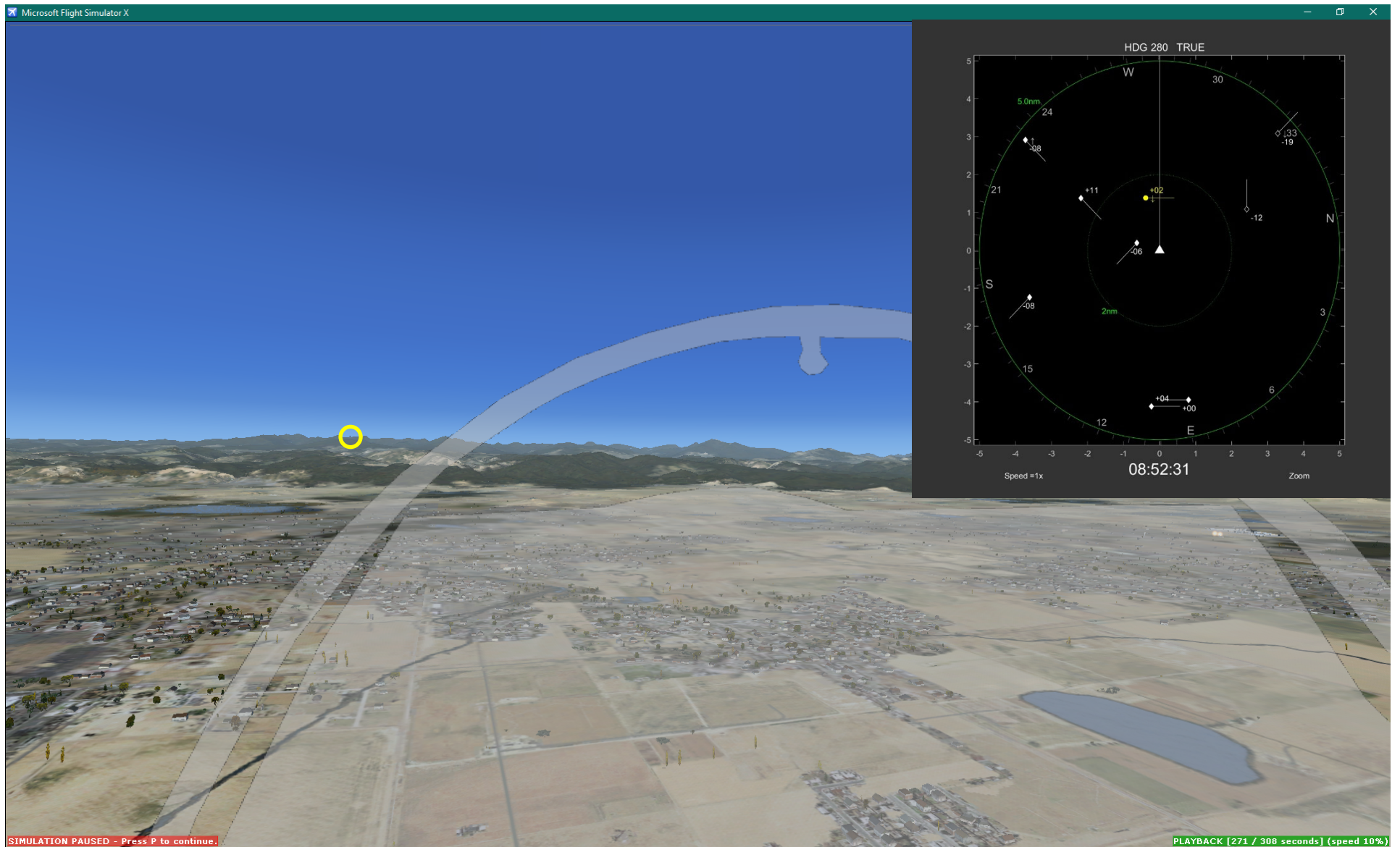


Figure 22a. Simulated view from the Sonex pilot seat at 08:52:31.6 (30 seconds before the collision). The Cessna is located in the yellow circle.

