National Transportation Safety Board

Memorandum

Date: June 18, 2018

To: Andrew Swick
Air Safety Investigator, Western Pacific Region
WPR16FA040 Investigator in Charge (IIC)

Cc: Zoë Keliher
Air Safety Investigator, Western Pacific Region
WPR16FA040 Operations Group Chairman

From: John O'Callaghan
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WPR16FA040 Aircraft Performance Specialist

Subject: Plots of GAU2000 data and performance estimates for WPR16FA040

References:

1. National Transportation Safety Board, Office of Aviation Safety, *Servo Transparency Study, NTSB Number LAX03MA292*, September 30, 2004
2. National Transportation Safety Board, Office of Research and Engineering, Vehicle Recorder Division, *Data Logger Specialist's Factual Report, NTSB Number WPR16FA040,* April 20, 2017
3. Eurocopter (now Airbus Helicopters), *Flight Manual, AS 350 B3, Arriel 2B1,* approved by EASA June 10, 2008
4. Bureau d'Enquêtes et d'Analyses pour la sécurité d l'aviation civile (BEA), Memorandum *N°CHRONO/BEA/I, Subject: Comments on memorandum related to the accident to the Rotorcraft Airbus Helicopter - AS350 - B3 registered N74317 operated by Air Methods Corp on 15th December 2015 near Apache Junction (Arizona)*, June 18, 2018

Andrew:

Attached please find plots of performance data and estimates of the "Servo Transparency Parameter" (STP)[1] for the Eurocopter (now Airbus Helicopters) AS 350 B3 (N74317) accident near Superior, AZ on December 15, 2015 (WPR16FA040). The plots present information recorded directly on or derived from recorded data on the Appareo GAU2000 "data logger" device recovered from the wreckage (see Reference 2). This information includes:

[1] The STP will be defined and discussed further below.

- Flight path, groundspeed, and altitude data based on the GAU2000's internal Global Positioning System (GPS) unit;
- Euler angles (pitch, roll, and heading), body-axis angular rates, and 3-axis load factors based on the GAU2000's mini attitude reference (AHARS) unit;
- Indicated (calibrated) airspeed, true airspeed, equivalent airspeed, and total air temperature recorded by the GAU2000 based on air data inputs from the helicopter's pitot-static system;
- Pressure and density altitudes derived from the air data recorded by the GAU2000;
- Two measures of the proximity of the helicopter state to the threshold of the "servo transparency" condition, computed using the recorded and derived GAU2000 data listed above.

As described in Reference 1, "servo transparency" is "a condition when the forces exerted from the rotor system overcome the force handling capability (output) of the flight control hydraulic actuators." This condition can result in "an uncommanded right and aft cyclic motion accompanied by down collective movement." These inputs can in turn result in uncommanded pitch and roll motions of the helicopter. Servo transparency, and the STP used to define the helicopter's proximity to flight conditions susceptible to the servo transparency phenomenon, are discussed in more detail below.

The recorded and computed data listed above support the following observations concerning the accident flight:

- N74317 lifted off from Phoenix-Mesa Gateway Airport (KIWA) at approximately 17:08:40 MST[2], and impacted terrain at 17:23:40, resulting in a total flight time of 15 minutes.
- Between 17:15 and 17:16, the helicopter circled over a housing development just south of Gold Canyon, AZ, descending from about 600 ft. above ground level (AGL) to about 400 ft. AGL during the 1-revolution turn.
- At about 17:18, the helicopter started overflying the Superstition Mountains range, with corresponding large variations in the elevation of the terrain underneath the helicopter.
- Between 17:18 and the end of the flight, the height of the helicopter above the terrain (its AGL altitude) varied considerably, as the terrain elevation rose and fell. Between 17:18 and 17:20, the AGL altitude varied between 240 ft. and 1150 ft. Between 17:20 and the end of the flight, the AGL altitude varied between 30 ft. and 770 ft. During this period, the AGL altitude dropped below 100 ft. AGL three times: at 17:20:30 (60 ft. AGL); 17:21:28 (30 ft. AGL); and 17:23:07 (30 ft. AGL). At these points, the airspeed was between 108 and 114 KIAS.[3]
- As the helicopter was clearing a ridge (by about 30 ft.) at 17:23:07, it was banked to the right, turning from a ground track of about 43° to a groundtrack of about 76°.
- At about 17:23:32, the helicopter started a relatively abrupt right roll. At the start of this roll, the STP was well below the threshold for the servo transparency condition, and of similar magnitude to its values during the previous 21 seconds. However, as the load factor

[2] All times in this memorandum are in Mountain Standard Time (MST), unless otherwise noted. MST = Universal Coordinated Time (UTC) – 7 hours.

[3] The MSL altitude of the helicopter is measured from the bottom of the skids. Terrain elevation is obtained from the *Google Earth* computer program, unless otherwise noted. The cited altitudes are rounded to the nearest 10 ft.

increased along with the roll angle to the right, the STP quickly climbed towards values consistent with the onset of the servo transparency condition.

- The STP value crossed the threshold for the servo transparency condition at about 17:23:34, and continued to increase until about 17:23:39 (about a second before the end of the recorded data).
- Between about17:23:33 and the end of the data, the angular rates recorded by the GAU2000 increased significantly above their previously recorded values during the flight, and were inconsistent with the angular rates corresponding to coordinated flight along the recorded GPS flight path.

These observations are discussed in greater detail in the sections that follow.

Altitude and terrain clearance

The GAU2000 altitude data is the basis of the altitude information presented in this memorandum. According to Appareo (the manufacturer of the GAU2000), the unit is intended to record GPS altitude above Mean Sea Level (MSL). Terrain elevations (both in the *Google Earth* computer program, and provided by the United States Geological Survey (USGS)) are also defined relative to MSL; however, at the three sub-100 ft. AGL times indicated above, the as-recorded GAU2000 altitude placed the helicopter *below* the *Google Earth* (and USGS) terrain elevations. Furthermore, while on the ramp at KIWA, the GAU2000 altitude is about 1297 ft. MSL, whereas the *Google Earth* terrain elevation at that point is 1345 ft. MSL. Hence, the recorded altitudes are clearly too low relative to the actual terrain elevation. I discussed this discrepancy with engineers at Appareo (the manufacturer of the GAU2000), and we agreed that the best estimate of the actual helicopter altitude would be obtained by correcting the GAU2000 data so that the altitude of the helicopter skids matched the *Google Earth* elevation of the ramp at KIWA. This was accomplished by adding 48 ft. to the recorded altitudes.

Figure 1 shows a plan view of the helicopter's flight path from KIWA to the crash site, overlaid on a *Google Maps* topographical map. The flight path is labeled every 30 seconds with the MST time (in black), corrected MSL altitude (in blue), and recorded indicated airspeed (in brown). The color of line depicting the flight path indicates the height above the terrain, as defined by the colormap legend in the plot. Figure 2 is similar to Figure 1, but enlarged to show detail near the end of the flight. Figures 1 and 2 indicate that the flight through the Superstition Mountains was characterized by flight through valleys, with climbs to clear ridges and subsequent descents back into valleys. The sub-100 ft. AGL points are indicated by the red-colored portions of the line in Figures 1 and 2, which coincide with ridges between valleys.

