Analysis of Aviation Accident Videos at NTSB

Dan T. Horak
National Transportation Safety Board (NTSB)
Washington, DC
USA

ABSTRACT

Over the last few years, videos became a major source of information for aviation accident investigations. To date, NTSB analyzed more than thirty aviation accident videos. In these accidents, videos were one of the main and often the only source of information for estimating trajectories, altitudes, speeds and orientation angles of crashing airplanes. These videos were recorded by cameras mounted on airport structures, on commercial buildings, on private homes, on crashing airplanes and on airplanes that recorded crashing airplanes. We also analyzed automobile dashboard camera videos and traffic camera videos that recorded crashing airplanes. An increasing source of aviation accident videos we analyze are cameras and smartphones hand-held by bystanders on the ground and even hand-held by a passenger in a crashing airplane.

The number of analyzed accident videos has been increasing from year to year, primarily due to the increasing number of installed high-resolution and high frame-rate security cameras and the increasing number of bystanders who record accident events with phone cameras. Since 2008, NTSB has been developing methodology, algorithms and software for analyzing aviation accident videos. We have reached a point where accurate estimates of trajectories, altitudes, speeds and orientation angles can be derived quickly, successfully handling the increasing rate at which aviation accidents requiring video analysis occur.

INTRODUCTION

Aviation accidents that require video analysis come in many flavors. Many aviation accident videos require only a basic factual summary report that does not involve estimation of numerical quantities. This paper does not discuss such cases and the more than thirty cases mentioned above do not include such straightforward video analyses.

Video Analysis Cases Classified by Complexity

In some runway accidents, the airplane passes by reference points seen in videos recorded by airport cameras. Speed estimates in such cases can be derived by dividing the travelled distance, usually along a runway, by the time it took to travel that distance. Analysis of such low-complexity cases is not discussed in this paper.

The over thirty cases mentioned above are in the medium complexity or high complexity categories. They involve airborne airplanes that do not pass by reference points seen in the videos. Analysis of such accidents requires the use of mathematical models of camera optics. Such models are calibrated using reference points on the ground. Once calibrated, the models can project points in the 3D field of view of a camera onto video frames acquired with that camera. The calibration and use of such camera optics models will be described in detail later in this paper. Video analysis cases can be classified by type and complexity based on the four criteria described next.

Interpolation vs. Extrapolation

If the ground reference points used for camera model calibration are surrounding the airplane or are close to it, the analysis can be viewed as interpolation. Even if the calibrated parameters of the camera optics model are somewhat inaccurate, if the camera optics model can accurately project the calibration reference points onto video frames, it will also accurately project points on the airplane onto the video frames.

The extrapolation cases involve available calibration reference points that are all near the camera, such as 50 meters from it or closer, and the estimation of airplane trajectory, altitude and speed of an airplane that is airborne and can be 500 meters or farther away from the camera. Most of the thirty cases mentioned above are in the extrapolation category.

The main problem facing the analyst of extrapolation cases is that small angular errors of the camera optics model parameters, i.e., the camera model yaw, pitch, roll and horizontal field of view angles, result in large trajectory, altitude and speed errors of the airplane that is far away. These small angular errors are not detectable during camera model calibration if all the reference points used for calibration are near the camera. In other words, the model can handle accurately the reference points or airplanes located near the reference points, but it cannot handle accurately airplanes that are far from the reference points that were used for camera calibration.

Fixed Camera vs. Moving Camera

The scenarios where the trajectory, altitude and speed of an airplane are being estimated can also be classified according to the location of the camera that recorded the video. The simplest cases are those where the camera location is fixed, typically because it is mounted on a building. A higher level of complexity involves smartphones and cameras that are hand-held by videographers on the ground. While the camera location is approximately constant, the camera orientation is changing because the camera is being rotated to keep the airplane in its field of view. Smartphones and cameras allow zoom adjustment while a video is being recorded. Analysis of videos with changing zoom requires recalibration of the field of view angle in addition to recalibration of the camera orientation angles for each analyzed video frame.

A video recorded by a camera mounted in an airplane can also be used for estimating the trajectory, altitude, speed and orientation angles of that airplane. Analysis of such videos requires the use of a large number of ground reference points along the ground track of the airplane because as the airplane moves, the reference points located in the camera field of view change. The analysis can be further complicated if the camera is hand-held by a passenger in the airplane and is changing its orientation with respect to the airplane. Analysis of such videos requires the recalibration of the camera orientation with respect to the airplane for each analyzed video frame, followed by the estimation of the airplane location and orientation with respect to ground reference points visible in that video frame. NTSB has the methodology and the tools for analyzing videos recorded by fixed or movable cameras whether they are on the ground or inside flying airplanes.

Airplane Details Visible vs. Airplane Details Not Visible

When the image of the airplane in video frames is sufficiently large so that its details such as nose, fuselage, tail and wings are visible, analysis can be based on wireframe model alignment. A 3D wireframe model of the airplane is constructed and projected onto a frame from the video using the camera optics model. The wireframe model is then moved and rotated until the projected image matches the image of the airplane in the video frame. Once optimal match is achieved, the location and orientation angles of the wireframe model are the optimal estimates of the location and orientation angles of the airplane at the time the analyzed video frame was recorded. The movement and rotation of the projected wireframe model is managed by an algorithm that uses the mathematical model of the optics of the camera. This model is described in detail later in this paper and an example later in this paper uses the wireframe model method.

When the airplane is far from the camera, its image in a video frame can be as small as one or several pixels. In such cases, the wireframe model approach cannot be used and the orientation angles of the airplane cannot be estimated based on the video. Estimation of the location and altitude of the airplane is usually possible, but it requires some additional information, such as the ground track of the airplane. An example later in this paper uses radar-based ground track to supplement the information in a video that does not show airplane details.

Many Reference Points Available for Camera Calibration vs. Few Reference Points

Video analysis is based on the mathematical model of camera optics. As described later in this paper, the model requires seven parameters that must be estimated in a calibration process that is based on ground references. When there are many available reference points that are distributed throughout the field of view of the camera, calibration is relatively simple and the resulting calibrated camera optics model is accurate.

