NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, D.C. 20594

May 27, 2020

Video-Based Visibility Study

NTSB Case Number:
DCA20MA059

A. ACCIDENT

Location:	Calabasas, California
Date:	January 26, 2020
Time:	0945 PST
Aircraft:	Sikorsky S-76B helicopter

B. AUTHOR

Dan T. Horak
NTSB

C. ACCIDENT SUMMARY

On January 26, 2020, about 0945 PST, a Sikorsky S76-B helicopter, N72EX, was destroyed when it was involved in an accident near Calabasas, California. The pilot and eight passengers were fatally injured. The helicopter was operated as a Title 14 Code of Federal Regulations Part 135 charter flight.

D. DETAILS OF INVESTIGATION

The goal of this investigation was estimating visibility in the accident area. Analysis was based on three videos that were recorded by cameras on Agoura Pony Baseball fields near Lupin Hill Elementary School in Calabasas, California. The cameras did not record the image of the flying helicopter but recorded its sound. They also recorded images of terrain at the time of the accident. The fact that the cameras did not record the image of the helicopter that was in their fields of view and the distance to the farthest terrain features that the cameras recorded were used for estimating the visibility at the time of the accident.

Figure 1 is an aerial image of the accident area with superimposed fields of view of the three cameras. The cameras were installed behind the home plates in the three baseball fields that were named Mustang, Bronco and Pinto. The ground track of the helicopter based on ADS-B data and the crash location are also shown in the figure.

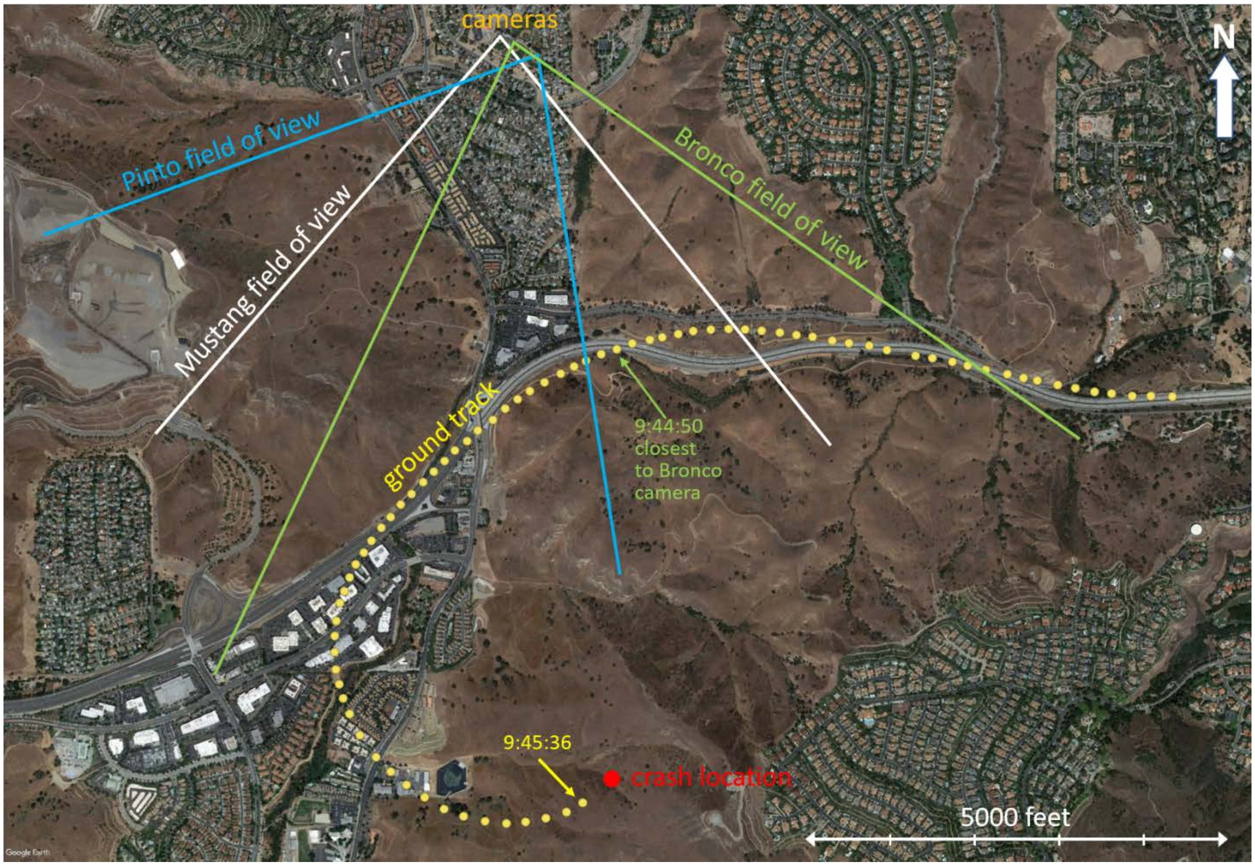

Figure 1. Fields of View of the Three Cameras

Figure 1 shows that the Bronco camera provided the best coverage of the ground track. The ADS-B data provided accurate timing of the helicopter locations along the ground track. The three videos had time stamps but they were not accurate because the clocks in the video recording hardware were not set exactly. This necessitated synchronization of the videos with the ADS-B data that was not based on the time stamps in the videos. Once synchronized, analysis could concentrate on the segments in the videos where the helicopter should have been visible if within the visibility range at the time of the accident. The sound of the helicopter as recorded by the Bronco camera was used to synchronize the videos with ADS-B data, as follows.

<u>Bronco Camera Sound Analysis</u>

Figure 2 shows the helicopter sound signal as recorded by the Bronco camera. The horizontal axis is time after the camera time was synchronized with the ADS-B time, as explained next.