Figure 3 plots MSL altitude, terrain elevation under the helicopter, and the resulting AGL altitudes vs. time for the entire flight. The rapid changes in the AGL altitude as the helicopter flies through the rugged terrain of the Superstition Mountains is apparent, as are the three sub-100 ft. AGL points where the helicopter "shaves" the ridges.

Figure 4 plots MSL altitude and terrain elevations vs. time for the last minute of the flight. The color of the MSL altitude (GPS altitude + 48 ft.) in this plot also indicates the "STP margin," a measure of the value of the STP from the threshold of flight conditions conducive to the servo transparency phenomenon (servo transparency is possible when the margin reaches 0). The plot shows that the margin decreases to zero (the line turns red) at about 17:23:34, as the helicopter is approaching higher terrain.

The brown-shaded terrain data in Figure 4 is taken from *Google Earth*. For comparison, 1-arc second elevation data (i.e., elevation data sampled every arc-second, or about every 100 ft.) from the USGS[4] is plotted as the purple line. The datasets show some differences, but are in general agreement. The AGL altitudes plotted in Figure 3 are computed using the *Google Earth* elevations.

Figure 4 also plots additional altitude parameters computed from the GAU2000 data, including pressure altitude and density altitude. The computation of these altitudes and of the STP is described in the next section.

Atmospheric properties and the Servo Transparency Parameter

As noted above, the servo transparency phenomenon is described at length in Reference 1:

> According to Eurocopter (Aerospatial) servo transparency is a condition when the forces exerted from the rotor system overcome the force handling capability (output) of the flight control hydraulic actuators. The condition manifests itself when the aerodynamic forces of the main rotor system in flight are higher than that of the hydraulic servo control force. The main rotor system forces are transmitted (feedback) back through the flight control pushrod/bellcrank system through all three main servos of the AS350 helicopter to the pilot's controls. The feedback forces usually occur only during extreme maneuvering. The servo transparency is also known as hydraulic transparency, servo reversibility, and jack stall.
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> …
>
> According to Eurocopter, servo transparency begins when the aerodynamic forces generated by the main rotor system exceed the hydraulic forces from the control system and the difference between the forces is transmitted back to the pilot's cyclic and collective controls. On clockwise turning main rotor systems, the right servo receives the highest load when maneuvering, so when servo transparency condition occurs, it results in an uncommanded right and aft cyclic motion accompanied by down collective movement. The force transmitted through the controls tends to be progressive and the feed back forces through the controls could give an unaware pilot the impression that the controls are very hard to move or are jammed. The amplitude of the induced control feedback loads is proportional to the severity of the maneuver, but the phenomenon normally lasts less than 2 seconds when the pilot is aware of the condition and relaxes the pressure on the flight controls.
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> …
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> On December 4, 2003, Eurocopter published Service Letter No. 1648-29-03 concerning servo transparency. In the service letter, pilots were advised about the servo transparency phenomenon, what happens during the event, how it manifests itself, factors that increase the likelihood of encountering the condition, what to do in the event it is encountered, and the best way to avoid the condition. According to the Eurocopter, servo transparency occurs

[4] The USGS data was downloaded from the USGS "The National Map" interactive web site; see https://viewer.nationalmap.gov/basic/.

> smoothly and is not dangerous, if properly anticipated by a pilot during an abrupt or excessive high load maneuver, such as high positive g turn or pull-up. …
>
> The FAA issued a Special Airworthiness Information Bulletin (SAIB) on January 23, 2004, concerning servo transparency in the AS350 and EC120 series helicopters …. The SAIB referenced Eurocopter's Service Bulletin and advised helicopter pilots of these helicopters that they (the pilot) should follow (not fight) the control movement. Pilots should allow the collective pitch to decrease to reduce the overall load. The pilot should be aware that as the load is reduced, hydraulic assistance will be restored and force being applied to the controls could result in undesired opposite control movement. The SAIB advises pilots to follow the aircraft limitations in accordance with the Aircraft Flight Manual.
>
> The SAIB states that pilots should understand that servo transparency is a natural phenomenon for any flyable helicopter. Basic airmanship should prevent encountering this phenomenon by avoiding combinations of high speed, high gross weight, high-density altitude, and aggressive maneuvers, which exceed the aircraft's approved flight limitations.

Reference 1 also notes that "the AS350 helicopter was flight tested during its original certification process in 1985. During the flight tests the servo transparency condition was noted versus changes in gross weight, altitude, and airspeed." Furthermore:

> The AS350 helicopter was tested again during December 2003 for the effects of servo transparency by Eurocopter's Chief test pilot and an FAA test pilot …. According to the flight test results, servo transparency was impossible to encounter if the collective is less than 50% raised. With a speed of less than 100 knots, servo transparency was very difficult to enter. According to the flight test results, all of the entries and sustainment in the servo transparency region were accomplished with deliberate high g-forces, at high gross weights, at very high entry airspeeds, and were very difficult to sustain. All of the servo transparency conditions were exited immediately when the collective was reduced.
>
> Eurocopter provided a summary of their certification tests, formulas relevant to the calculations for servo transparency onset, flight tests with the FAA, and examples of servo transparency onsets in typical conditions similar to previous accidents.

Reference 1 provides the results of the flight tests and the Eurocopter servo transparency data in various Appendices. Of greatest relevance is a document that references Eurocopter certification document H/EV number 17530, dated 12 November 1985, and that presents a plot of the conditions under which the servo transparency condition was encountered. This plot is reproduced here as the top plot in Figure 5. The STP is plotted on the y-axis versus true airspeed on the x-axis, and is defined as

$$STP = \frac{nM}{\sigma} \qquad [1]$$

Where:

n = normal load factor (G's);
M= helicopter mass (kg);
σ = density ratio = ρ/ρ_0, where
ρ = air density at altitude, and
ρ_0 = standard atmosphere air density at sea level

Since n and σ are dimensionless ("G" is a dimensionless ratio), STP has dimensions of kg.

The document that presents the plot reproduced in Figure 5 also presents the following linear curve fit through the data:

$$STP = -(28.18)(V_T) + 7627 \quad [2]$$

Note that the STP decreases with true airspeed. It is of interest whether an "alternate STP" parameter can be found that would provide a single threshold value across all airspeeds. The bottom plot of Figure 5 plots such an alternative STP, defined as

$$STP2 = (10^{-5})(STP)\sqrt{V_T} \quad [3]$$

Note that the scatter of the STP2 values across the airspeed range is relatively level. Based on this plot, it appears that the servo transparency condition can be encountered when the value of STP2 reaches a value in the range of 0.414 to 0.494, regardless of airspeed.

To evaluate Equation [1] and determine the actual value of the STP at each point in the accident flight, the load factor n, mass M, and density ratio σ are required. n is recorded directly on the GAU2000; M is assumed to be 4446 lb. (2017 kg);[5] and σ can be computed from other parameters recorded on the GAU2000. Specifically, the recorded air temperature and true airspeed data can be used to compute the Mach number. The Mach number and recorded indicated (calibrated) airspeed can be used to find the static air pressure; and the static air pressure and air temperature can be used to compute pressure altitude, air density, density altitude, and the density ratio. The pressure and density altitudes are plotted in Figure 4.