In many cases, however, there are few reference points and they may not be distributed throughout the field of view of the camera. Calibration in such cases is time consuming and it results in camera optics models that may have lower accuracy.

Based on the four criteria described above, it is possible to classify video analysis cases by their overall complexity. Figure 1 illustrates this classification. On the bottom, in blue, is the simplest case where all four complexity criteria point to a low complexity case. On top, in red, is the most complex case where all four criteria point to a high complexity case. Most cases are in the medium-high complexity range, where two or three criteria point to a high-complexity case.

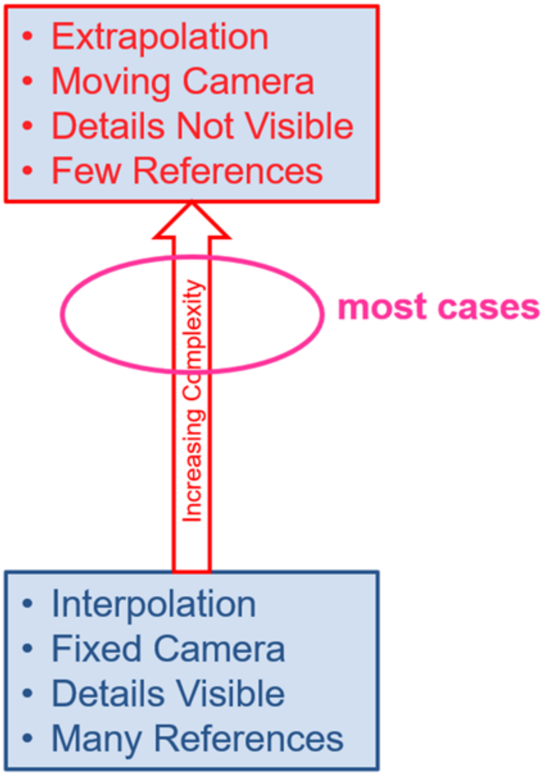

Figure 1. Classification of Video Analyses by Complexity

MATHEMATICAL MODEL OF CAMERA OPTICS AND ITS USE FOR ANALYSIS

Video analysis aimed at estimating trajectories, altitudes, speeds and orientation angles of airplanes is based on the use of mathematical models of camera optics. The strategy behind the use of such models is quite simple. Assume that a 3D model of the airplane, with its dimensions specified in units of distance such as meters, is placed and oriented by an analysis program at a 3D location in the field of view of a camera. The 3D location is specified in meters and the airplane orientation is specified by its Euler yaw, pitch and roll angles. The analysis program is then used to project points on the airplane model onto frames from the analyzed video using the mathematical model of camera optics. These points can be located on the airplane nose, tail, wingtips, on the fuselage and on the wings, depending on the visibility of airplane details in the video.

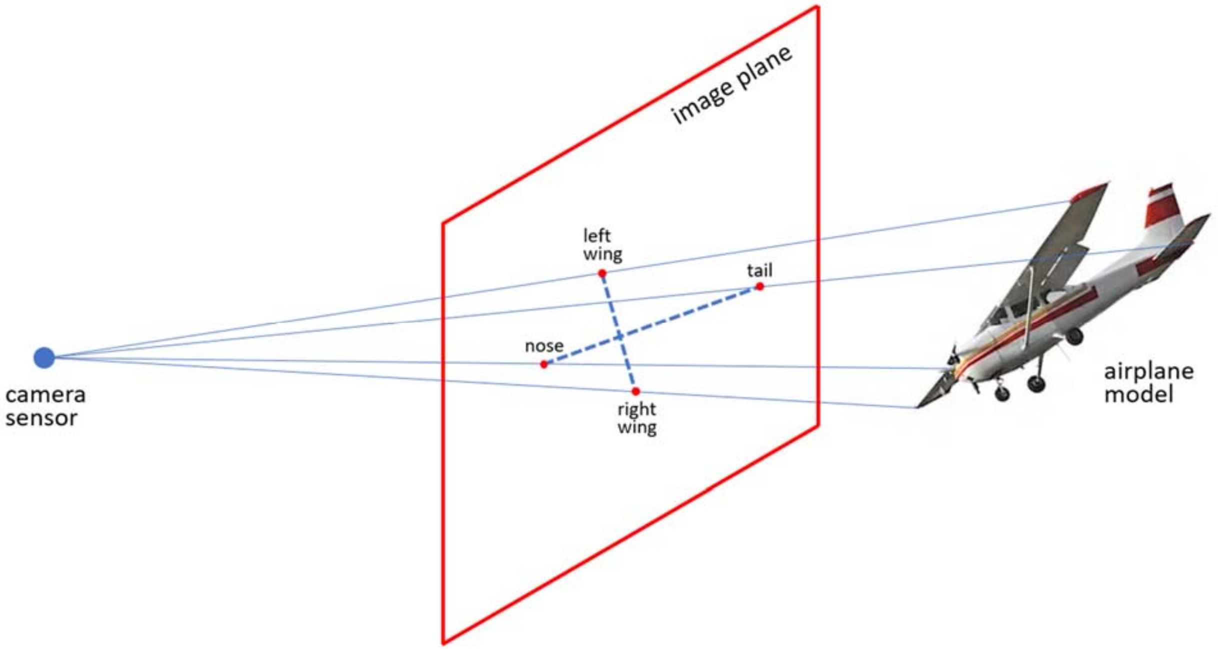

Figure 2. Projection from 3D Field of View onto a 2D Video Frame

Figure 2 illustrates the computational process of projecting points in the 3D field of view of a camera onto 2D video frames, simulating the process cameras use to record video frames. The camera sensor in the figure is at the location of the camera that recorded the video. The airplane model is located and oriented in the 3D field of view of the camera. The image plane is placed in front of the camera sensor and is oriented according to the orientation of the camera. A point on the airplane model is projected onto a point in the video frame that is at the intersection of the image plane with a line from the camera to that point on the airplane model.