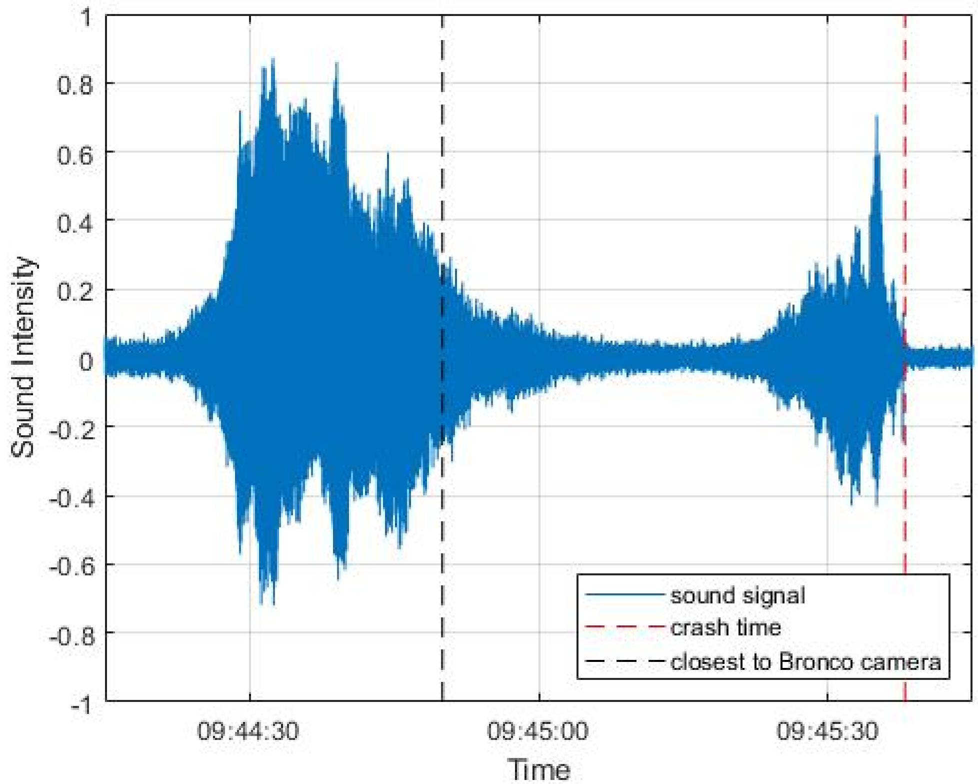

Figure 2. Helicopter Sound Recorded by the Bronco Camera

The sound signal in Figure 2 posed three questions. The first was whether both time segments of high sound intensity represented sound generated by the accident helicopter. The second question was the timing of the helicopter's terrain impact relative to the sound signal. The third question was whether the time history of the sound signal in Figure 2 was consistent with the ground track of the helicopter shown in Figure 1.

The rated rotor speed of the S-76B helicopter is 293 rpm at 100% and 313 rpm at 107%. It was assumed that the rotor speed of the accident helicopter was within this range when the helicopter was near the closest point to the Bronco camera shown in Figure 1. The shape of the ground track in Figure 1 suggests that near the closest point, the helicopter transitions from having a small speed component toward the camera to having a small speed component away from the camera. The Doppler effect due to this transition was expected to be reflected in the spectrum of the sound signal.

Figure 3 shows the results of spectrum analysis of the sound signal. It was expected that near the point of closest distance to the camera, the helicopter speed will have no component toward or away from the camera and the recorded rotor sound will not be affected by the Doppler effect. Since the rotor speed was expected to be in the 293 rpm to 313 rpm range, and the S-76B rotor has four blades, the frequency range of interest was 293×4 cycles/minute to 313×4 cycles/minute, i.e., 1172 cycles/minute to 1252 cycles/minute.

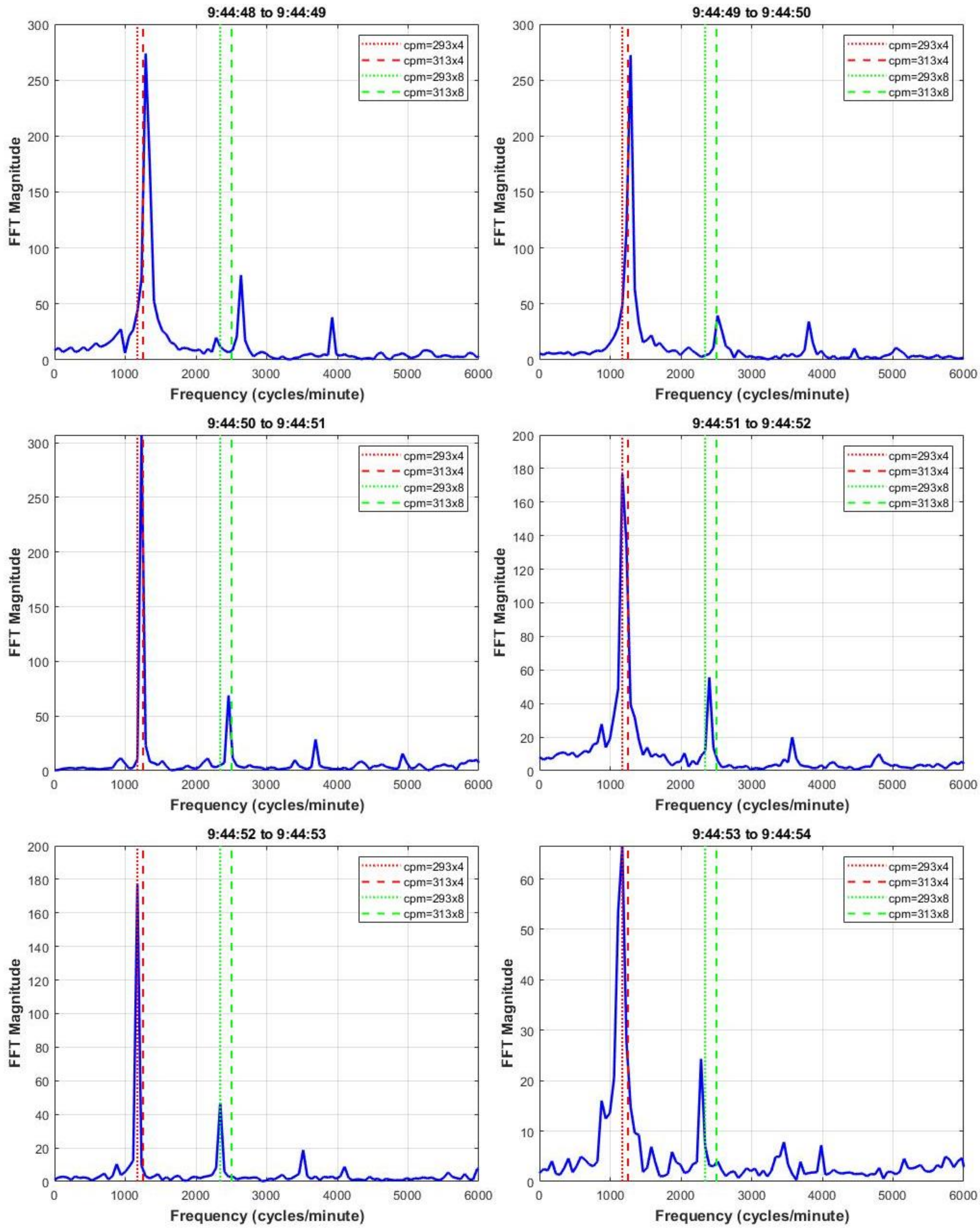

Figure 3. Spectrum of Helicopter Sound Recorded by the Bronco Camera

This frequency range is marked in Figure 3, as is the frequency range corresponding to the second harmonic, i.e., 293×8 cycles/minute to 313×8 cycles/minute. Examination of Figure 3 reveals that at about time 9:44:50, the recorded rotor sound frequency was in the expected range between 100% and 107%, indicating that the ground track at that time was approximately perpendicular to the line of sight from the camera to the helicopter. This analysis made it possible to assign time 9:44:50 to the 'closest to Bronco camera' location shown in Figure 1. This time is quite accurate because Figure 3 shows that three seconds earlier or three seconds later, the recorded sound frequency was outside of the expected range where the Doppler effect is minimal.

The sound signal in Figure 2 has two segments of high intensity separated by more than 20 seconds of low intensity. To answer the question whether both high-intensity segments are the sound of the accident helicopter, spectrum analysis similar to that shown in Figure 3 was performed along the time period shown in Figure 2. The rotor blade frequency between 100% and 107%, modified by the Doppler effect, was detected in both segments of high intensity and even in the low-intensity segment between them. The blade frequency component was not detected past the 'crash time' marked by the red broken line in Figure 2. Consequently, it was concluded that the sound corresponding to the two segments of high intensity in Figure 2 was generated by the accident helicopter.