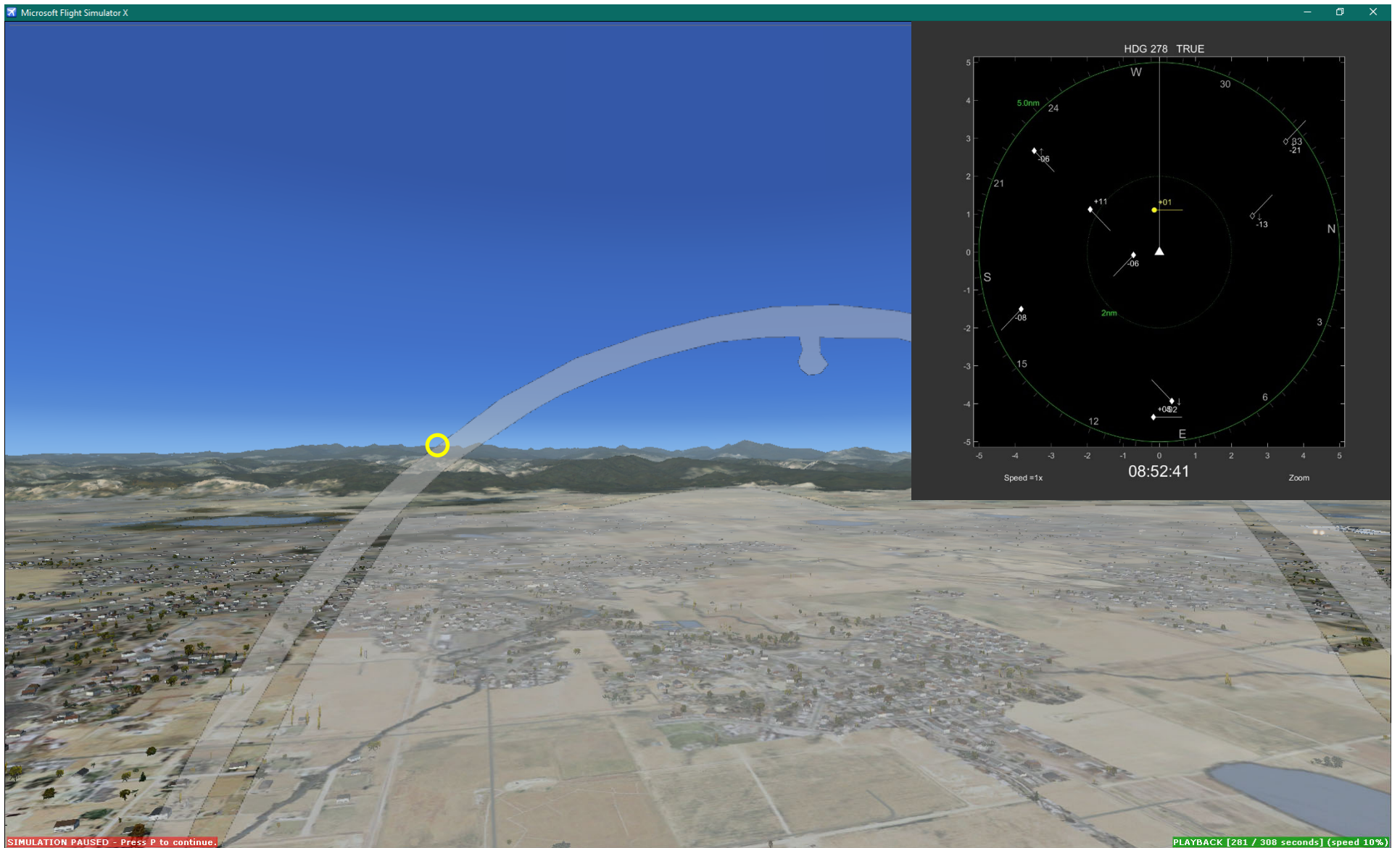


Figure 22b. Simulated view from the Sonex pilot seat at 08:52:41.6 (20 seconds before the collision). The Cessna is located in the yellow circle.

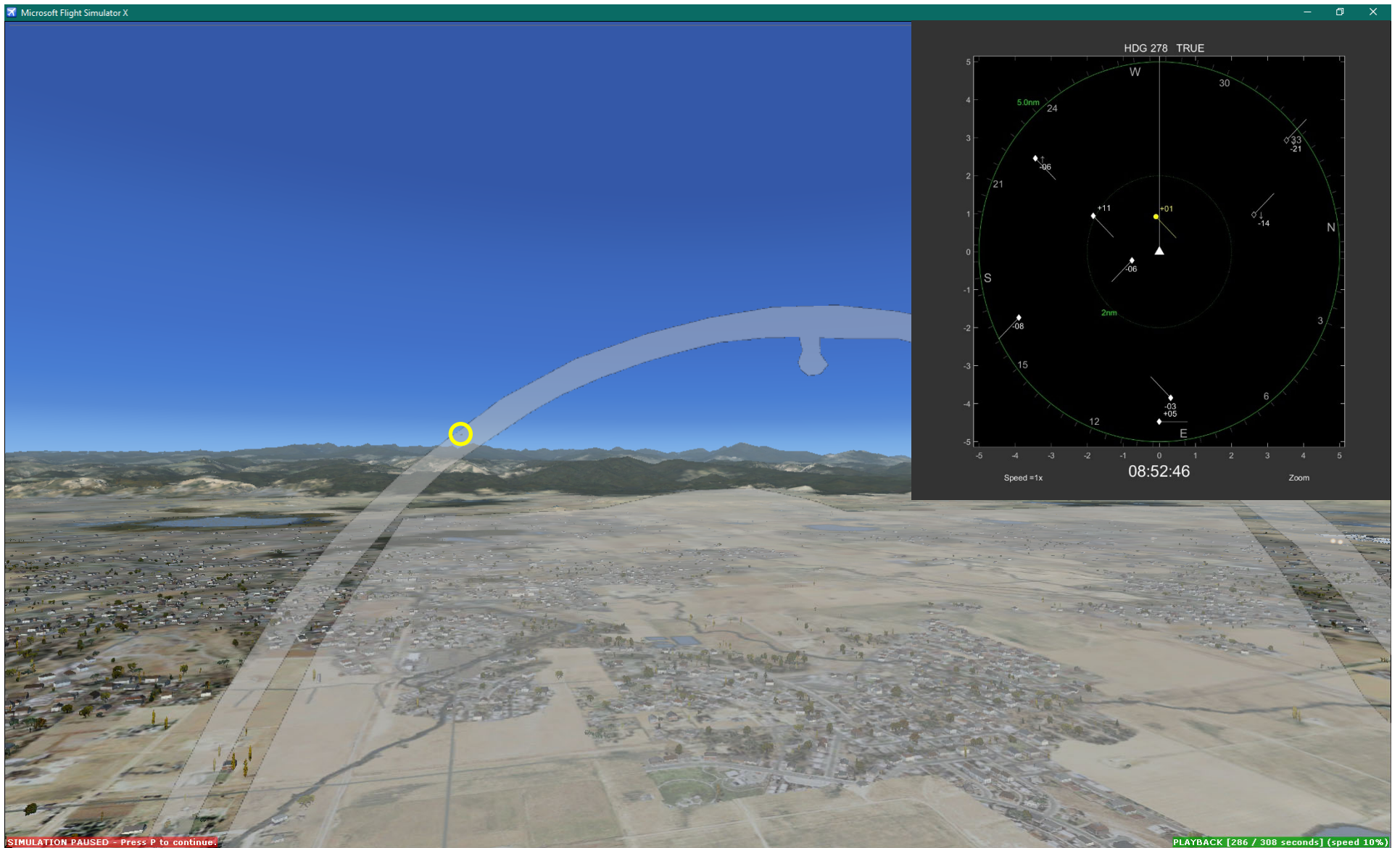


Figure 22c. Simulated view from the Sonex pilot seat at 08:52:46.6 (15 seconds before the collision). The Cessna is located in the yellow circle.