If the projected airplane model points are accurately placed on the images of these points on the real airplane as recorded in the analyzed video frame, then the airplane model 3D location and its Euler angles used by the analysis program are the accurate estimates of the real airplane location and orientation angles. The process of aligning the projected points with their images has two stages. First, the mathematical model of camera optics must be calibrated. The model has seven parameters. Three are the X, Y and Z location coordinates of the camera. Three are the yaw, pitch and roll orientation angles of the camera. The seventh parameter is the horizontal field of view angle (HFOV) of the camera.

The seven camera model parameters are estimated in an iterative calibration process where they are varied until reference points on the ground, projected onto a video frame, are optimally aligned with their images in the video frame. At that time, the values of the seven camera parameters are their optimal estimates. The references used for calibration typically include points on buildings, roads, runways and taxiways. These points must be visible in the video frame and their ground coordinates must be known from aerial images or from an optical survey of the area. The resolution of Google Earth aerial images became sufficiently high in recent years so that optical surveying is needed only infrequently.

Once the camera is calibrated, the location and orientation of the airplane is estimated in the second stage of the analysis process. The location and the orientation angles of a 3D wireframe airplane model are varied in an iterative process until the points on it, projected onto a video frame, are optimally aligned with their images in the video frame. At that time, the three location coordinates and the three Euler angles are the optimal estimates of these parameters of the airplane at the time the analyzed video frame was recorded. This airplane location and orientation estimation process is repeated for each analyzed video frame.

In many cases, the details of the airplane are not visible in a video frame. The wireframe model of the airplane in such situations is just a point. While it is not possible to estimate the orientation angles of the airplane based an image that is just a point, partial information on the location of the airplane can be derived and fused with information from other sources to derive an estimate of the location of the airplane.

The calibration and the use of mathematical models of camera optics is illustrated next using the analysis of a recent accident. It involves both the use of the wireframe model approach and the fusion of information from a video that does not show airplane details with radar information.

DESCRIPTION OF THE ANALYZED ACCIDENT

NTSB accident number DCA17FA109 is used to demonstrate the video analysis process. A Shorts SD3-30 airplane crashed during landing on May 5, 2017 on runway 5 at the Charleston Yeager International Airport, Charleston, West Virginia (CRW). The airplane was destroyed and the two pilots suffered fatal injuries. The flight was a scheduled cargo flight from Louisville, Kentucky. At the time of the accident, weather was reported as an overcast ceiling at 500 feet (152 meters). Two cameras recorded the airplane as it was approaching the runway. One camera was on the top floor of a parking garage building in the city of Charleston, about 2 miles (3.2 km) from the airport runway. Its frame rate was 6 frames per second. The other camera was on the airport control tower. It displayed new video frames at the rate of 2.857 frames per second.

Figure 3 shows a frame from the parking garage camera video. It was taken before the airplane became visible. Figure 4 shows a top segment of a frame from the airport tower camera video. It was taken before the airplane became visible. The airport tower camera video frame shows severe barrel distortion caused by the wide field of view angle of the camera.

Figure 3. Frame from the Parking Garage Video

ACCIDENT ANALYSIS

The two videos recorded information that was extracted and analyzed to provide insight into two aspects of this accident. The parking garage video recorded the descending airplane as it emerged from the cloud cover. The estimated altitude of the airplane when it became visible in the video for the first time was considered an estimate of the overcast ceiling. This video-based estimate was used to determine whether the reported 500 foot (152 meter) overcast ceiling was accurate.

The airport tower video recorded the airplane as it impacted the ground on the runway. Analysis of this video provided estimates of the airplane speed and orientation angles at the time of ground impact. The analyses of the two videos are described next.

Camera Calibration

The analysis of this accident required a calibrated mathematical model of the camera optics of each camera. 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 location coordinates of both cameras in this accident could be measured in Google Earth. The other five parameters of each camera had to be estimated.