The accident values of STP as defined by Equation [1], and the "threshold" values of STP and STP2 defined by Equations [2] and [3], are plotted as a function of time in Figure 6. The top plot in Figure 6 compares the actual STP condition of the helicopter, evaluated using Equation [1] and the values of n, M, and σ as determined above, with the threshold values of STP defined by Equation [2] corresponding to the V_T at each time point.[6] Equation [1] is represented in Figure 6 by the heavy, black "Server transparency parameter, accident" line, and Equation [2] by the blue "ST threshold per Equation [2]" line. The "Servo Transparency margin, kg" parameter used to color the altitude line in Figure 4 is given by

$$STP_{margin} = STP_{Equation[2]} - STP_{Equation[1]} \quad [4]$$

Note that the actual STP of the helicopter crosses the ST threshold at about 17:23:34 (6 seconds before the end of the data).

The bottom plot in Figure 6 compares the in-flight values of STP2 defined by Equation [3] (with STP in this equation defined by Equation [1]) with the range of STP2 values indicating the servo transparency condition, per the bottom plot in Figure 5. The STP2 enters this range at about 17:23:34, coincident with the crossing of the ST threshold in the top plot.

[5] Per the NTSB Operations Group Chairman.

[6] V_T is recorded directly on the GAU2000.

The GAU2000 recorded load factors are plotted in Figure 7. Note that both STP and STP2 are very sensitive to the normal load factor n, and follow its shape. It is the increase in n starting about 17:23:32, as the helicopter rolls into a right turn, that drives STP and STP2 past their thresholds.

Euler angles and angular rates

Since the servo transparency condition can result in uncommanded control inputs and changes in the helicopter's attitude, the time-history of the Euler angles and angular rates are of interest, as they may provide evidence of an unusual or unexpected maneuver that could be the result of servo transparency. Unfortunately, towards the end of the flight, but well before the STP reaches its threshold value, all three Euler angles recorded on the GAU2000 exhibit unrealistic behavior; that is, they describe helicopter attitudes that appear incompatible with helicopter flight mechanics and the flight path recorded by the GPS data. Since the GPS data is consistent with the wreckage location, it is the Euler angle data, and not the GPS track, which appears most suspect. Furthermore, Appareo was asked about the suspect Euler angle data, and replied that the observed incongruities were not surprising, given the relatively dynamic maneuvering of the helicopter at the times in question. Consequently, it appears that the algorithms used by the GAU2000 to compute Euler angles from sensed location, acceleration, and angular rates can break down during dynamic maneuvers, and alternative methods must be used to estimate the Euler angles during these periods.

One method used to estimate the actual Euler angles during the final minute of the flight was to compute the Euler angles that an airplane (not a helicopter) would require to fly through the recorded GPS points in a coordinated manner (i.e., with zero lateral load factor (n_y)). This "airplane" solution provides a reasonable estimate of roll angle (since both airplanes and helicopters turn by banking the lift vector produced by the wings or rotor) and heading (since both airplane and helicopter flight is generally coordinated at high speeds). However, the "airplane" estimate of pitch does not correlate with a helicopter's pitch angle, since the helicopter must pitch the rotor disk down to produce forward thrust, but an airplane's pitch angle is determined by the lift required from its wings.

Nonetheless, the angular *rates* about each of the aircraft axes should be generally similar for both the airplane and the helicopter, since the angular velocity vector defining a turn will have components along the aircraft lateral and vertical body axes that are primarily determined by the roll angle. The angular velocity component along the lateral (y, or side to side) axis is the pitch rate, and the angular velocity component along the vertical (z, or up and down) axis is the yaw rate. The angular velocity component along the longitudinal (x, or forward and aft) axis is the roll rate.[7] Consequently, comparing the "airplane" and GAU2000 angular rates can help identify unusual maneuvers performed by the helicopter.

The pitch angle of the helicopter was also estimated using the groundspeed and longitudinal load factor (n_x) recorded on the GAU2000, and the following equation:

$$\sin\theta = n_x - \frac{1}{g}(\dot{u} + wQ + vR) \qquad [5]$$

[7] When the airplane velocity is not parallel to the longitudinal axis (i.e., when the longitudinal axis has a non-zero angle of attack), then a steady, level turn will contribute an angular velocity component along the longitudinal axis as well; i.e., a steady turn will induce a roll rate, even though the roll angle remains constant.

Where:

θ is the pitch angle,
g is the acceleration due to gravity,
$\{u, v, w\}$ are the linear velocity components long the aircraft $\{x, y, z\}$ axes, respectively; and
$\{P, Q, R\}$ are the angular velocity components long the aircraft $\{x, y, z\}$ axes, respectively.

Assuming that

$$wQ + vR \cong 0 \quad [6]$$

And

$$\dot{u} \cong \frac{dV_G}{dt} \quad [7]$$

Then

$$\theta \cong \sin^{-1}\left[n_x - \left(\frac{1}{g}\right)\left(\frac{dV_G}{dt}\right)\right] \quad [8]$$

Where V_G is the groundspeed.[8]

Finally, the pitch angle was also estimated by "hand flying" a model of an AS 350 helicopter through target points placed coincident with the recorded GPS positions in the *Microsoft Flight Simulator X* computer program (*FSX*; see Figure 8). While not derived from a rigorously correct (or skillfully flown) model of the AS350, the pitch angles required by the helicopter in the simulation program should be more representative of the actual pitch angles than those computed from the "airplane" model.

The recorded Euler angles are plotted in Figure 9. The top plot in Figure 9 presents the computed flight path angle (blue line), and compares the recorded pitch angle (black line) with the pitch angle estimated from Equation [8] (green line) and the pitch angles obtained in two attempts to fly through the target points in *FSX* (magenta and brown lines). The recorded and Equation [8]-based pitch angles are comparable until about 17:23:07, when the Equation [8] estimate jumps about 5°. This is the result of the 0.1 G jump in n_x at the same time (see Figure 7); unfortunately, the 0.1 G resolution of the load factor data is too large to be very useful in this calculation. Furthermore, the Equation [8] estimate becomes unreasonably high starting at about 17:23:34, when the computed groundspeed starts to reduce abruptly (see Figure 10). After 17:23:34, the high angular rates of the helicopter (see Figure 11) likely invalidate the assumptions of Equations [6] and [7], and so Equation [8] no longer holds.

The *FSX* – based pitch angles are of the same magnitude as the recorded pitch angle between 17:23:10 and 17:23:23, but then the recorded pitch angle starts to deviate downward, reaching -28° at 17:23:32, before climbing back to +29° at 17:23:39 and dropping to +4° at the end of the data. The *FSX* – based pitch angles oscillate (due to the difficulty of keeping a steady hand on the joystick), but remain relatively "level" between about -8° and +2° until 17:23:34. The simulation results are truncated at the time the STP threshold is exceeded.

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[8] In this case, the computed groundspeed shown in Figure 10 is used in Equation [8] instead of the groundspeed recorded on the GAU2000, since the latter is not consistent with the recorded GPS coordinates near the end of the flight; see further discussion below.