Figure 1 shows that the last ADS-B location was at time 9:45:36. Based on the distance from that location to the crash location, it was estimated that crash occurred at about time 9:45:38. This is the time marked as 'crash time' in Figure 2. Figure 2 also shows the 'closest to Bronco camera' time. This time is about 20 seconds past the time where the first elevated intensity segment in the figure reached its highest values. It is believed that this delay is due to terrain over which sound had to propagate to reach the camera. During the 20 seconds before reaching the 'closest to Bronco camera' location, sound propagated over hilly terrain with almost no vegetation. When reaching the closest point and after that time, sound had to propagate over residential and commercial buildings. It is possible that the hilly terrain provided lower sound attenuation than the urban area, which could explain why the signal intensity was not highest at the location that was closest to the camera.

Analysis of the Visual Evidence in the Bronco Camera Video

Figure 4 is a frame from the Bronco camera video that was recorded on a clear day after the day of the accident. It shows the baseball field and the terrain south of the field that the approximately south-pointing camera recorded. The camera had a wide-angle lens that caused the barrel distortion evident in the figure. Figure 5 is a frame from the Bronco camera recorded on the accident day, at a time when the helicopter sound was audible.

Figure 4. Frame from Bronco Camera Video Recorded on a Clear Day

Figure 5. Frame from Bronco Camera Video Recorded at Accident Time

The helicopter was not visible in the Bronco camera video that recorded the helicopter sound on the accident day. This led to the following strategy for estimating the visibility at the time of the accident. The clear-day video frame from Figure 4 can be used for developing a model of the Bronco camera optics. Such a model can predict where in a video frame an object would be located if it is in the field of view of the camera and is not obstructed by terrain or trees. The location of the helicopter in the field of view of the camera is known from the ground track and the altitude recorded in the ADS-B system. If the data show that the helicopter was in the field of view of the camera and was not obstructed but it was not seen in the video, it would indicate that the visibility was less than the distance from the camera to the locations of the helicopter. The first step toward implementing this strategy was the development of a model of the camera optics.

Calibration of the Bronco Camera Optics Model

The estimation of the visibility range required a calibrated mathematical model of the Bronco camera optics. The mathematical model of camera optics requires seven parameters. Three are the X, Y and Z camera location coordinates. Three are the yaw, pitch and roll camera orientation angles, and the seventh parameter is the camera horizontal field of view angle (HFOV). The X and Y coordinates of the camera could be estimated from Google Earth aerial images. The camera height above ground, Z, was measured by a baseball field staff member. The other four camera model parameters had to be estimated as described next.

The estimation was based on references that were visible both in aerial images of the Bronco baseball field and in video frames such as the one in Figure 4. The references used for calibration included the baseball field bases, the pitcher's mound, the score board, fences and trees. The heights of the fences and of the score board were measured by a baseball field staff member.

Since the video frames were barrel-distorted, the distortion was first mathematically removed. Then a computer program that simulates camera optics was used to project the references onto a frame from the video in an iterative process in which the four unknown camera parameters were varied so as to align the projected references with their images. When the projected references were aligned optimally with their images in the frame, the values of the four parameters were their optimal estimates. At that point, the model of the camera optics was calibrated. Note that the fields of view of the cameras shown in Figure 1 are based on the cameras' yaw orientations and their HFOV angles that were estimated in this calibration process.

Estimation of Visibility Based on Expected Helicopter Image Locations in Video Frames

The helicopter image was not seen in the Bronco camera video or in the Mustang or Pinto camera videos. To estimate visibility based on this fact, it had to be determined whether the helicopter passed locations where it would have been seen in a video recorded on a clear day. Using the camera model and the ADS-B data, it was estimated at which points on the ground track the helicopter was within the field of view of the camera and unobstructed by terrain or trees. Figure 6 shows an aerial image of the accident area where the points on the ground track where the helicopter would be visible are marked by large yellow markers, and points where the helicopter would not be visible are marked by small yellow markers. The start and end times of the segments where the helicopter would be visible on a clear day are also indicated.

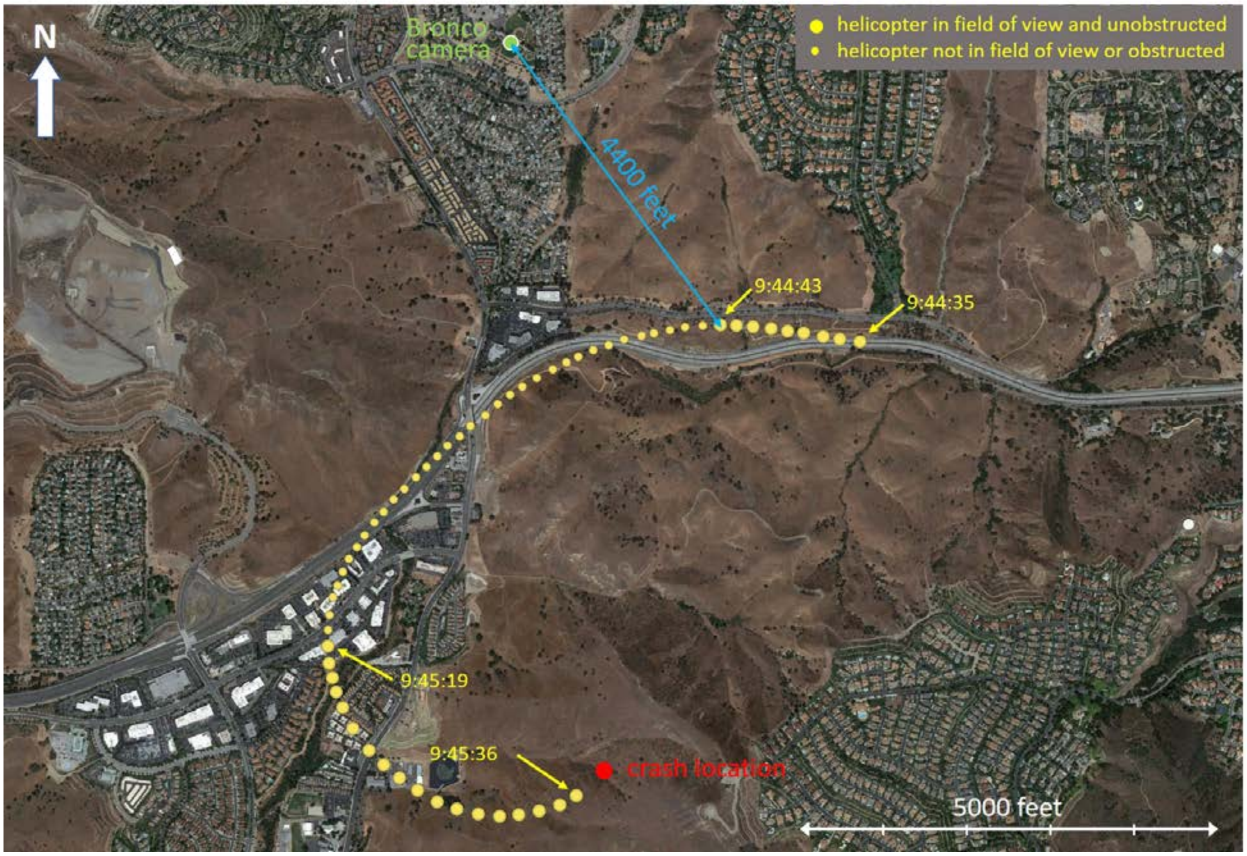

Figure 6. Clear-Day Visibility of the Helicopter – Bronco Camera

The points shown in Figure 6 where the helicopter would have been visible are also shown in the video frame in Figure 7 at the frame locations where the helicopter image would have been located on a clear day. The black area on top of the figure is due to the barrel-distortion removal process. Since the camera was pointed south, the helicopter image would have entered the clear-day video frame from the left, as it emerged from behind trees, at time 9:44:35. Past time 9:44:43 the climbing helicopter exited the field of view through the top boundary. It reentered the field of view at time 9:45:19 as it was descending. The last ADS-B location, at time 9:45:36, is also visible and is marked in the figure.