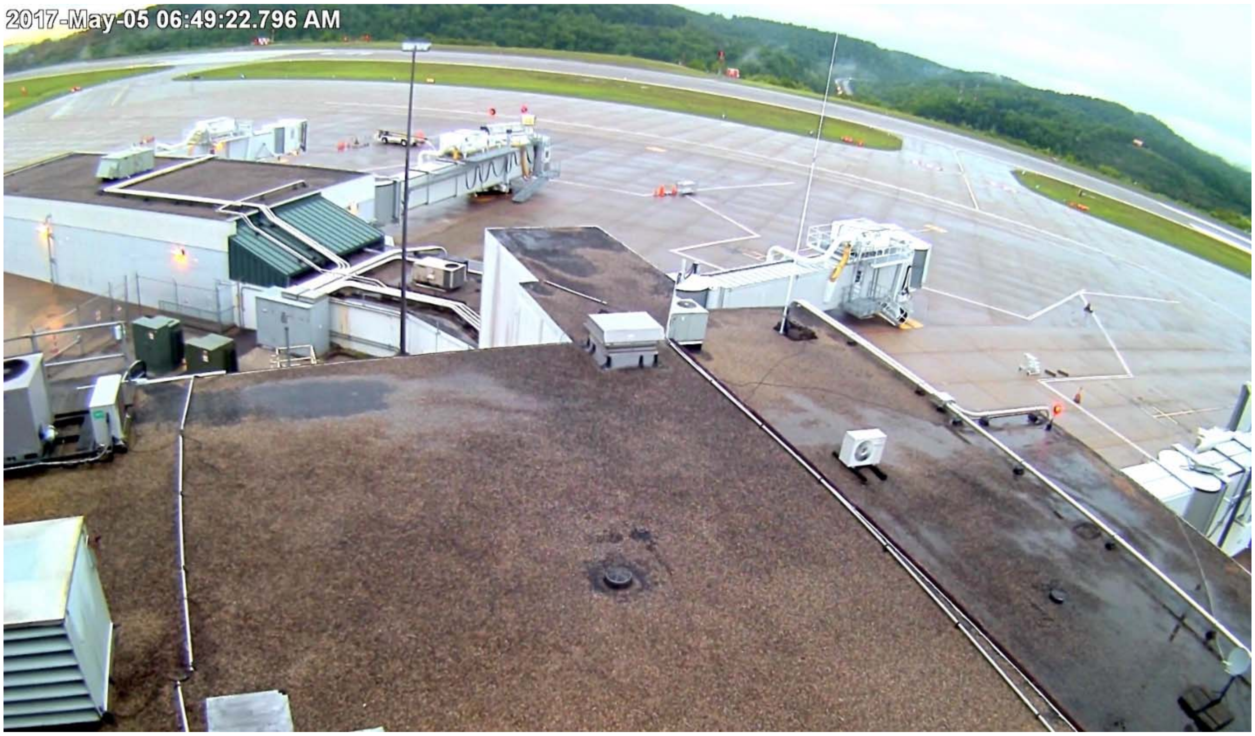

Figure 4. Barrel-Distorted Frame from the Airport Tower Camera Video

The estimation was based on reference points that were visible both in video frames and in aerial images. The references used for the parking garage camera calibration included five highway light poles and parking space markings. The light poles were located between 575 feet (175 meters) and 1200 feet (366 meters) from the camera. They are marked on the Google Earth aerial image in Figure 5. The parking space markings were located 130 feet (40 meters) of less from the camera. They are shown in the Google Earth aerial image in Figure 6.

Figure 7 shows a frame from the parking garage video with marked reference points that were used for calibration. The two points on each light pole were placed at fixed heights above ground because the heights of the light poles were not known.

Camera optics model calibration of each camera was performed as follows. A computer program that simulates camera optics was used to project the reference points onto frames from the video in an iterative process in which the five 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, values of the five parameters were their optimal estimates. At that point, the mathematical model of the camera optics was calibrated.