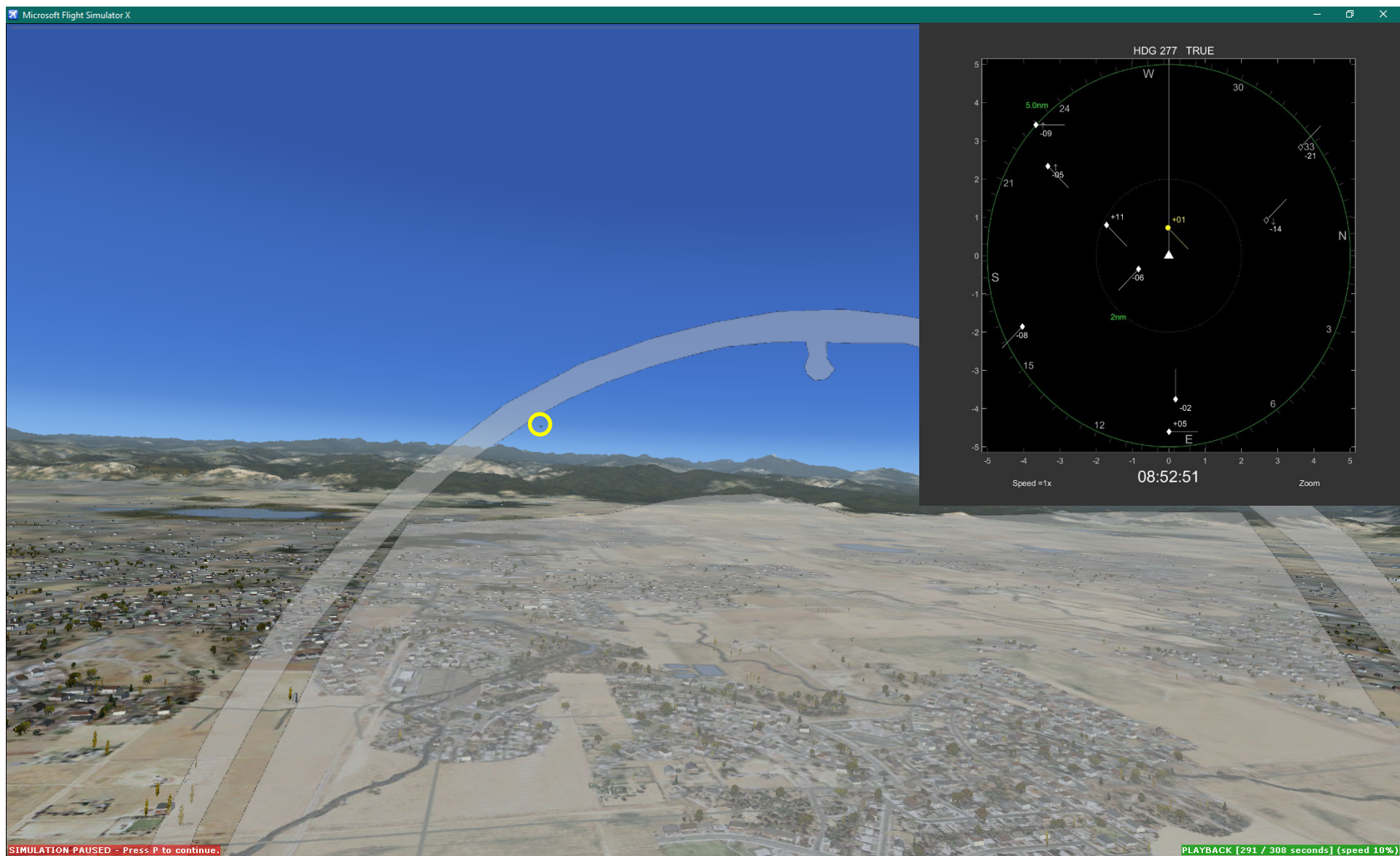


Figure 22d. Simulated view from the Sonex pilot seat at 08:52:51.6 (10 seconds before the collision). The Cessna is located in the yellow circle.