The middle plot of Figure 9 compares the recorded roll angle (black line) with the "airplane" computed roll angle (blue line) and the roll angles from the two *FSX* runs. The recorded and "airplane" angles are in good agreement, except between 17:23:06 and 17:23:10, when the recorded roll angle reaches 37° but the "airplane" roll angle only reaches 23°, and after about 17:23:12, when the recorded roll angle is consistently and notably higher than the "airplane" roll angle and the two *FSX* – based roll angles. Both the "airplane" and *FSX* – based angles increase abruptly starting between 17:23:29 and 17:23:31 in order to execute the right turn towards the south evident in the GPS track data.

The bottom plot in Figure 9 compares the recorded track angle (black line) with the ground track angle computed from the recorded GPS points (blue line), and the recorded heading angle (red line) with the "airplane" computed heading angle (green line). The recorded and computed track angles match, indicating that the recorded track is consistent with the recorded GPS positions. (Note, however, that the GAU2000 recorded groundspeed plotted in Figure 10 differs from the groundspeed computed directly from the recorded GPS coordinates, and that the shape of the computed groundspeed matches the recorded airspeeds better than the recorded groundspeed; this suggests that the recorded groundspeed may be filtered, and that the filtering is producing significant error in the groundspeed near the end of the flight.) In Figure 9, the "airplane" heading is offset a few degrees from the computed and recorded track angles because of the wind assumed in the calculation,[9] but otherwise matches the track angles very well, until the final right roll that starts at about 17:23:32.[10]

Note that the GAU2000 recorded heading angle differs substantially from the track angles and computed heading angle after about 17:23:14. This deviation appears to be the earliest and clearest evidence of the GAU200 Euler angle solution becoming invalid near the end of the flight.

The pitch, roll, and yaw rates recorded by the GAU2000 are plotted in Figure 11, and compared to the "airplane" angular rates, and to the rates of change of the recorded ground track and computed heading. The recorded and "airplane" roll rates match relatively well, but the recorded and "airplane" pitch and yaw rates differ significantly. The high angular rates recorded by the GAU2000 after 17:23:34 are notably larger and more erratic than the "airplane" rates; this suggests that the helicopter motion may not be coordinated in this region (and the excursions in the recorded longitudinal and lateral load factors (n_x and n_y) after 17:23:37 are consistent with this observation; see Figure 7).

The jumps in the recorded pitch and roll rates at 17:23:32 are of interest, and are consistent with a cyclic control input both aft and to the right, which as indicated in Reference 1 are characteristics of the servo transparency condition. However, as shown in Figure 6, at 17:23:32 the STP is below

[9] The assumed winds were from 265° true at 11 kt., based on a National Oceanographic and Atmospheric Administration (NOAA) High-Resolution Rapid Refresh (HRRR) upper air computer model for the accident site at 17:00 MST, provided by an NTSB meteorologist. These winds are consistent with the GAU2000 recorded groundspeed and true airspeed near the end of the flight.

[10] The deviation of the "airplane" computed heading from the track angle after 17:23:32 is not surprising, since at high roll angles an airplane's angle of attack makes its heading angle "lead" its track angle (in the extreme case of a "knife edge" turn, the track and heading angles differ by the angle of attack). Consequently, for this case the "airplane" heading becomes increasingly irrelevant after 17:23:32.

the servo transparency threshold, and so the abrupt change in the pitch and roll rate at this time would *not* appear to be the result of servo transparency. Consequently, in the absence of a different cause of uncommanded pitch and roll inputs, the maneuver initiated at 17:23:32 would appear to be the result of pilot inputs, and a deliberate abrupt roll to the right accompanied by aft cyclic. The subsequent right turn and sudden loss of airspeed are consistent with such inputs.

Position of N74317 at 17:23:32 relative to terrain and destination

If the maneuver initiated at 17:23:32 was deliberate, possible motivations for such a maneuver are of interest, even if the actual motivation can never be known. It suffices to find a *plausible* motivation, given other information about the flight.

The destination of the flight was the operator's base at Globe, AZ. The location of Globe relative to KIWA, the route of flight, and the accident flight is shown in Figure 12. Figure 13 is an image from *Google Earth* depicting the helicopter's flight path, with annotations every 2 seconds displaying information in the following format:

> Time MST / Altitude, ft. MSL / Airspeed, KCAS / Rate of climb, ft/min / n, G's

A model of the AS350 helicopter is also shown (not to scale) at each annotation, depicting the aircraft's attitude. The image shows the flightpath turning to the right starting at 17:23:32. Before the turn, the helicopter is headed toward the left side of a local summit. The image shows a ridge, or gap, between this summit and another to the west of it; a sudden right turn may have been motivated by a desire to overfly this ridge and pass through the gap between the summits.

Figure 14 is a plan-view of this area, similar to Figures 1 and 2, and shows the local summits and the ridge between them more clearly. The direction towards Globe, the helicopter's destination, is also shown (18 nm away on a 97° bearing). A right turn through the gap may have appeared to the pilot like a more "direct" route to Globe than passing to the left of the eastern summit; and "shaving" a ridge by a few tens of feet would be consistent with maneuvers the pilot had already performed three times earlier in the flight. Consequently, a possible motivation for the turn, given the nature of the flight in general, was a desire by the pilot to pass through the gap "shaving" the ridge, thereby putting the helicopter on a more direct track towards Globe.

In their comments on a draft version of this Memorandum (Reference 4), the BEA offered an alternative motivation for the right turn starting at 17:23:32:

> [Airbus Helicopters] can propose another scenario which is more in line with its experience during accident investigation where servo-transparency phenomenon has been discussed.
>
> BEA proposes to add this scenario "The pilot was surprised by the proximity of the terrain at high speed of the aircraft and performed a sudden right turn to escape and pass through the gap between the summits (avoidance maneuver)."

Assuming the maneuver initiated at 17:23:32 was deliberate, a possible scenario for the subsequent crash is as follows: as the load factor increased in the turn, the STP exceeded its threshold, resulting in a servo transparency condition and uncommanded pitch and roll inputs. Since the helicopter was already headed at high speed towards rising terrain, the pilot did not have sufficient time to recover from the uncommanded inputs before the helicopter impacted the terrain.

Maneuvering limitations and discussion of servo transparency in the RFM

Reference 1 notes the Eurocopter Service Letter No. 1648-29-03 and FAA SAIB addressing the servo transparency phenomenon on the AS350 helicopter. However, pilots are most likely to have access to and be familiar with the information about servo transparency published in the AS350 Rotorcraft Flight Manual (RFM) (Reference 3). Servo transparency is discussed in section 2.3.6, *Maneuvering Limitations*, of the RFM:

> 2.3.6 MANEUVERING LIMITATIONS
>
> - Continued operation in servo transparency (where force feedback are felt in the controls) is prohibited.
>
>   Maximum load factor is a combination of TAS, Hσ, gross weight. Avoid such combination at high values associated with high collective pitch.
>
>   The transparency may be reached during maneuvers, steep turns, hard pull-up or when maneuvering near VNE. Self-correcting, the phenomenon will induce an un-commanded right cyclic force and an associated down collective reaction. However, even if the transparency feedback forces are fully controllable, immediate action is required to relieve the feed back forces: decrease maneuver's severity, follow aircraft's natural reaction, let the collective pitch naturally go down (avoid low pitch) and counteract smoothly the right cyclic motion.
>
>   Transparency will disappear as soon as excessive loads are relieved.
> - In maximum power configuration, decrease collective pitch slightly before initiating a turn, as in this maneuver power requirement is increased.
> - In hover, avoid rotation faster than 6 sec. for one full rotation.