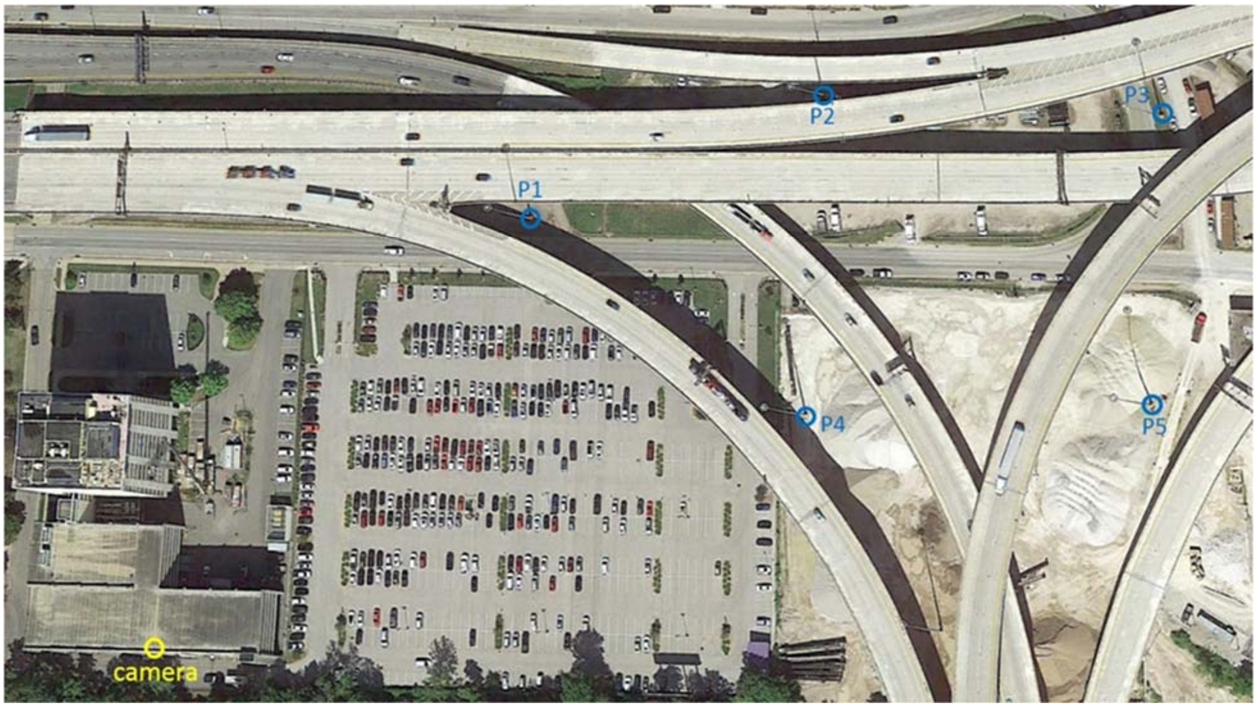

Figure 5. Light Poles P1-P5 Used for Calibration of Parking Garage Camera

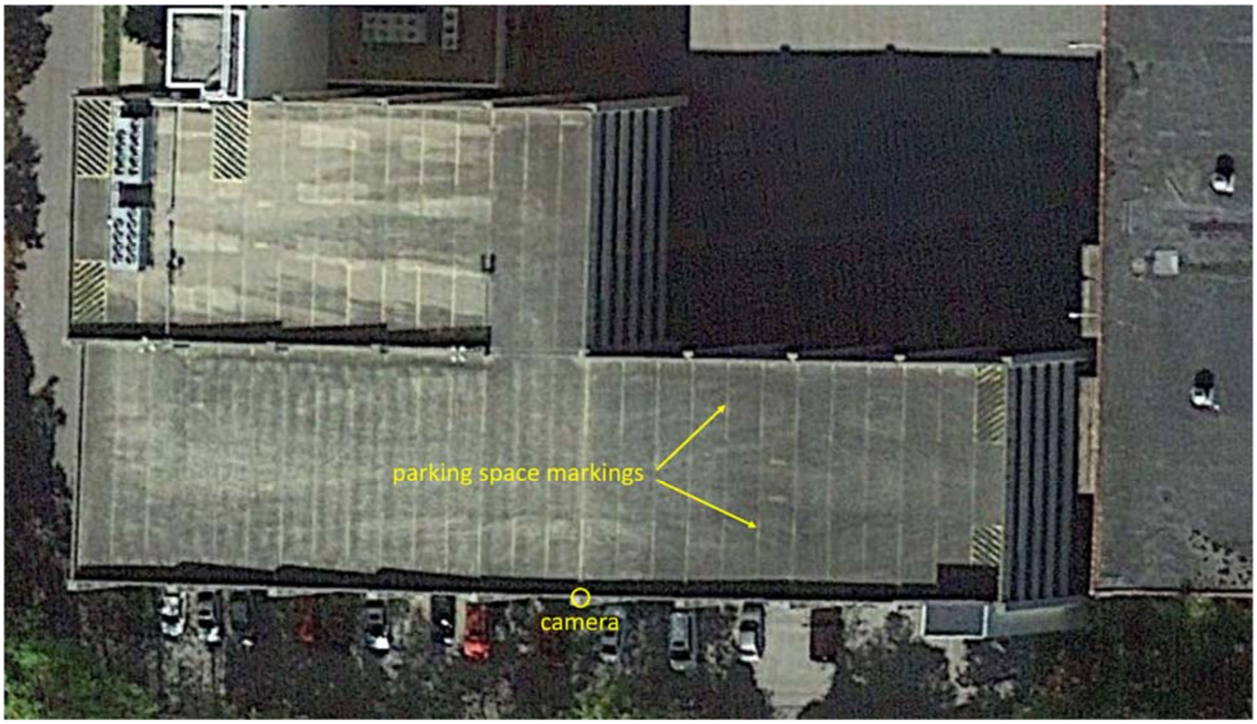

Figure 6. Parking Space Marking Lines Used for Calibration of Garage Camera

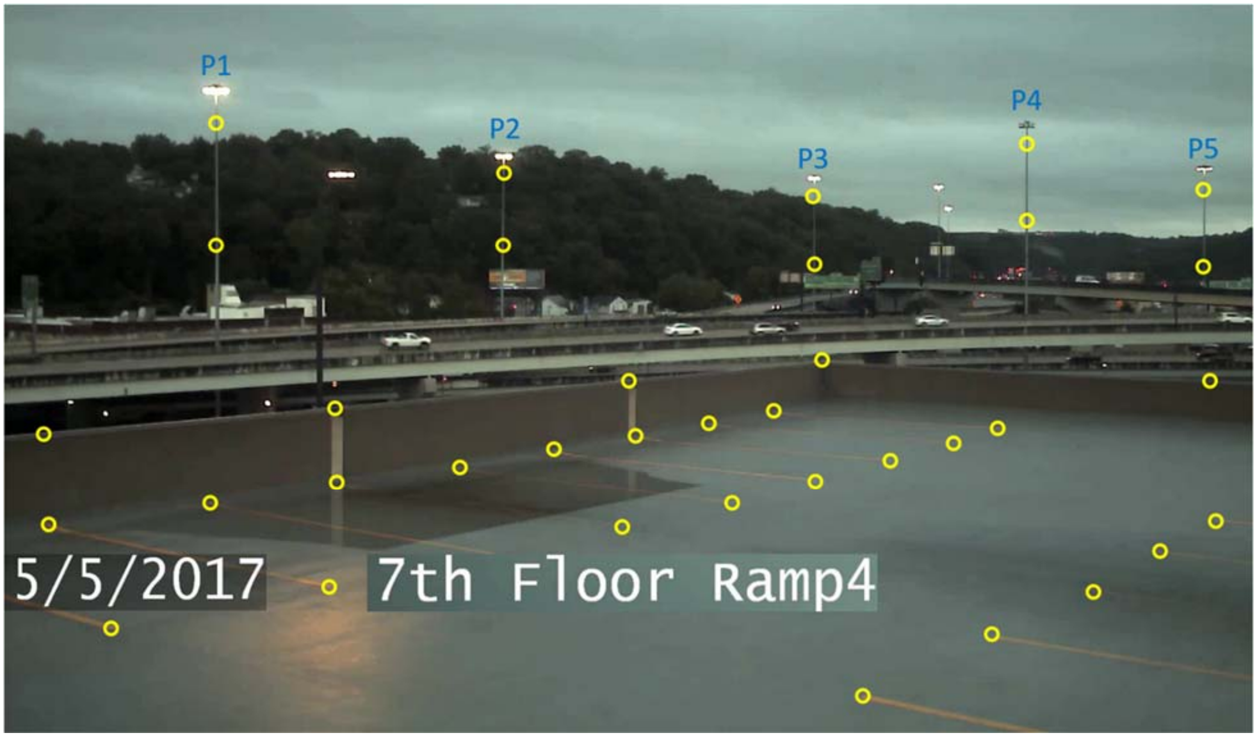

Figure 7. Frame from the Parking Garage Video with Marked Reference Points

Figure 8 shows a block diagram of the calibration process of the parking garage camera where a frame from the video and an aerial image of the scene covered by the camera are analyzed to generate a mathematical model of the parking garage camera optics. The calibration of the airport tower camera followed the same logic and will be described below.

Figure 9 illustrates the capability of the mathematical model of camera optics to project points from the 3D space in the field of view of a camera onto a 2D video frame. It shows that the model can project from the 3D space that includes large amount of information onto a 2D video frame that includes much less information.

However, this is not what is needed for analysis of accident videos. We need information to flow in a direction opposite to what is shown in Figure 9, from the small amount in a 2D frame to the 3D space where three coordinates are needed to specify a location. This may initially look as an impossible task. However, it becomes possible when the 3D to 2D projection capability of the camera model is combined with additional information. That information can be coming from sources such as wireframe model alignment, or a known ground track, or a second camera. The example below illustrates the use of such additional information sources.