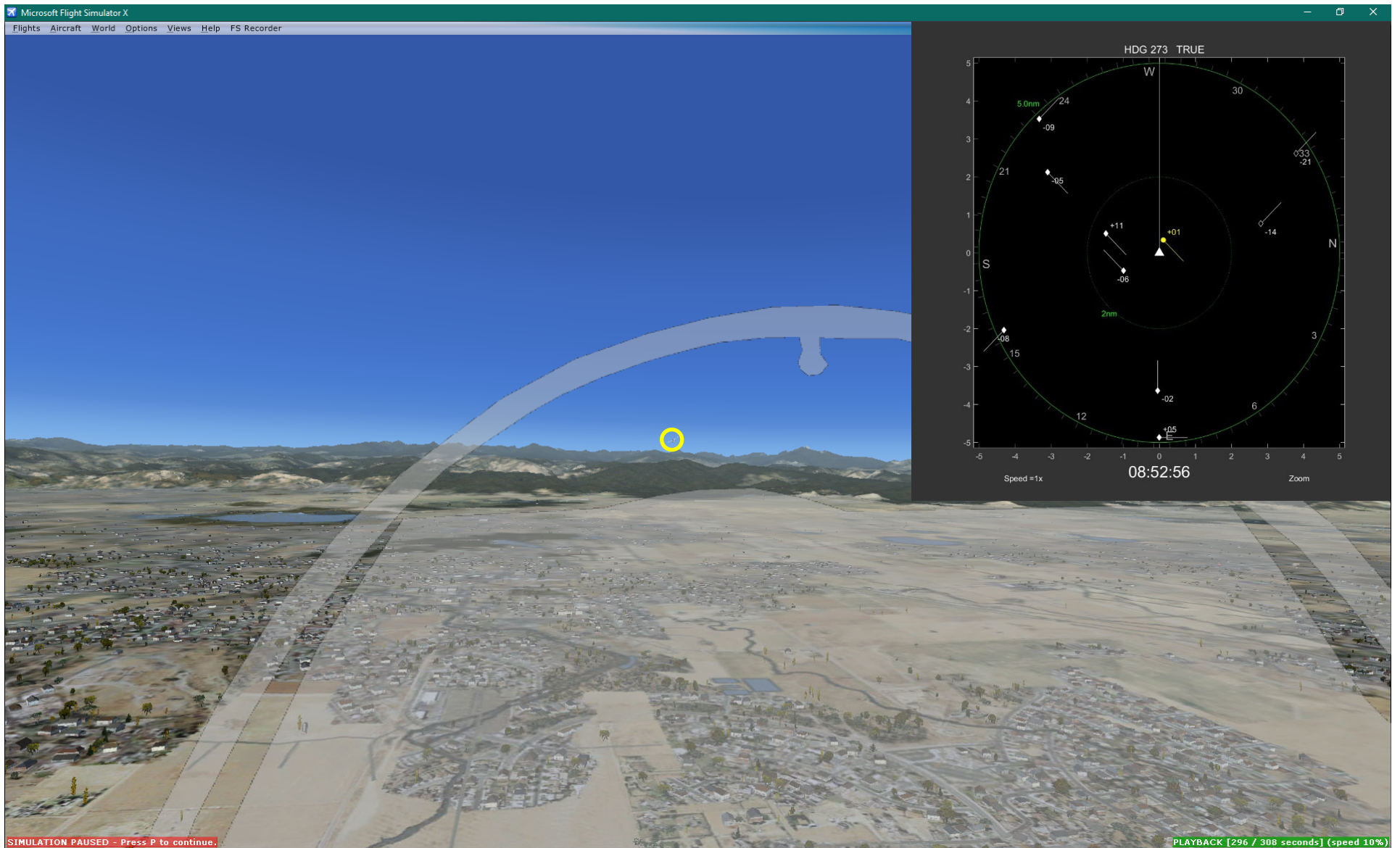


Figure 22e. Simulated view from the Sonex pilot seat at 08:52:56.6 (5 seconds before the collision). The Cessna is located in the yellow circle.