While this information reflects that presented in the Eurocopter Service Letter, the FAA SAIB, and Reference 1, it is generally qualitative rather than quantitative. For example, while the RFM points out that, qualitatively, the “maximum load factor is a combination of TAS, Hσ, gross weight” and advises pilots to “avoid such combination at high values associated with high collective pitch,” it does not define “high collective pitch.” The “maximum load factor” that results from the “combination of TAS, Hσ, [and] gross weight” is quantified by Equation [2] (taken from Reference 1), but this equation is not published in the RFM, and so pilots cannot determine the maximum allowable load factor at any specific condition using the RFM alone. Furthermore, the RFM notes that “transparency can be reached … when maneuvering near VNE,” but “near VNE” is not defined. Figure 10 plots the power-on and power-off VNE speeds (which decrease as a function of altitude); at the accident condition, the power-on VNE was 140 KIAS, and at 17:23:32, the recorded airspeed was about 122 KIAS, or 18 knots below VNE. It is hard to tell whether this should be considered “close to VNE.” In addition, the RFM does not define a “steep turn.” In this accident, the STP threshold was crossed when the roll angle was increasing through 44°.

The RFM notes that servo transparency is “self-correcting” and that it is possible that “the transparency feedback forces are fully controllable.” However, if servo transparency is encountered close to terrain (as may be the case in this accident), then even a minor upset may leave insufficient time to recover before a collision with the terrain occurs. Hence, pilots should operate with greater margins from the servo transparency threshold when flying close to terrain. Publishing a quantitative threshold or boundary in the RFM (such as Equation [2]) could assist pilots in planning their margins accordingly.

Of note, however, the BEA's comments in Reference 4 convey additional information from Airbus Helicopters (AH), describing the challenges of including more specificity in the RFM, and highlighting pilot training material relevant to the servo transparency phenomenon. Regarding the RFM, Reference 4 states

> First, AH recalls that the equation to determine the servo-transparency limit phenomenon is based on some flight tests and is an average limit.
>
> AH recalls as well that the introduction of an equation in the FLM is not the policy and that the aircraft was not equipped with a g-load indicator. So, the pilot won't know to use this information.
>
> NTSB spoke about value from the speed and the bank angle during g-turn maneuver. AH recalls that load factor can also be encountered without bank angle during a pull up maneuver. This led to complex the possibility to quantify the phenomenon (even more if we consider a mix between a g-turn and a pull-up maneuver).
>
> AH experience during accident investigations where servo-transparency phenomenon has been discussed led to conclude:
>
> - All these accidents occurred pending a flight not consistent with a good airmanship: very close from the ground,
> - In this kind of flight, even with a g-load indicator, the accident would probably not have been avoided.

Regarding pilot training concerning the servo transparency phenomenon, Reference 4 notes that:

> Operational manual (as done by military for tactical flight) or Training is not discussed in the memo (only RFM).
>
> For your information, in our Training center, pilots are well trained to this phenomenon:
>
> - In the Ground Qualification type AS 350: The servo-transparency is part of the § limitation (for safety aspect) and of the § hydraulic (for the description of the phenomenon)
> - In the Flight Qualification type AS 350: The servo-transparency is demonstrated in flight. Of course we do not know exactly which Training program is followed by others centers, but servo transparency is a TASE (Training Areas of Specific Emphasis) part of the OEB (Operational Evaluation Board) AS350, so the other training organizations in Europe have the information for defining adequately their training program (see below the extract of the OEB AS350).

Extract of the OEB AS350:

8.9.2 TASE / Demonstration methodology for Flight Instructors and Type Rating Instructors:

Servo-transparency (called also servo-reversibility):

Except for EC 130 B4 and AS 350 B3 Arriel 2B1 & AS 350 B3e when fitted with dual Hydraulic system.

The servo-transparency training could be performed in the following way:

- Complete procedure should be performed above 1000 ft (AGL),
- Achieve airspeed between 130 and VNE (with a rate of descend),
- Perform a 30° left turn,
- Slowly increase the load factor by a backwards cyclic action,
- When the servo-transparency is achieved, the tendency of the aircraft is to pitch up and turn to the right,
- As soon as the load decreases, servo-transparency disappears

Pay attention to the following:

- Due to control loads linked to servo-transparency, the collective pitch tendency is to decrease. The collective pitch decrease and the pitch up may lead to rpm increase.
- The procedure should not be done too aggressively
- The exercise is easier when high All Up Weight is important and/or high density altitude.

As these comments point out, training concerning the servo transparency phenomenon already exists, and providing quantitative information (such as Equation [2]) in the RFM in a manner that is meaningful to pilots can be challenging. Nonetheless, “accident investigations where servo-transparency phenomenon has been discussed” continue to occur, despite the available training. Furthermore, aircraft flight manuals manage to present complex quantitative information without the use of equations (through look-up charts or tables, for example).

Reference 4 points out that N74317 was not equipped with a g-meter. Perhaps an addition to the helicopter that would make the existing training and the description of servo transparency in the RFM more effective would be a specialized instrument that incorporates a g-meter and other required sensors to display the helicopter’s proximity to the STP threshold in real-time. While this would be yet another gage in the cockpit, pilots would only need to refer to it in relevant conditions (i.e., while maneuvering at relatively high speeds).

Summary

The data recorded on the GAU2000 device, and derived from information recorded on the device, indicates that after entering the Superstition Mountains, the helicopter flew at relatively low-level, winding through valleys and "shaving" ridges, and coming within 100 ft. of the terrain on three separate occasions prior to the accident. Just prior to the accident, at 17:23:32, the GAU2000 recorded an abrupt increase in the pitch rate and the roll rate to the right, consistent with right and aft cyclic inputs. At the time of these inputs, the STP was below the threshold that Reference 1 indicates is conducive to the servo transparency phenomenon, and so these initial inputs do not appear to be the result of servo transparency.

In the absence of any other explanation for an uncommanded control input, the sudden right roll and pitch inputs starting at 17:23:32 were most likely commanded by the pilot. However, during the resulting right roll and turn the load factor n increased, and at 17:23:34, when n reached 1.6 G's at an estimated bank angle of about 44°, the STP value crossed the critical threshold and kept increasing, making servo transparency likely.

Beyond 17:23:34, there is not much that can be said with certainty based on the recorded GAU2000 data. However, a scenario that is consistent with the remaining data, and that provides a plausible explanation for the subsequent crash, is as follows: At around 17:23:34 or soon after, the helicopter encountered the servo transparency condition, which introduced additional and uncommanded right and aft cyclic inputs, taking the helicopter off the pilot's intended flight path. The large and erratic angular rates and load factors recorded between 17:23:34 and the end of the data are not consistent with coordinated flight, and may reflect the pilot's attempt to regain control of the helicopter. However, because of the helicopter's high speed and proximity to terrain, control was not regained prior to impact with the terrain.