The blue line in Figure 6 indicates the shortest distance between a visible location and the Bronco camera. This distance was 4400 feet. The helicopter was relatively far from the camera and its 52.5 foot length would have been seen in the video frame on a clear day as indicated by the red line marked ‘helicopter length.’ That is the size if the longitudinal axis of the helicopter was perpendicular to the line of sight from the camera to the helicopter. When the helicopter reentered the field of view past time 9:45:19, its length in the video frame would have been less than half of the marked size in Figure 7 because then it was more than twice as far from the camera.

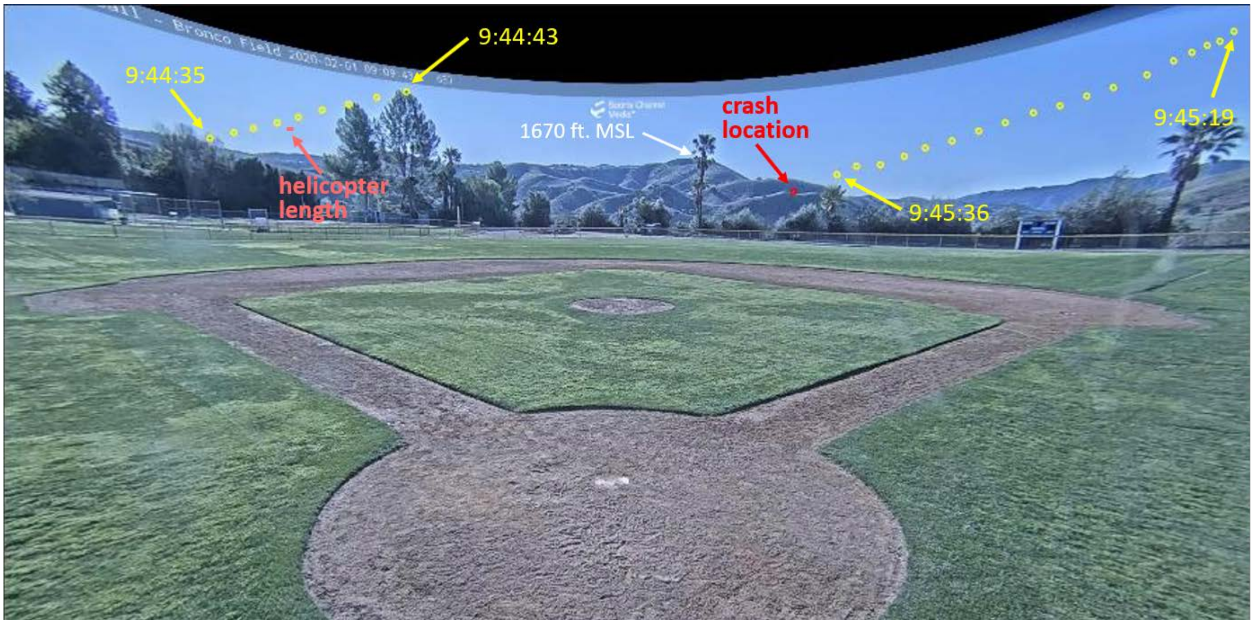

Figure 7. Helicopter Visibility on a Clear Day (Bronco Camera Video)

Consequently, the estimated visibility range based on the analysis above was shorter than 4400 feet. The analysis did not provide information on how much shorter than 4400 feet it was. The estimated visibility was of an object that was very small compared to the 4400-foot distance from the camera. Therefore, this analysis did not provide information on the visibility of large objects, such as the hills seen in Figure 7, that is more representative of the visibility the helicopter pilot was facing. Visibility range to larger objects was likely to be longer than 4400 feet. The following analysis does provide information of the visibility of larger objects.

Estimation of Visibility Range Based on Visibility of Terrain Features in Video Frames

Examination of Figure 4 and Figure 5 reveals that some but not all the hilly terrain visible in the background in Figure 4 is visible in Figure 5. This opens the possibility of estimating visibility range based on the farthest terrain features that were visible in the video recorded at the time of the accident.

The USGS 1/3 arc-second National Elevation Dataset was used to construct a 3D topographical model of the hilly terrain seen in Figure 7. The topographical model was then combined with the calibrated Bronco camera model to perform the following analysis.

For yaw angles within the horizontal field of view of the camera, lines from the camera were drawn in 100-foot length increments up to an assumed visibility distance from the camera. At each 100-foot distance increment, the pitch angle above horizontal to the terrain elevation at that location was computed. There was a largest pitch angle for each analyzed yaw direction that was not necessarily at the assumed visibility distance or at the distance where the highest elevation was. It was so because a lower elevation close to the camera can result in a larger pitch angle than a higher elevation far from the camera.

Figures 8 and 9 are color-coded elevation maps of the accident area. The black markers in Figure 8 are the locations where the pitch angles from the Bronco camera to terrain were the largest when the assumed visibility range was 8000 feet. Figure 9 shows the locations where the pitch angles to terrain were the largest when the assumed visibility range was 10000 feet. The color bars on the right in the figures show the terrain MSL elevation in feet. The Bronco camera is at location (0,0) in the figures. Its elevation is 990 feet MSL.