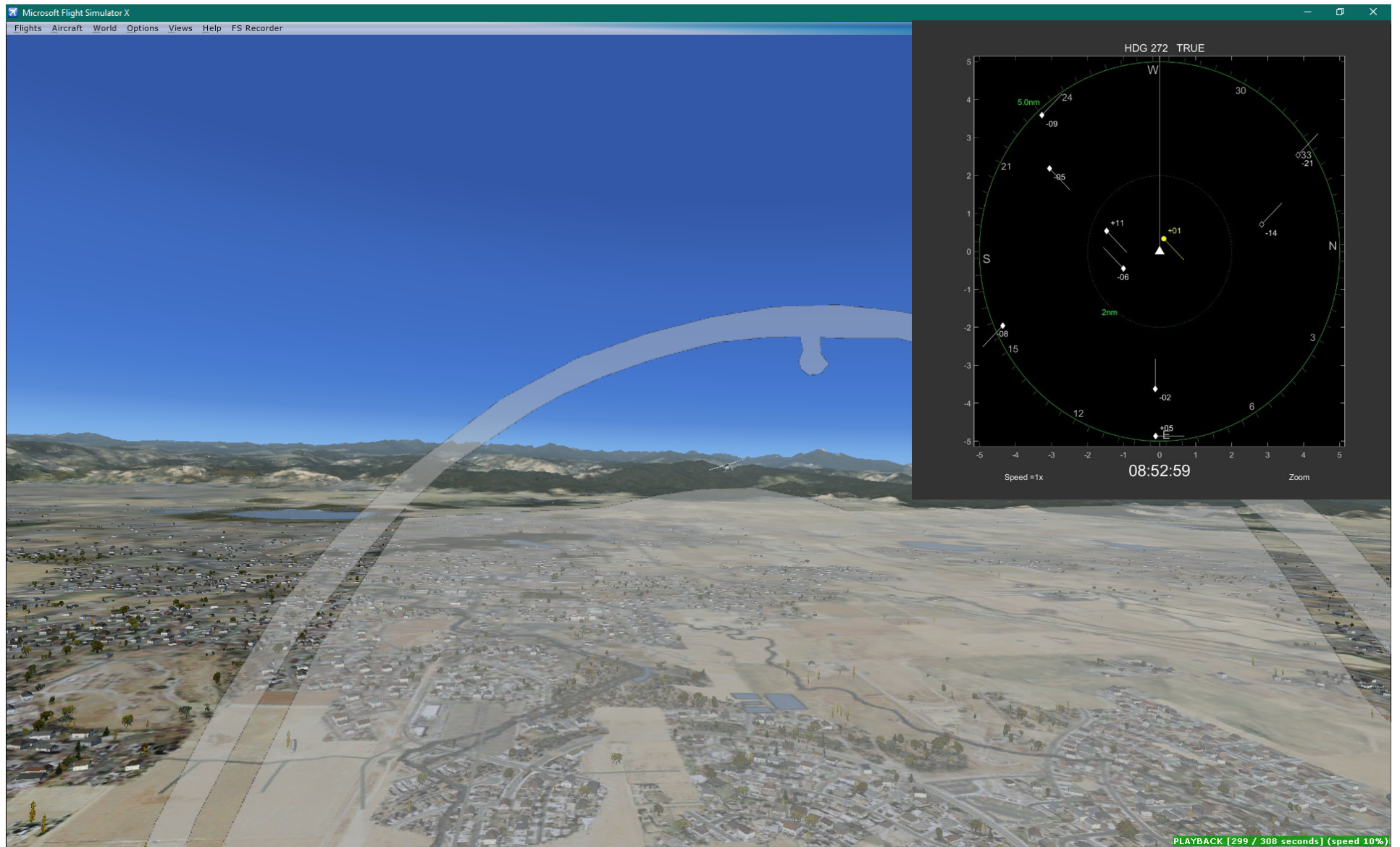


Figure 22f. Simulated view from the Sonex pilot seat at 08:52:59.6 (2 seconds before the collision).