The RFM provides a qualitative discussion of the servo transparency phenomenon and its causes, but could benefit from quantitative information (such as Equation [2], or equivalent charts or tables) that would help pilots to design appropriate margins into their operations when flight near terrain is required. In addition, a specialized cockpit instrument that incorporates a g-meter and other required sensors to display the helicopter's proximity to the STP threshold could help make existing training and information about the servo transparency phenomenon more effective.

If you have any questions about the data shown in the plots, the calculations, or the discussion of these items, please let me know.

Regards,

John O'Callaghan

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015

Plan view of entire flight

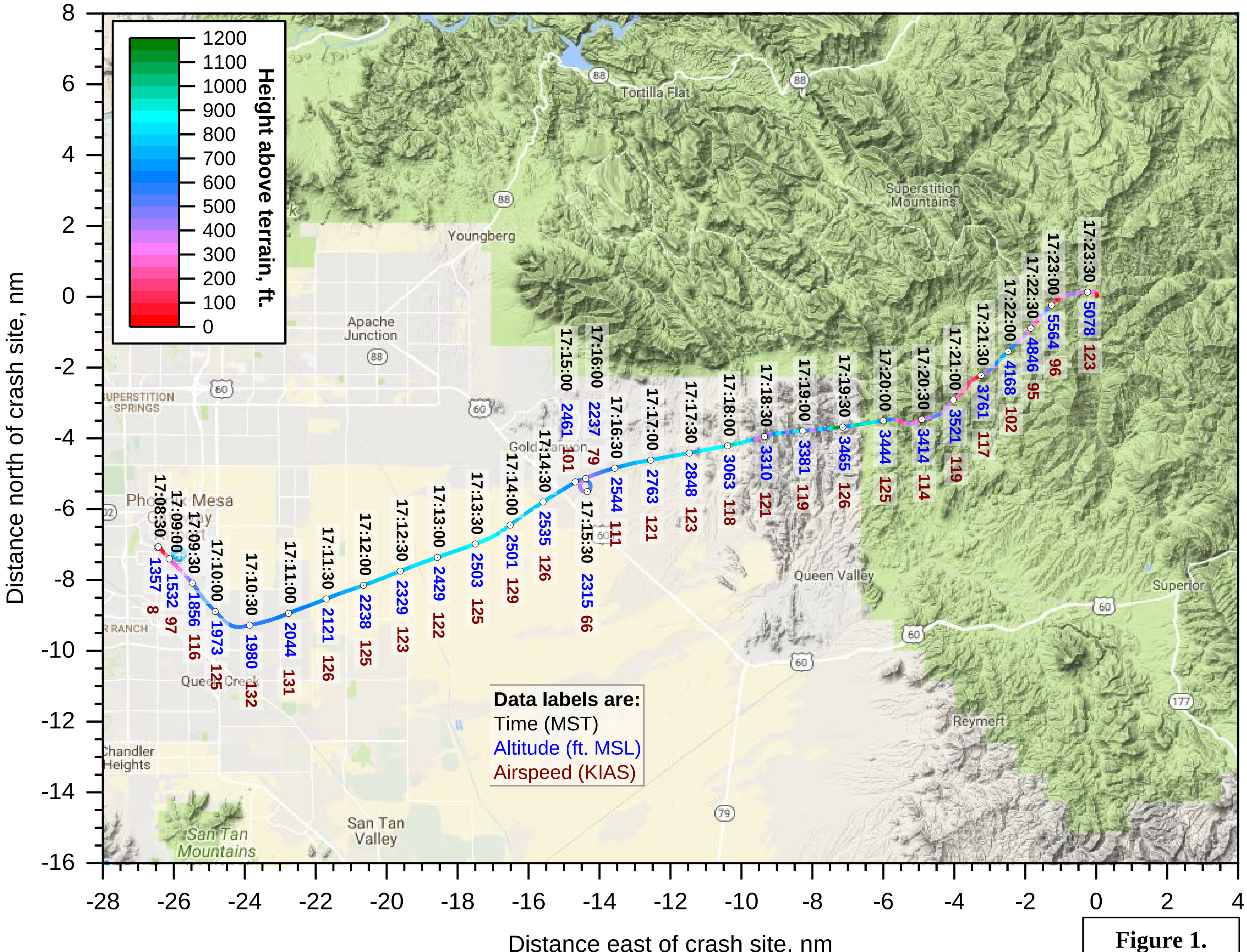


Figure 1.