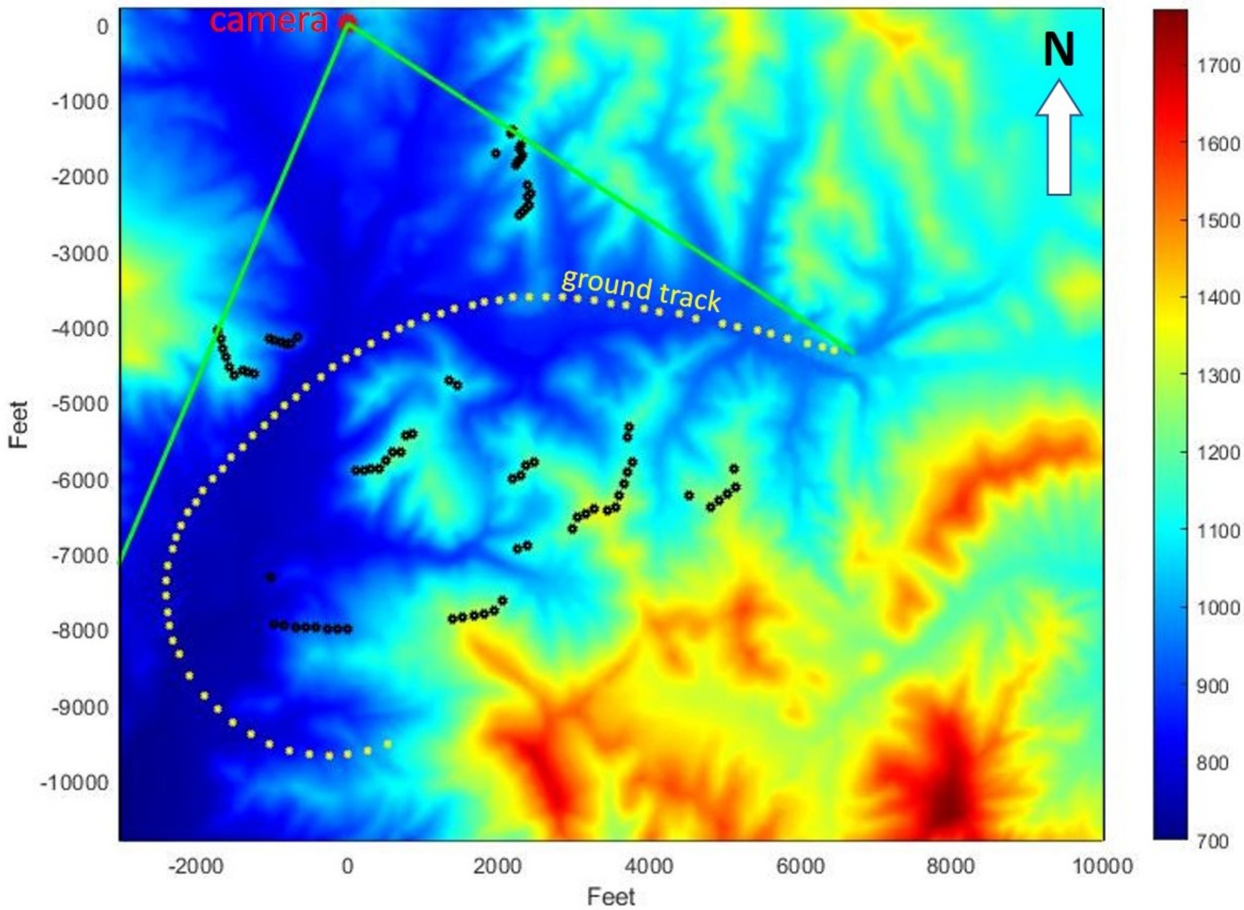

Figure 8. Elevation Map with Marked Locations of Largest Pitch Angles from Bronco Camera to Terrain that Is Closer than 8000 feet

When the largest pitch angles to terrain are plotted vs. the yaw angles from the camera to where the largest pitch angles were measured, the plot forms the outline of the terrain the camera would record if the visibility range was as was assumed when the data for Figure 8 and Figure 9 were generated. This analysis was repeated for assumed visibility ranges of 7500 feet and 8500 feet. To allow superposition of the terrain outline on the video frames, their barrel distortion had to be corrected. Figure 7 above shows the corrected frame from a video recorded on a clear day. Figure 10 shows the corrected video frame that was recorded at the time of the accident. Figure 11 shows the corrected video frame that was recorded at the time of the accident with superimposed terrain outline curves computed for visibility ranges of 7500 feet, 8000 feet, 8500 feet and 10000 feet.

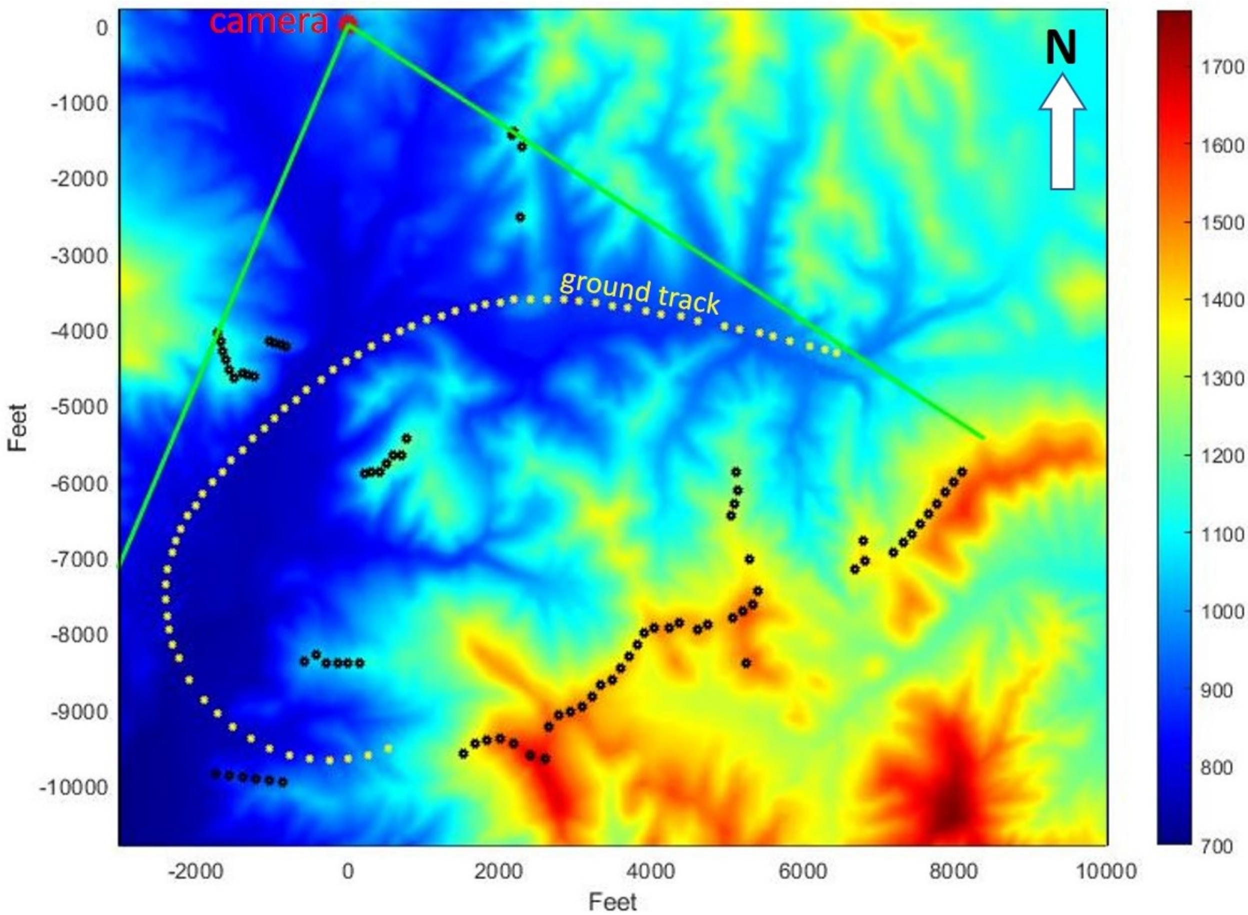

Figure 9. Elevation Map with Marked Locations of Largest Pitch Angles from Bronco Camera to Terrain that Is Closer than 10000 feet

The purpose of displaying Figure 10 is to allow more accurate estimation of the terrain outline in Figure 11. Once the curves are superimposed on the video frame, the barely-visible outline of the terrain is difficult to see.