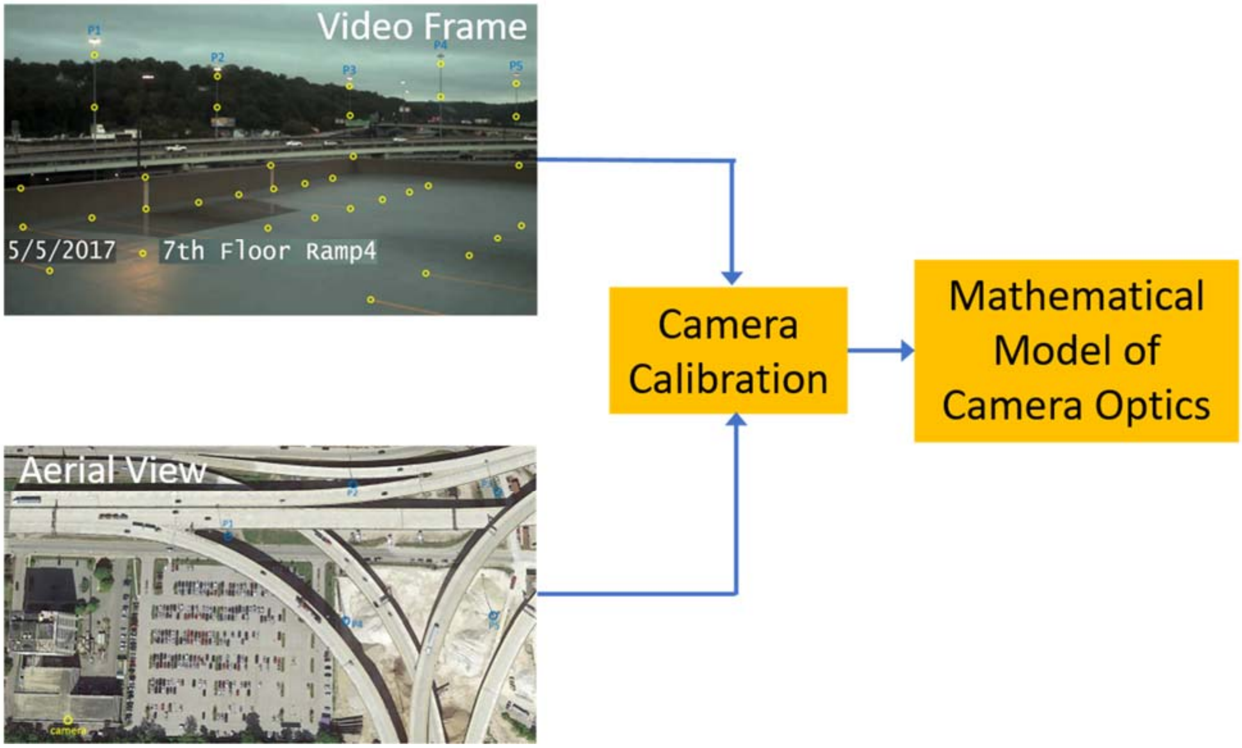

Figure 8. Block Diagram of the Calibration of the Parking Garage Camera Model

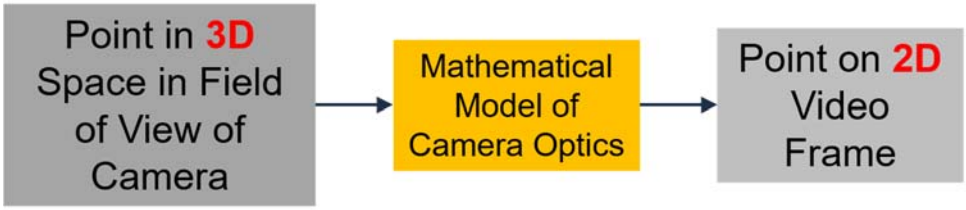

Figure 9. Camera Model Projection Capability from 3D to 2D

Analysis of the Parking Garage Camera Video

Once the parking garage camera model was calibrated, it could be used for analysis of the video. Figure 10 shows the first frame from the video where the descending airplane could be seen. It is marked by the yellow circle. Because of the distance from the camera, no airplane details are visible. The estimation of the distance of an airplane from a camera is ideally based on the dimensions of the airplane image in a video frame using the wireframe model approach. However, since the airplane image in this case was only a dot in the video frame, the distance could not be estimated this way and, without a distance estimate, the altitude of the airplane could not be estimated either. Estimating the altitude was the goal because it was an estimate of the overcast ceiling. The only quantities that could be estimated without any additional information were the azimuth direction and the elevation angle from the camera to the airplane.