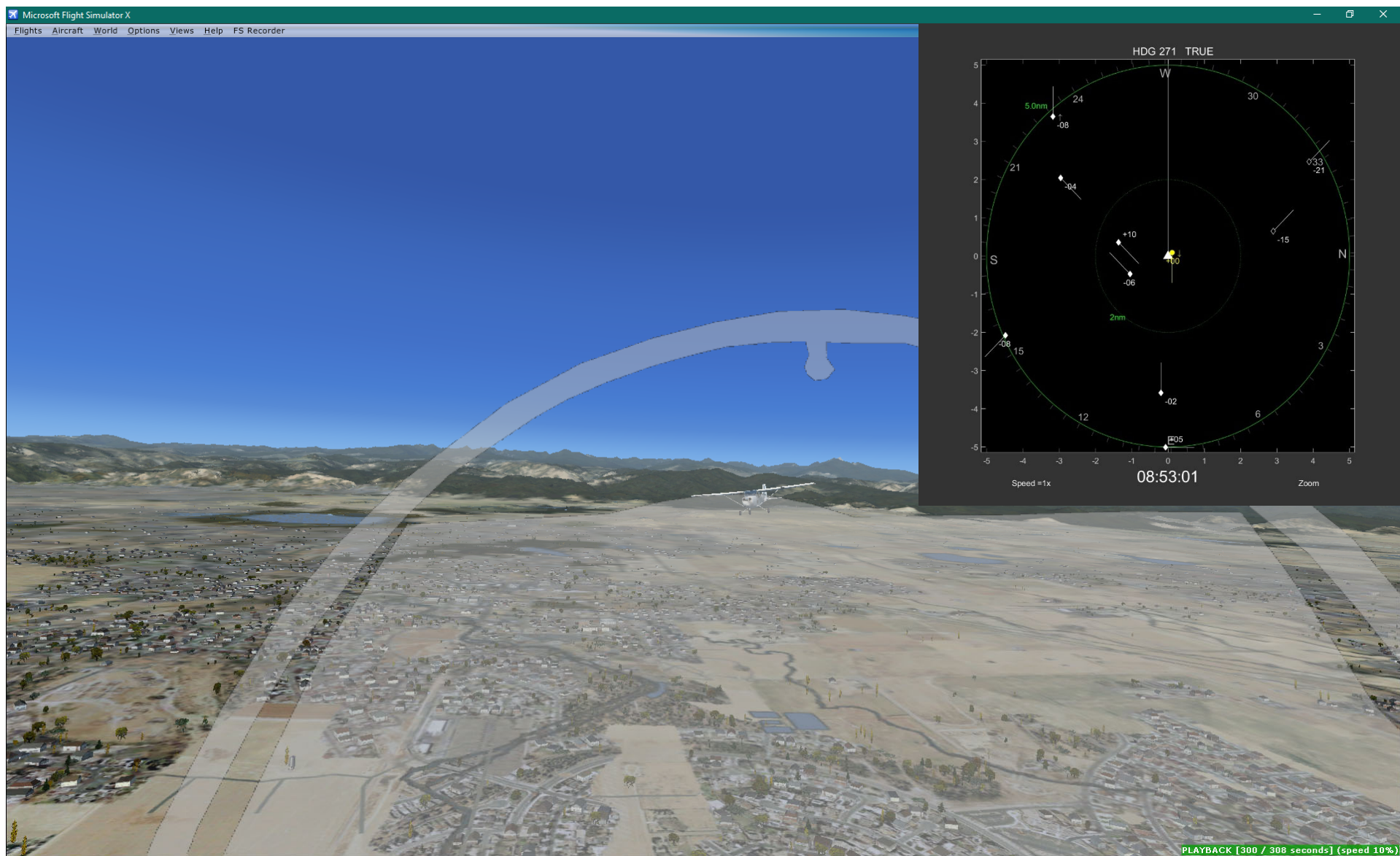
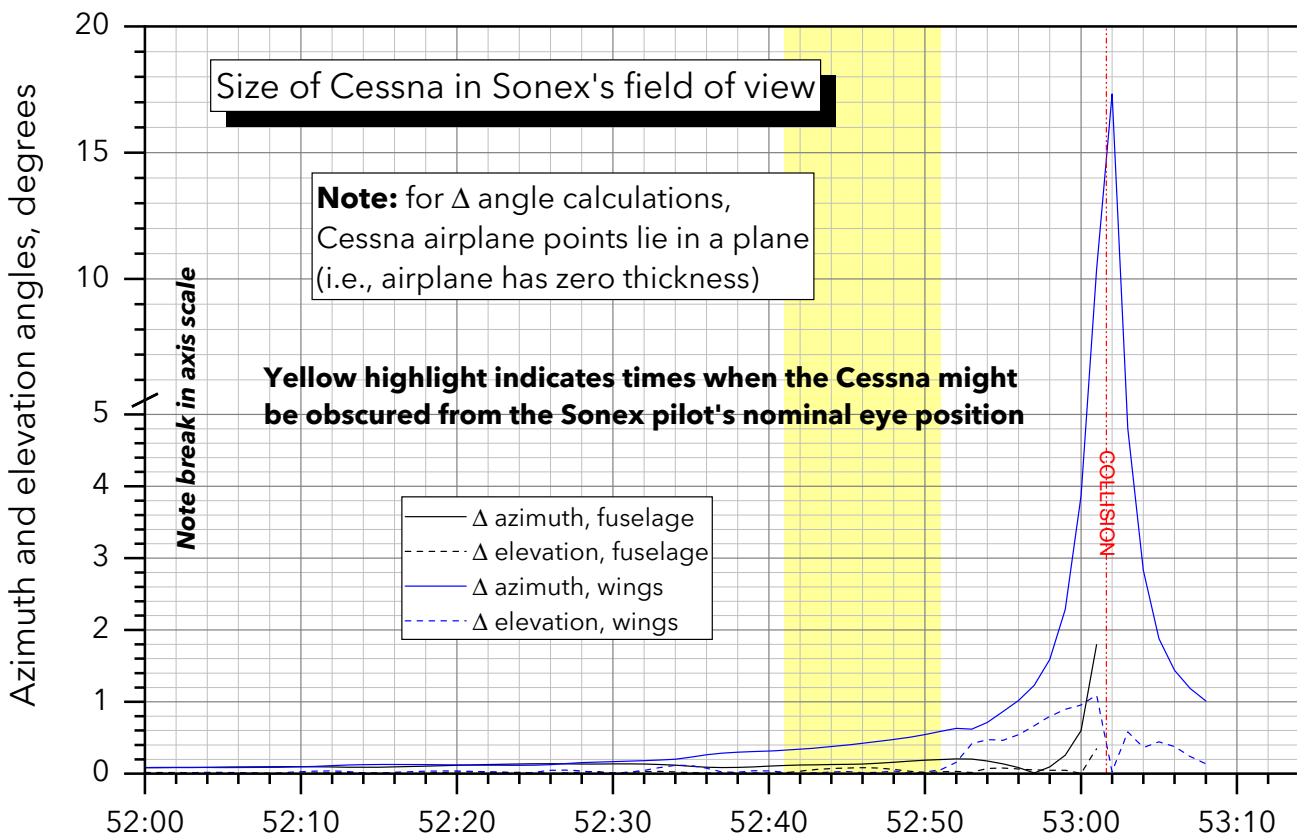
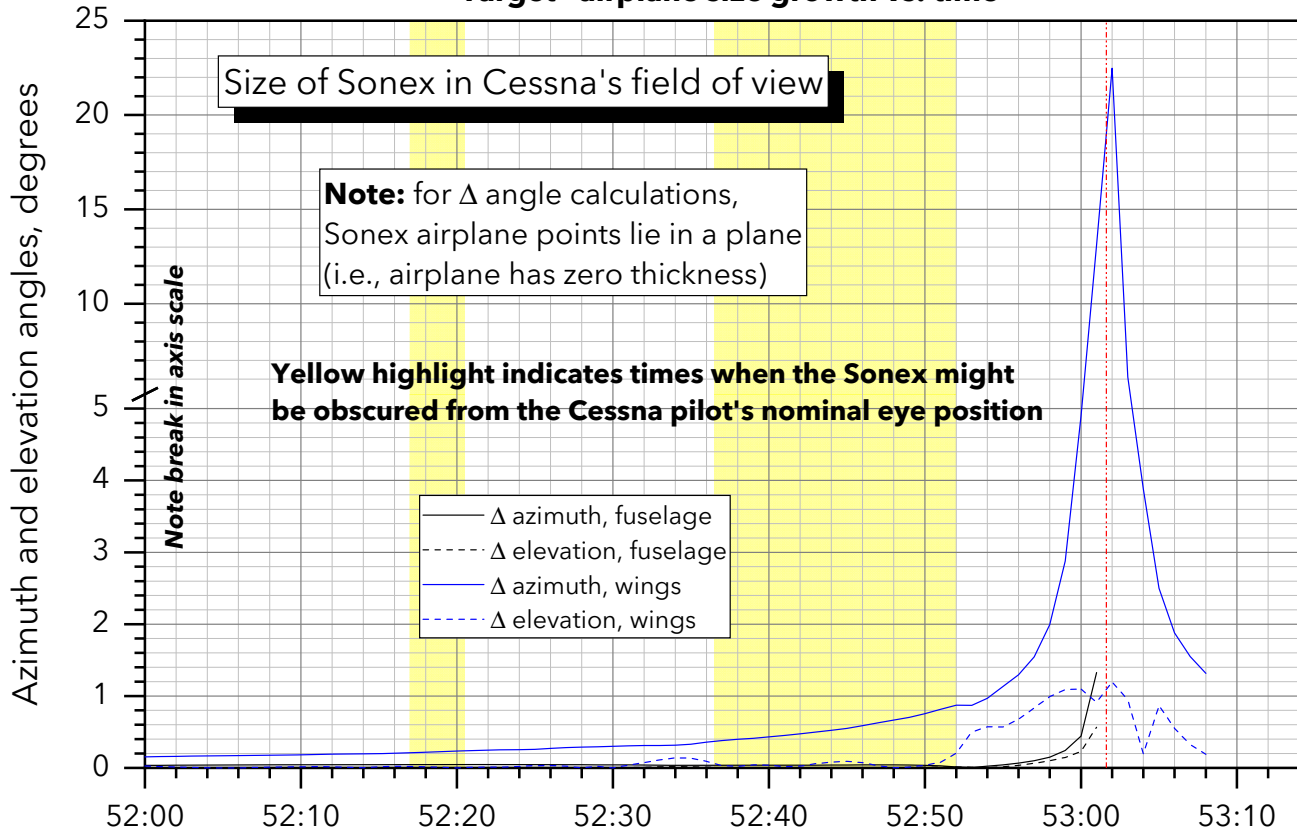


Figure 22g. Simulated view from the Sonex pilot seat at 08:53:01.0 (0.6 seconds before the collision).