The four curves in Figure 11 correspond to four assumed visibility ranges. The curves are drawn so that if two curves coincide, the color shown is the one corresponding to the longer visibility range. The actual visibility range at the accident time can be estimated based on Figure 11 if there is a curve corresponding to visibility range R_1 that matches the outline of terrain in the figure and a curve corresponding to visibility range R_2, where $R_2 > R_1$, that is higher than the terrain outline. If the condition is met, the visibility range is somewhere between R_1 and R_2. It was decided that the upper limit of this range, R_2, will be the estimate of the visibility range.

The tree marked in Figure 11 can be used to estimate the visibility range. Examination of Figure 11 and Figure 7 shows that visibility was less than 10000 feet because the hill behind the tree is visible in Figure 7 but not visible in Figures 10 and 11.

Figure 10. Frame from Bronco Video at Accident Time (Distortion Corrected)

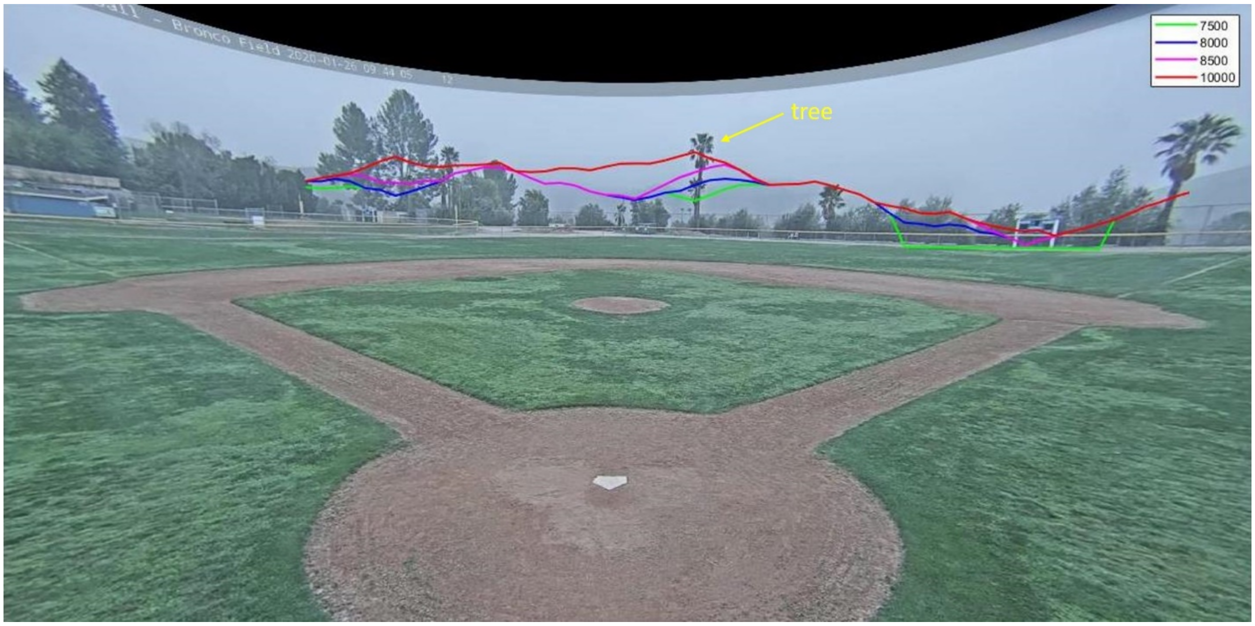

Figure 11. Frame from Bronco Video with Superimposed Terrain Outlines

A more detailed examination of Figure 11 reveals that terrain details are visible at the distance of 7500 feet, the green curve, but are not visible at the distance of 8000 feet, the blue curve. Therefore, the visibility range estimate based on the Bronco camera video is 8000 feet or 1.5 miles.

The Bronco video provided a visibility range estimate of 1.5 miles based on the visibility of terrain features in video frames. It was a specific estimation based on a camera at 990 feet MSL and a hilltop at 1670 feet MSL. The hilltop is located about 10000 feet from the camera and is not visible in the video. The video did not contain clear information on what limited the visibility range. There are three possible visibility-limiting mechanisms. Figure 12 is used to explore the three possibilities.