Figure 10. Video Frame Recorded when Airplane Became First Visible

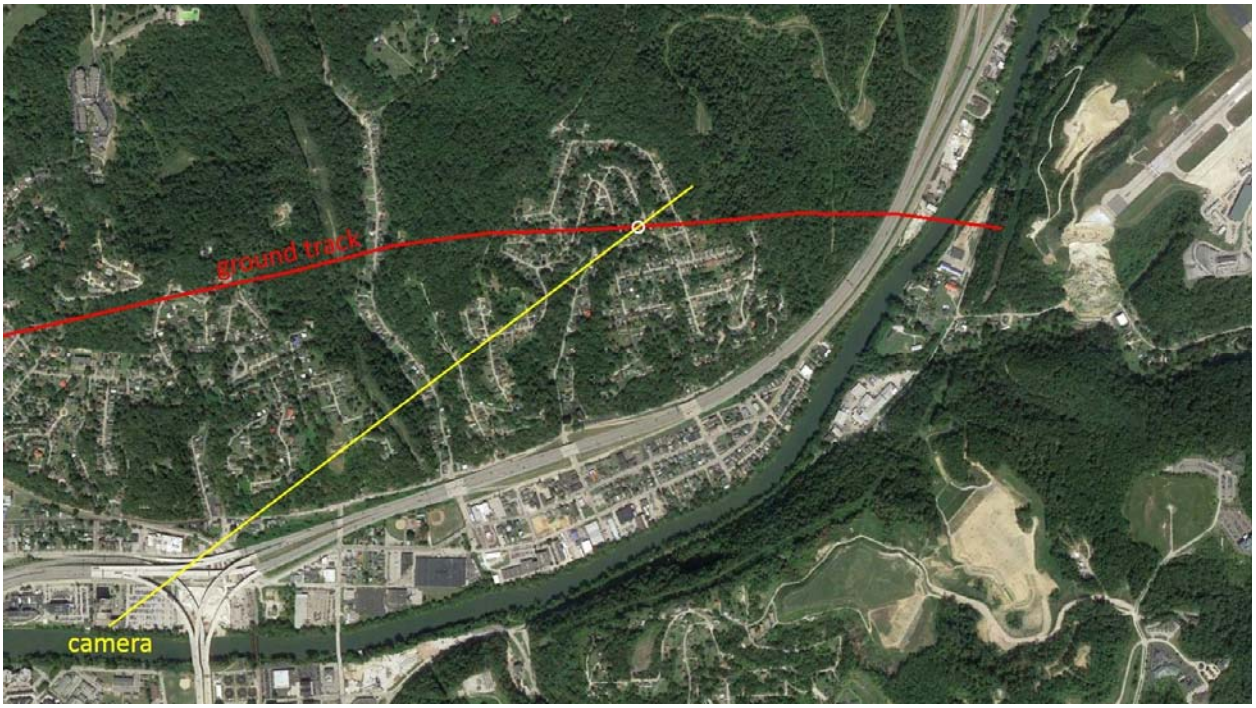

Figure 11. Accident Area with Superimposed Ground Track and Azimuth Direction from the Parking Garage Camera to the Airplane

The additional information that made estimating the altitude of the airplane possible as it emerged from the cloud cover was radar data. Analysis of radar data provided the ground track of the airplane as it was approaching the airport.

Figure 11 shows an aerial view of the accident area. The ground track of the airplane derived based on radar data is shown in red in the figure. The yellow line is the azimuth direction from the parking garage camera to the airplane that was estimated with the camera optics model based on Figure 8, as described above. The video analysis estimated the azimuth angle and the elevation angle from the camera to the airplane but not the location of the airplane along that direction. Fusing the video information and the radar information made it possible to estimate the ground coordinates of that location. That location is at the intersection of the red radar-based ground track and the yellow video-based azimuth line seen in Figure 11.

With the ground coordinates of the airplane location estimated, the altitude of the airplane could be estimated by multiplying the ground distance from the camera to the airplane by the tangent of the elevation angle. The estimated altitude was 683±60 feet above the airport runway. Note that this estimate is based on cloud cover at a location about 3800 feet (1158 meters) west of the landing spot on the airport runway.

Analysis of the Airport Tower Camera Video

Figure 12 shows an aerial image of the airport with marked reference points that were used for airport tower camera calibration. Figure 13 shows the frame from Figure 3 after the barrel distortion was mathematically corrected. When compared to the distorted video frame in Figure 3, the pixels near the corners of the frame in the corrected frame are located farther away from the center of the frame. Marked on the frame are the reference points that were used for the airport tower camera calibration. These points correspond to the reference points marked in Figure 12. The calibration process was similar to the calibration of the parking garage camera, i.e., using the block diagram shown in Figure 8 with Figure 13 and Figure 12 being the Video Frame and the Aerial View, respectively.

The airport tower camera video was used for estimating the speed of ground impact and the orientation of the airplane as it impacted ground. The airplane was visible in seven frames in the video over approximately 2.4 seconds. Only the last three frames showed the fuselage and both wings. In earlier frames, part of the airplane was not in the field of view of the camera.

Analysis of the airport tower camera video was based on a wireframe model of the airplane. Such models can consist of points on the nose, the fuselage, the tail and the wings. The points can optionally be interconnected with lines. The wireframe models are dimensioned in units of distance, such as meters or feet, corresponding to the actual dimensions of the analyzed airplane.