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"Target" airplane size growth vs. time



Time after 08:00:00 MDT, MM:SS

Figure 23.

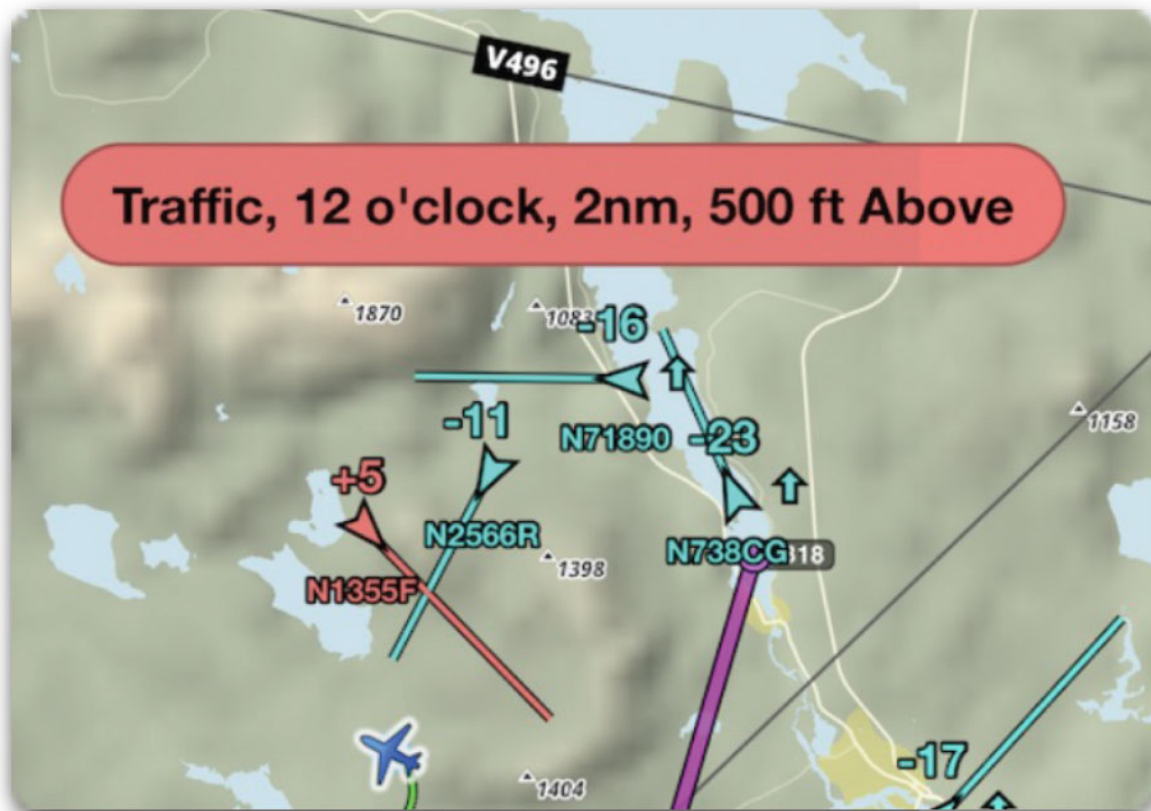


Figure 24. Example traffic alert depicted in the *ForeFlight Mobile Pilot's Guide* (Reference 11).