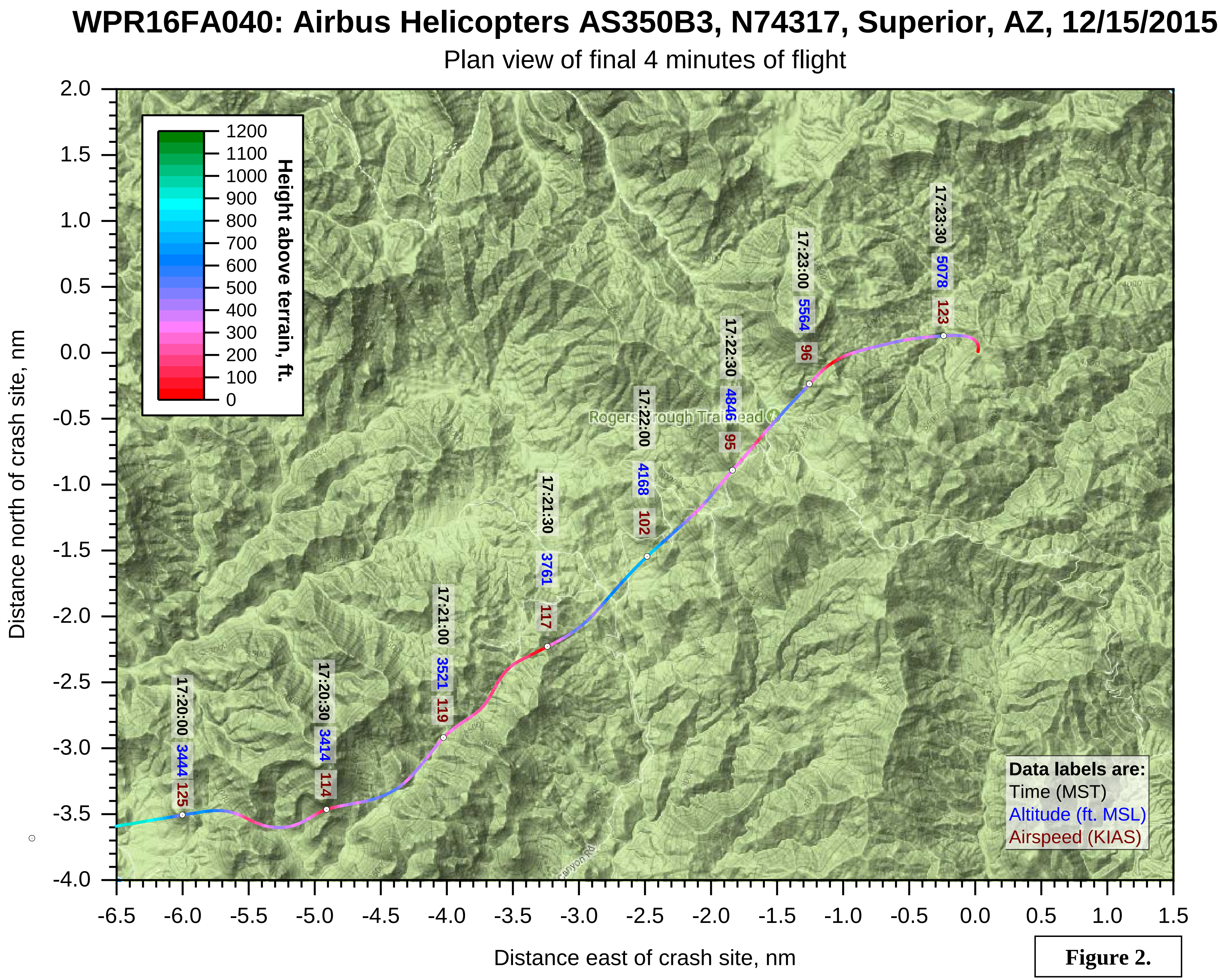

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Plan view of final 4 minutes of flight
Height above terrain, ft.
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Distance north of crash site, nm
Distance east of crash site, nm
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-6.5
-6.0
-5.5
-5.0
-4.5
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
17:20:00 3444 125
17:20:30 3414 114
17:21:00 3521 119
17:21:30 3761 117
17:22:00 4168 102
17:22:30 4846 95
17:23:00 5564 96
17:23:30 5078 123
Data labels are:
Time (MST)
Altitude (ft. MSL)
Airspeed (KIAS)

Figure 2.

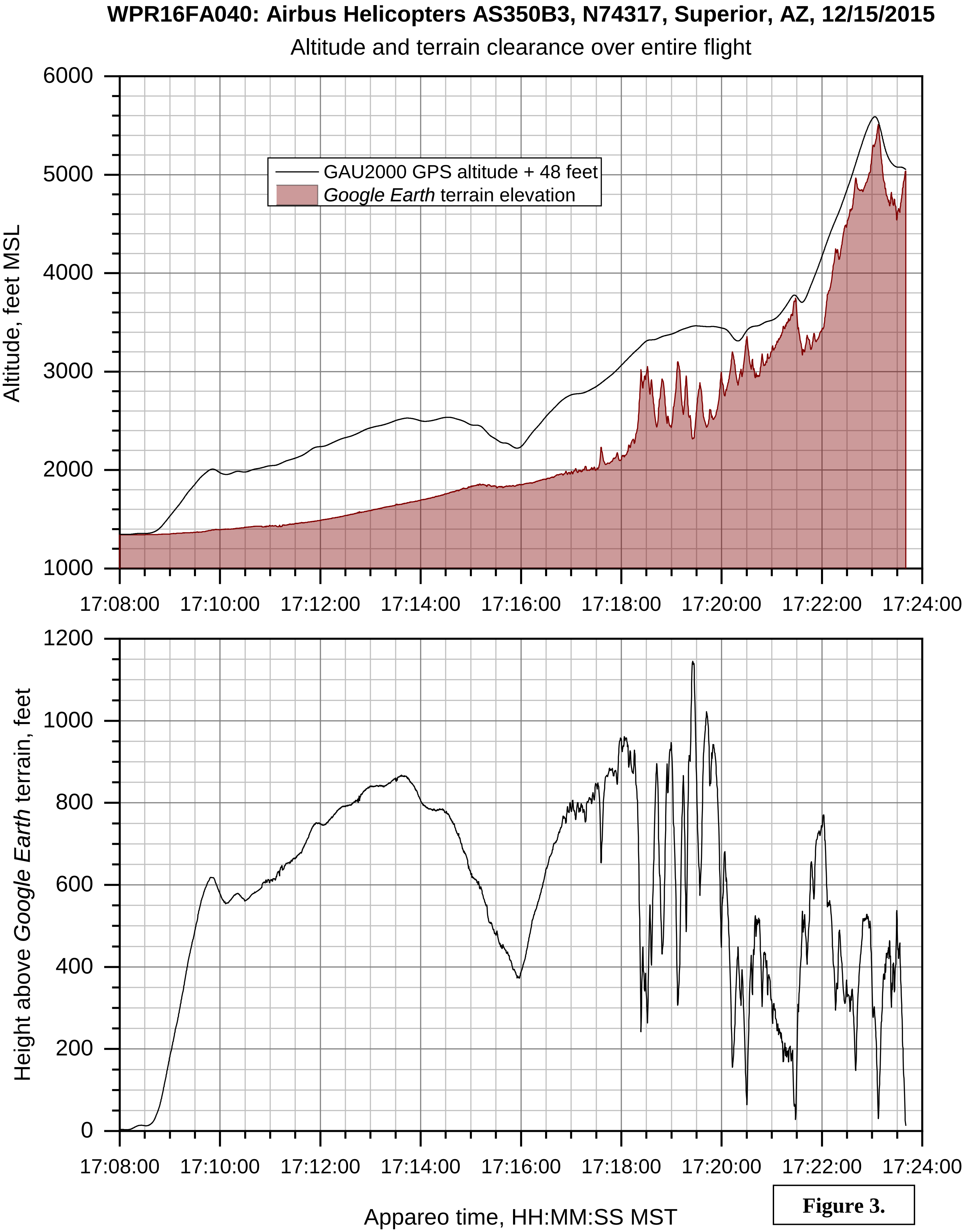

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Altitude and terrain clearance over entire flight
GAU2000 GPS altitude + 48 feet
Google Earth terrain elevation
Altitude, feet MSL
6000
5000
4000
3000
2000
1000
17:08:00
17:10:00
17:12:00
17:14:00
17:16:00
17:18:00
17:20:00
17:22:00
17:24:00
Height above Google Earth terrain, feet
1200
1000
800
600
400
200
0
Appareo time, HH:MM:SS MST

Figure 3.