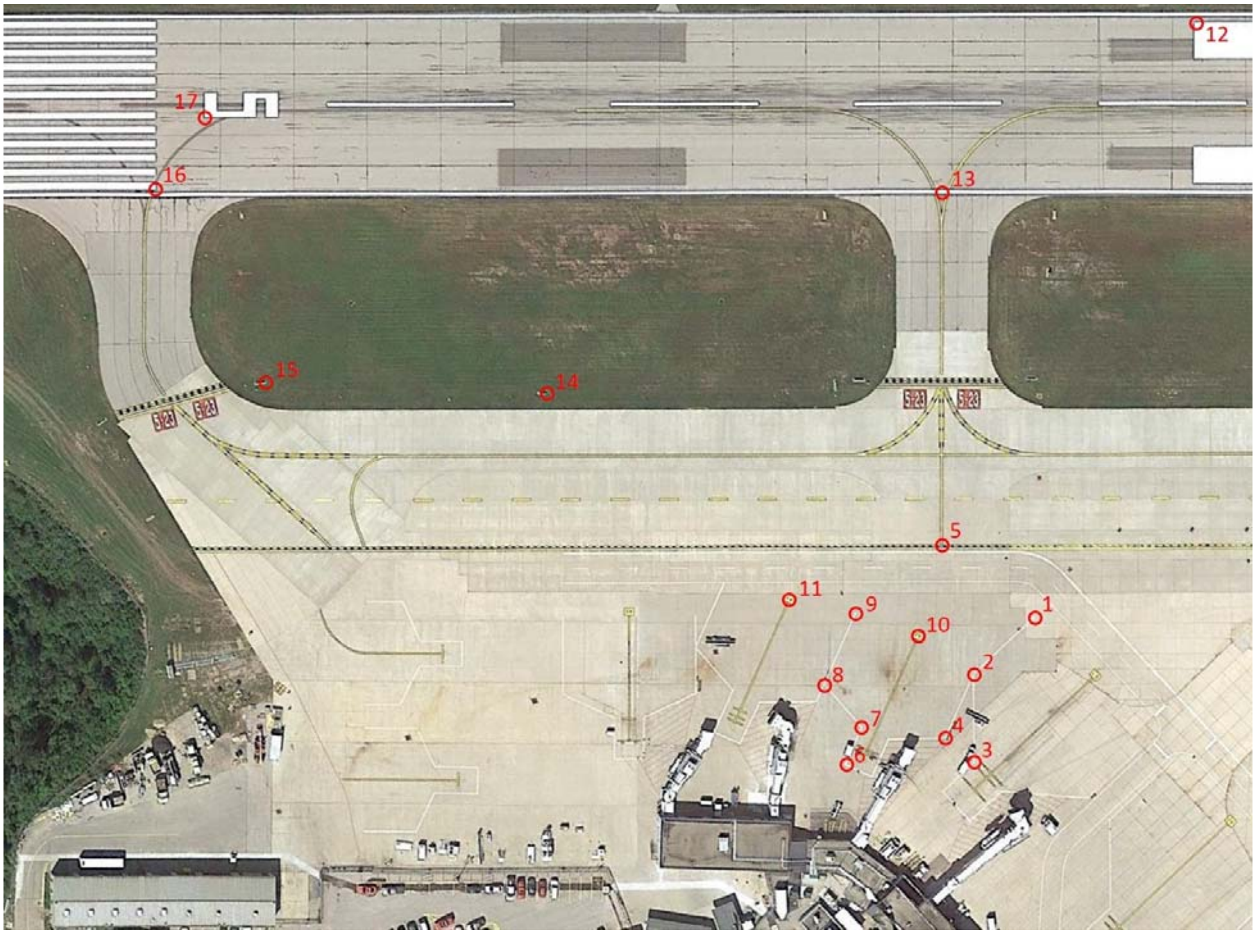

Figure 12. Aerial View of the Airport with Marked Reference Points

In this case, because of the distance from the camera, only points on the nose, the tail and the wingtips could be pinpointed in the video. Consequently, only these points were used in the wireframe model. The model nose was marked in blue, the tail in yellow, the left wingtip in red and the right wingtip in green. The nose and tail markers were interconnected with a red line and the wingtips were interconnected with a blue line.

The calibrated camera model was then used to project the wireframe model onto frames from the video. The model automatically projected the 3D wireframe model dimensioned in units of distance into its 2D image in a video frame, dimensioned in pixels. The camera model was then used to iteratively move and rotate the wireframe model until its projection coincided optimally with the image of the airplane in a video frame. At that time, the location and orientation of the wireframe model were the optimal estimates of the location and orientation of the accident airplane at the time the analyzed video frame was recorded.

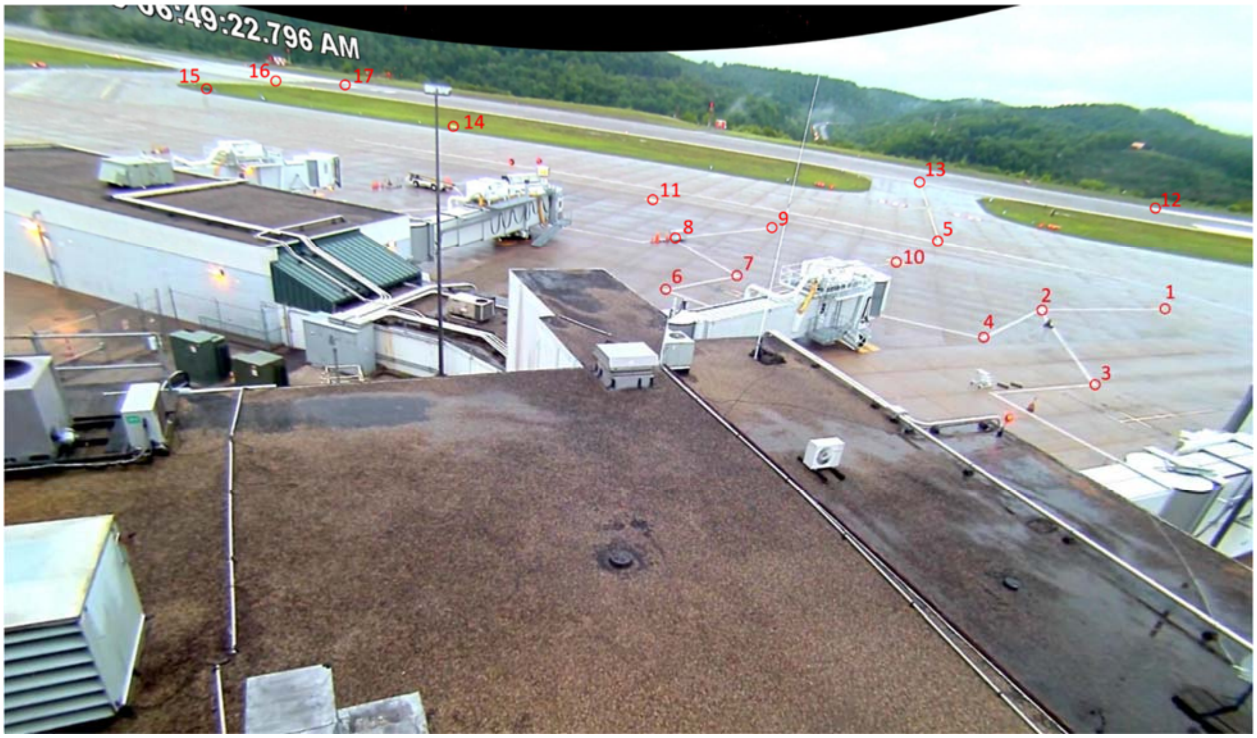

Figure 13. Frame from the Airport Tower Camera with Marked Reference Points

Figure 14. Frame from the Airport Tower Camera Showing the Airplane and its Wireframe Model Shortly before Ground Impact

Figure 14 shows the last video frame before the left wing of the airplane contacted the ground and broke. It shows the wireframe model optimally superimposed on the image of the airplane. The previous and the next video frames were analyzed in a similar process. The three estimated locations of the airplane were then used to estimate the magnitude of the velocity vector of the airplane. It was estimated as 92±4 knots. The left-wing-down roll angle was estimated as 42° at the time of ground impact and the nose-down pitch angle of the fuselage was estimated as 14°.

CONCLUSIONS

This paper described the aviation accident video analysis activities at NTSB. The analyses were classified based on their type and complexity. The core component of the tools used for video analysis, the mathematical model of camera optics was introduced and explained. The analysis of a recent case was then described in detail. The accident involved an airplane that crashed at an airport while attempting to land. Videos from two cameras were used for estimating the overcast ceiling at the time of the accident, the speed of ground impact, and the orientation of the airplane at the time of ground impact. The analysis required calibrated mathematical models of the optics of the two cameras and used fusion of video and radar information for extracting airplane altitude data from one of the videos.