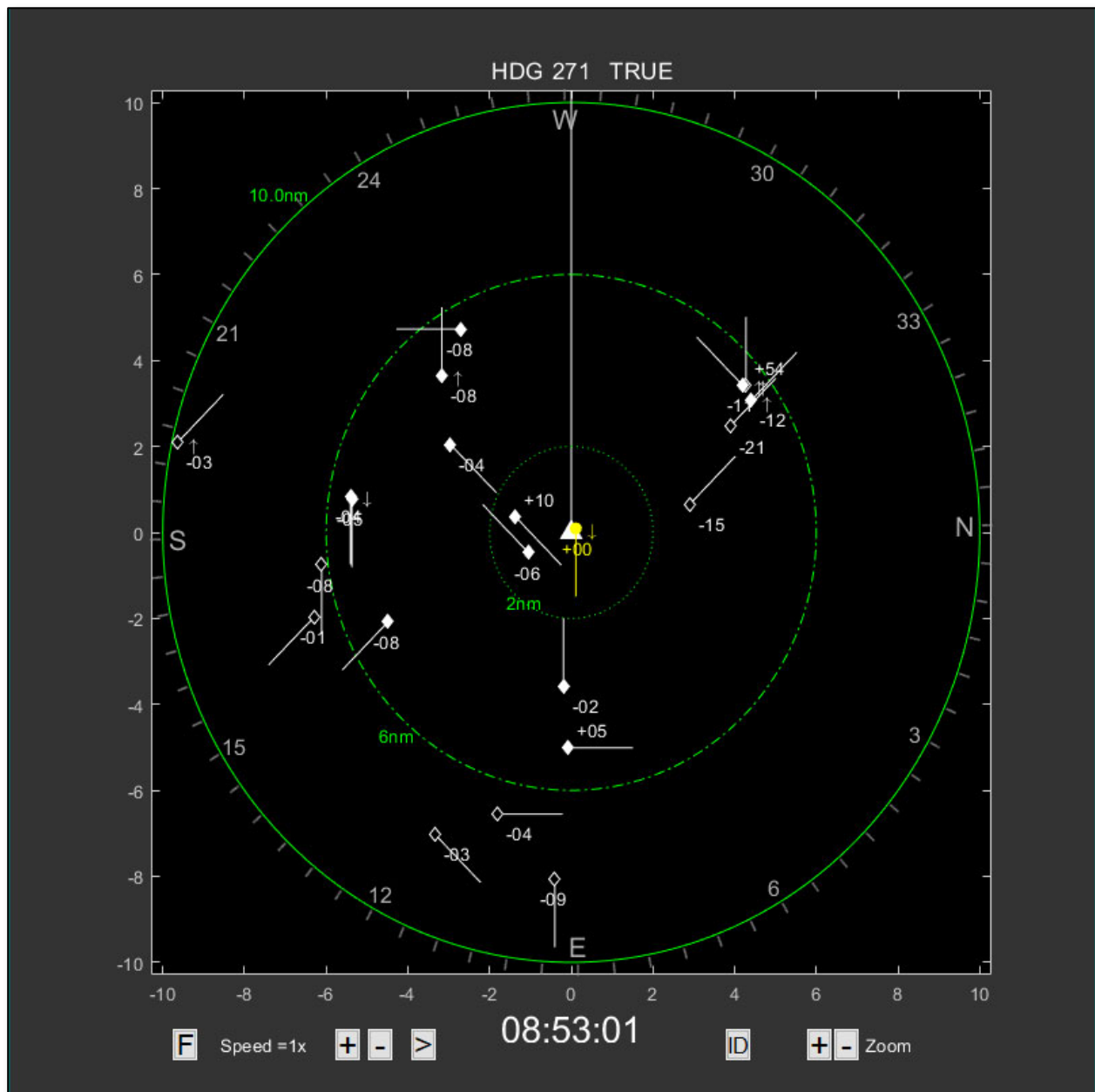


Figure 25. Image of the simulated Garmin 430W traffic display at the time of the collision, showing the traffic density within 10 nm of the collision.

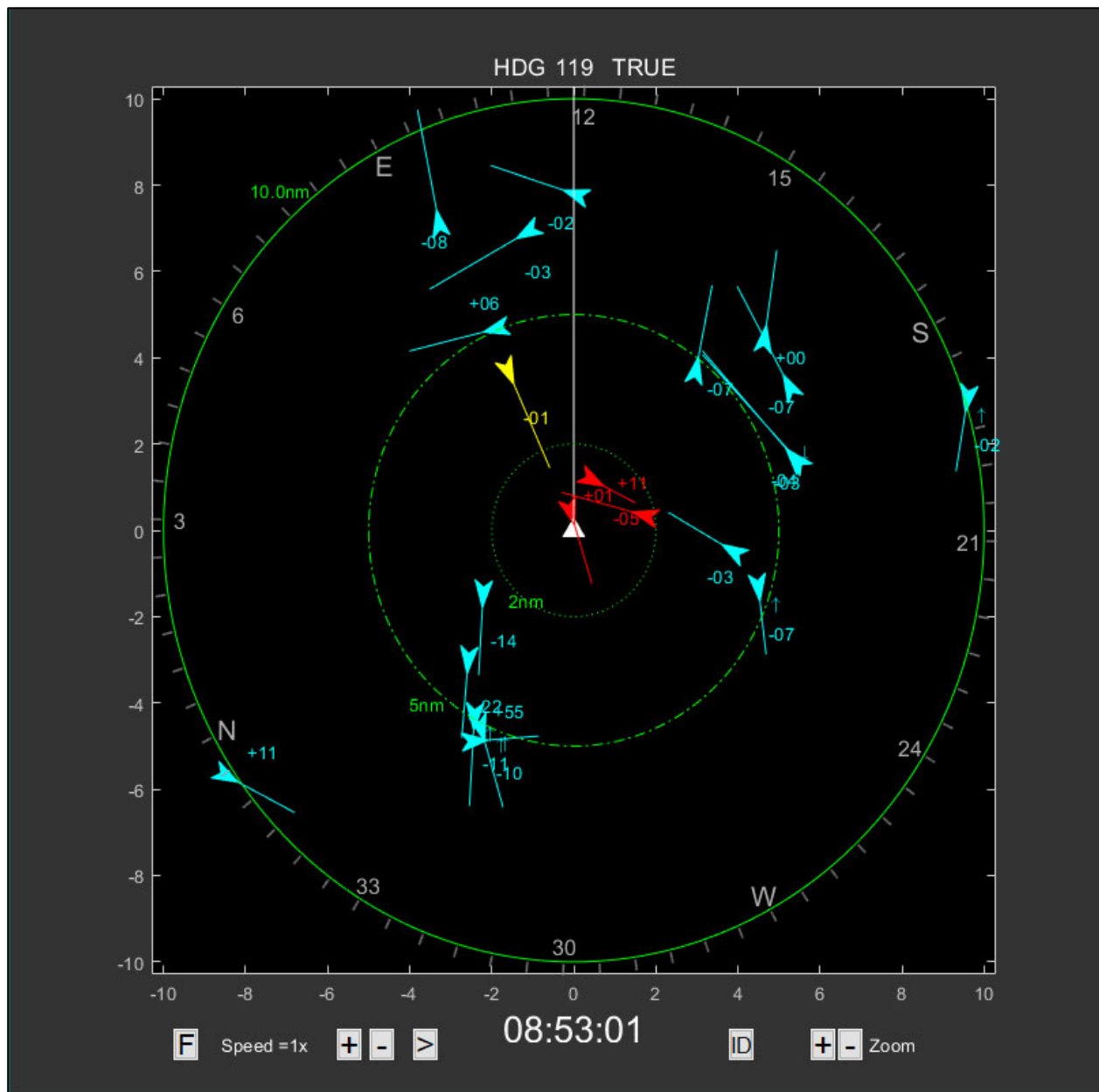


Figure 26. Image of the simulated *ForeFlight* traffic display at the time of the collision, showing the traffic density within 10 nm of the collision.