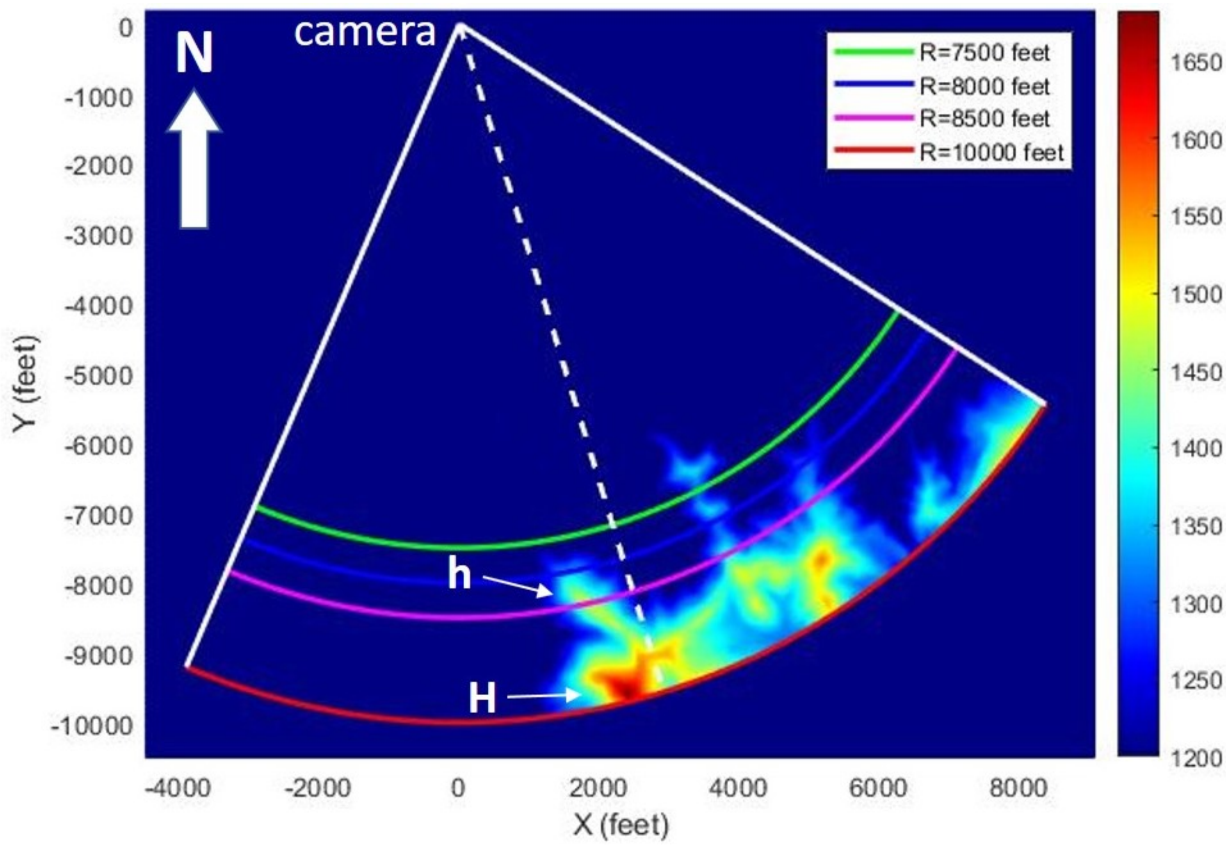

Figure 12. Terrain Elevation in Field of View of Bronco Camera

Figure 12 is a map of the terrain elevation in the field of view of the Bronco camera. The figure shows a subset of the information in Figures 8 and 9. The shown area is limited to be within the field of view of the camera and at a distance of 10000 feet or less from the camera. The elevation scale starts at 1200 feet MSL. The broken white line marks the yaw orientation of the camera. Terrain along that line maps onto a vertical line passing through the horizontal center of video frames such as the one in Figure 11.

The four arcs in the figure, at 7500 feet, 8000 feet, 8500 feet and 10000 feet from the Bronco camera, correspond to the four terrain contour lines in Figure 11. Since the

Y axis in Figure 12 is oriented along the north direction and the Bronco camera is oriented approximately in the south direction, locations right of the broken white line in Figure 12 correspond to locations that are left of the horizontal center of Figures 7, 10 and 11. The hilltop at 1670 feet MSL marked in Figure 7 is marked as H in Figure 12. Location h marked in the figure is a ridgeline, at about 1450 feet MSL, that is part of an area of higher elevation that starts at about 7700 feet from the camera and is visible in Figure 10 and in Figure 11.

The key question is why the terrain near ridgeline h was visible in the Bronco camera video and hilltop H was not visible. The three possibilities are:

1. Visibility was limited by mist caused by uniformly-distributed high relative humidity. Ridgeline h, part of the elevated area that starts at about 7700 feet from the camera, was at the limit of the visibility range, as can be appreciated in Figures 10 and 11. The additional distance from there to hilltop H pushed hilltop H beyond the visibility range.
2. Visibility was limited by mist caused by non-uniformly-distributed high relative humidity. It is possible that the relative humidity beyond 8000 feet was higher than what it was up to 8000 feet, thus limiting the visibility range to approximately 8000 feet.
3. Mist was caused by uniformly-distributed relative humidity but the cloud base was about 1450 feet MSL in the area near locations h and H. This placed the area near ridgeline h below the cloud base and hilltop H above the cloud base. Since the altitude of the helicopter based on ADS-B data was higher than 1450 feet, it could have been flying above the cloud base. If this was the case, the visibility range that the pilot was facing was probably less than the 1.5 miles estimated above.

Analysis of the Visual Evidence in the Pinto and Mustang Camera Videos

Figures 6 through 12 document the details of the analysis of the Bronco camera video. Such analysis was then repeated for the Pinto and Mustang camera videos. Figure 13 shows a frame from the Pinto camera video that was recorded on a clear day and after the barrel distortion was corrected. Figure 14 shows a frame from the Mustang camera video that was recorded on a clear day and after the barrel distortion was corrected.

Figure 15 shows a frame from the Pinto video that was recorded at the time of the accident and after the barrel distortion was corrected. Figure 16 shows that video frame with superimposed terrain outline curves computed for visibility ranges of 4000 feet, 4500 feet, 5000 feet and 6000 feet.

Examination of Figures 13, 15 and 16 reveals that at the frame location marked as A in Figure 13 and in Figure 16, the terrain outline curve corresponding to assumed visibility range of 4500 feet matches the terrain outline but the curve corresponding to visibility range of 5000 feet does not. Therefore, the visibility range estimate based on the Pinto camera video is 5000 feet or one mile. Note that frame location A marked in Figure 13 and in Figure 16 is west of the ground track shown in Figure 1.

The Pinto video continued for about 17 minutes after the helicopter crashed. During this time, there was a period when the visibility was slightly worse than in Figure 15 and a period when the visibility was slightly better than in Figure 15. These variations did not change the 5000 feet or one-mile visibility range estimate. However, these variations could be an indication that the cloud base was about at the elevation of hilltop A that is marked in Figure 13, i.e, 1440 feet. The observed visibility range variations could be due to clouds with slightly different bases moving between the camera and hilltop A.

Figure 13. Frame from a Clear-Day Pinto Video (Distortion Corrected)

Figure 14. Frame from a Clear-Day Mustang Video (Distortion Corrected)

Figure 15. Frame from Pinto Video at Accident Time (Distortion Corrected)

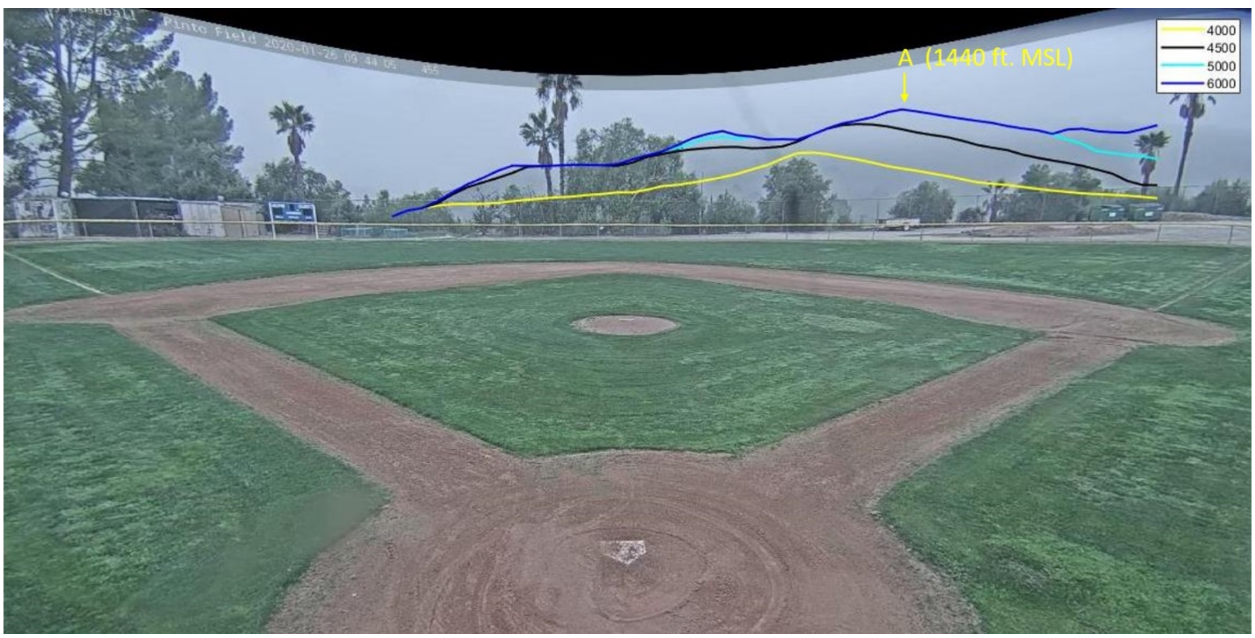

Figure 16. Frame from Pinto Video with Superimposed Terrain Outlines

Figure 17. Frame from Mustang Video at Accident Time (Distortion Corrected)

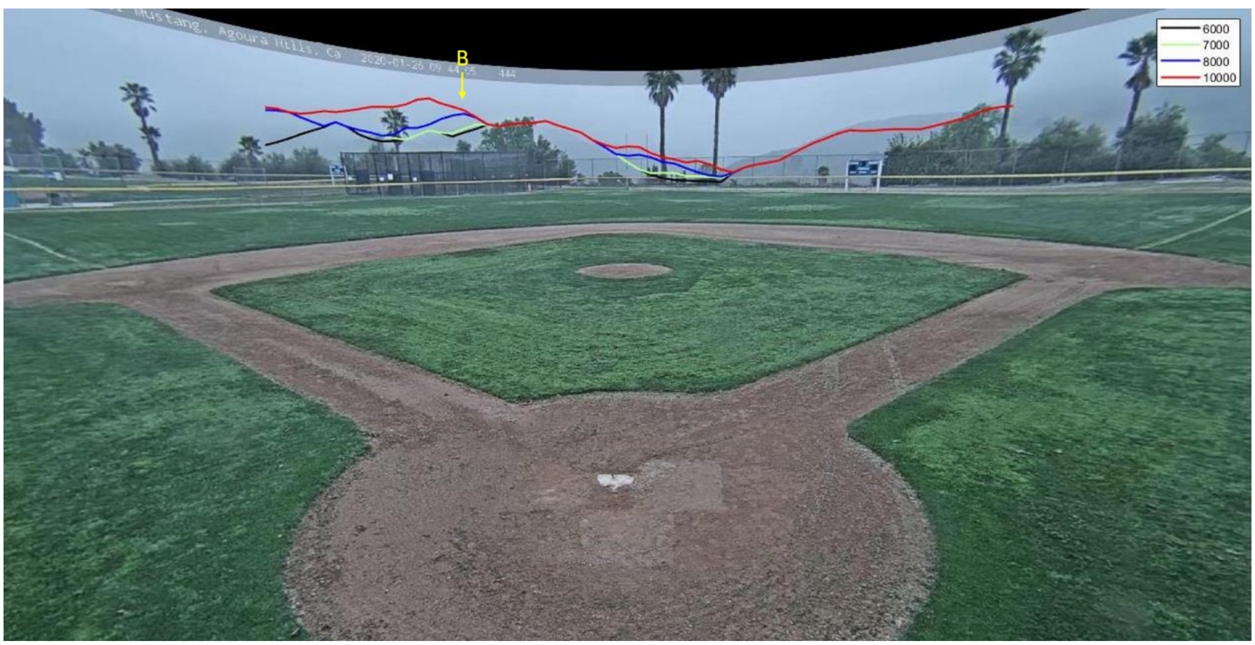

Figure 18. Frame from Mustang Video with Superimposed Terrain Outlines

Figure 17 shows a frame from the Mustang video that was recorded at the time of the accident and after the barrel distortion was corrected. Figure 18 shows that video frame with superimposed terrain outline curves computed for visibility ranges of 6000 feet, 7000 feet, 8000 feet and 10000 feet.

Examination of Figures 14, 17 and 18 reveals that at the frame location marked as B in Figure 17, the terrain outline curve corresponding to assumed visibility range of 7000 feet matches the terrain outline but the curve corresponding to visibility range of 8000 feet does not. Therefore, the visibility range estimate based on the Mustang camera video is 8000 feet or 1.5 miles.

<u>Discussion of Visibility Range Estimates</u>

This study estimated visibility in the accident area based on the visibility of objects in videos recorded by cameras that were located north of the ground track of the helicopter. As seen in Figure 1, the fields of view of the three cameras extended from southeast to southwest relative to the cameras. The closest distance from the cameras to the ground track of the helicopter was about 4000 feet and the farthest distance was about 9600 feet.

The visibility range was not estimated from the locations of the helicopter and in the directions where the pilot would be looking. It was estimated based on cameras that were located north of the helicopter. However, the area that includes the ground track and the cameras is only about 2 miles (north to south) by 1 mile (east to west) and the estimated visibility range was 1.5 miles or shorter. Therefore, it is believed that the estimated visibility range is representative of the visibility the pilot was facing.

The visibility was first estimated based on the observation that the helicopter was in the fields of view of three cameras but was not visible in the videos. The estimated visibility range was 4400 feet or shorter. However, this was visibility of an object of a size that was very small compared to its distance from the camera. Such visibility is not representative of the visibility of roads and large terrain features from the cockpit of the accident helicopter.

Visibility range was then estimated based on the visibility of terrain details in videos recorded by three cameras. The three estimates were 8000 feet, 5000 feet and 8000 feet (1.5 miles, one mile and 1.5 miles). The 0.5 mile difference between the shortest and the longest estimates could be an indication that visibility was not uniform in the accident area. It was concluded that the visibility range the pilot was facing could have been as short as one mile, the shortest of the three estimates, or less if the visibility was not uniform.

The helicopter ground speed just before terrain impact was about 160 knots or 270 ft/s. The shortest visibility range estimated above was 5000 feet. This visibility range corresponds to about 5000/270=18.5 seconds of flight. If the visibility range was not uniform and was less than 5000 feet in the area where the helicopter crashed, it would correspond to less than 18.5 seconds of flight, leaving the pilot limited time to avoid terrain.

Figures 7, 13 and 14 show the MSL elevation of the highest hills that were just beyond the visibility range of the Bronco, Pinto and Mustang cameras, respectively. The hill marked in Figure 14 is the same as the hill marked in Figure 7. The hilltops, at 1670 feet MSL and 1440 feet MSL, were not visible in the accident-day videos. The weather at Van Nuys airport (elevation 802 feet MSL), about 14 miles northeast of the accident site, was reported as overcast at 1,100 feet above ground level. It is possible that the marked hills were not visible in the videos because they were above the cloud base in the accident area, as explained in detail in the analysis of the Bronco and the Pinto videos.

If the hilltop at 1440 feet MSL was above the cloud base, so was the helicopter until several seconds before it impacted terrain. ADS-B data indicate that its altitude was above 1450 feet MSL until time 9:45:33. The visibility range estimates in this study were based on cameras that were looking up at terrain features from their locations under the cloud base. If the helicopter was flying above the cloud base, the pilot was looking down at terrain features from above the cloud base. Consequently, the visibility range from the cockpit would have been shorter than the ranges estimated based on the videos. There is no information in the videos that would allow estimation of the visibility range from the cockpit of the helicopter if it was above the cloud base.

E. CONCLUSIONS

The visibility range in the area where a helicopter crashed into hilly terrain was estimated based on videos recorded by three cameras. Estimation was based on the visibility of terrain details in the videos and on the observation that the helicopter was in the field of view of the cameras but was not visible in the videos. The estimated visibility ranges were between one mile and 1.5 miles. If the helicopter altitude was above the cloud base, a possibility explored in this study, the visibility range from the cockpit was shorter than these estimates.