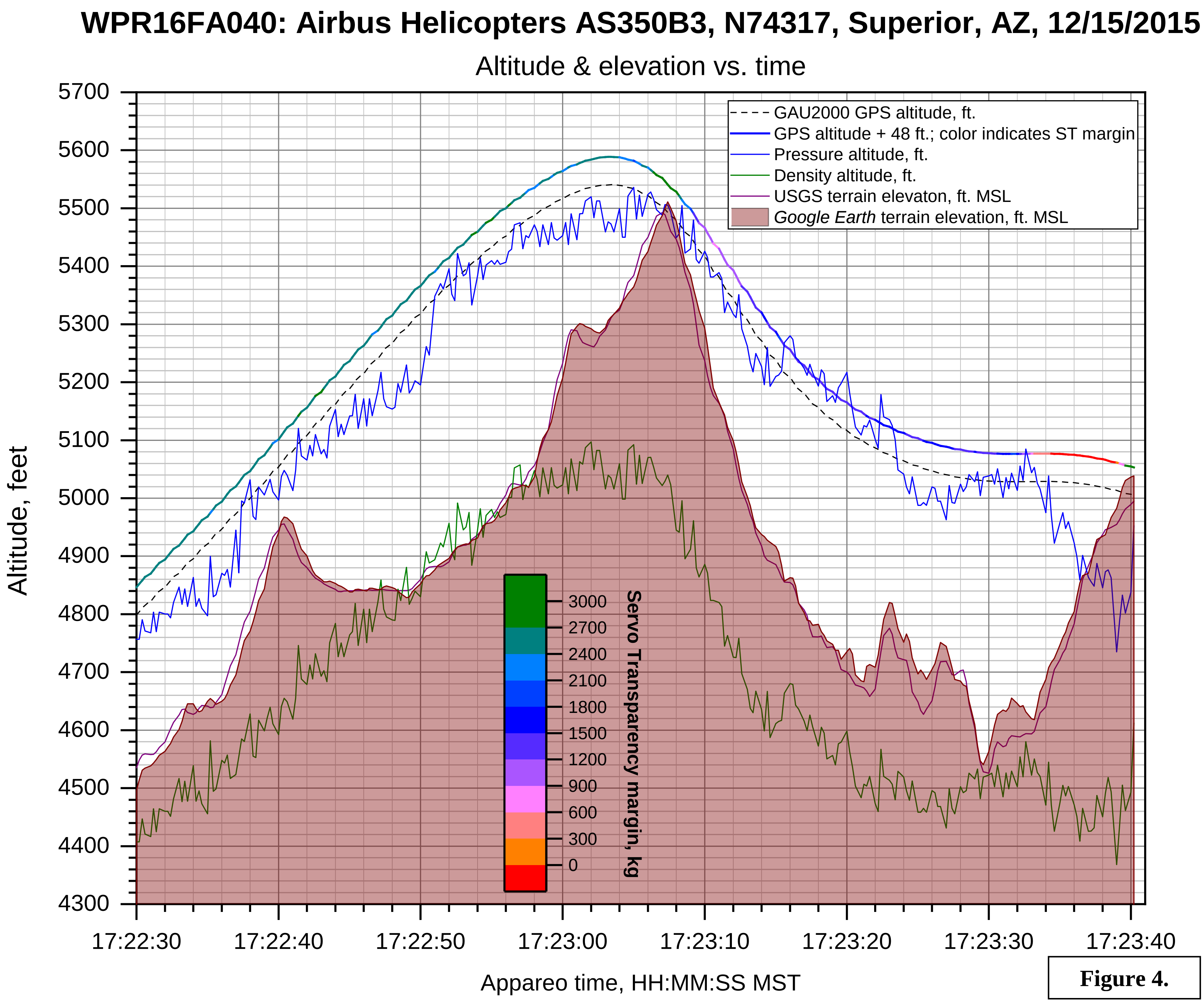
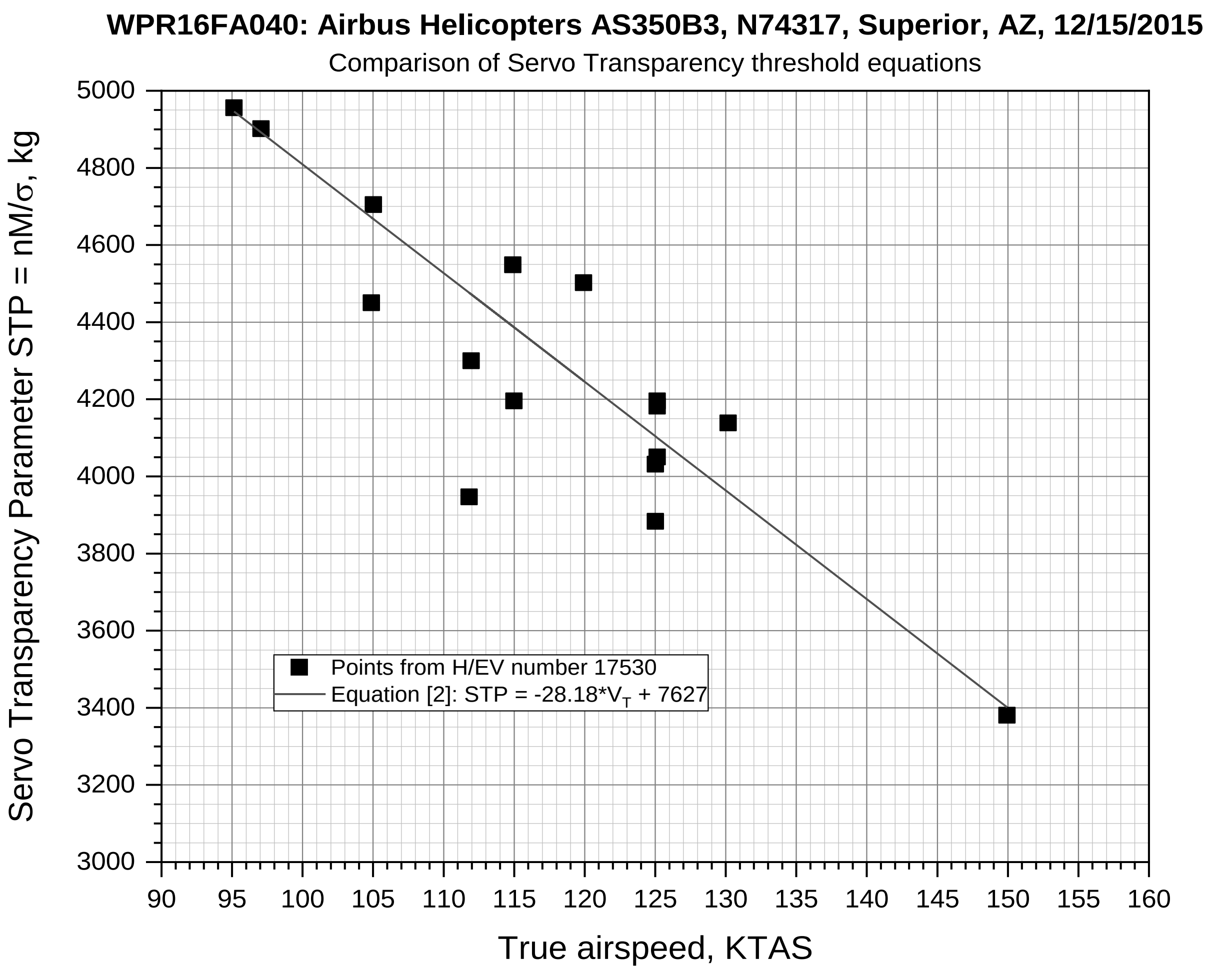

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Altitude & elevation vs. time
Altitude, feet
5700
5600
5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
4500
4400
4300
17:22:30
17:22:40
17:22:50
17:23:00
17:23:10
17:23:20
17:23:30
17:23:40
Appareo time, HH:MM:SS MST
GAU2000 GPS altitude, ft.
GPS altitude + 48 ft.; color indicates ST margin
Pressure altitude, ft.
Density altitude, ft.
USGS terrain elevaton, ft. MSL
Google Earth terrain elevation, ft. MSL
Servo Transparency margin, kg
3000
2700
2400
2100
1800
1500
1200
900
600
300
0

Figure 4.


WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Comparison of Servo Transparency threshold equations
Servo Transparency Parameter STP = nM/σ, kg
True airspeed, KTAS
Points from H/EV number 17530
Equation [2]: STP = -28.18*VT + 7627

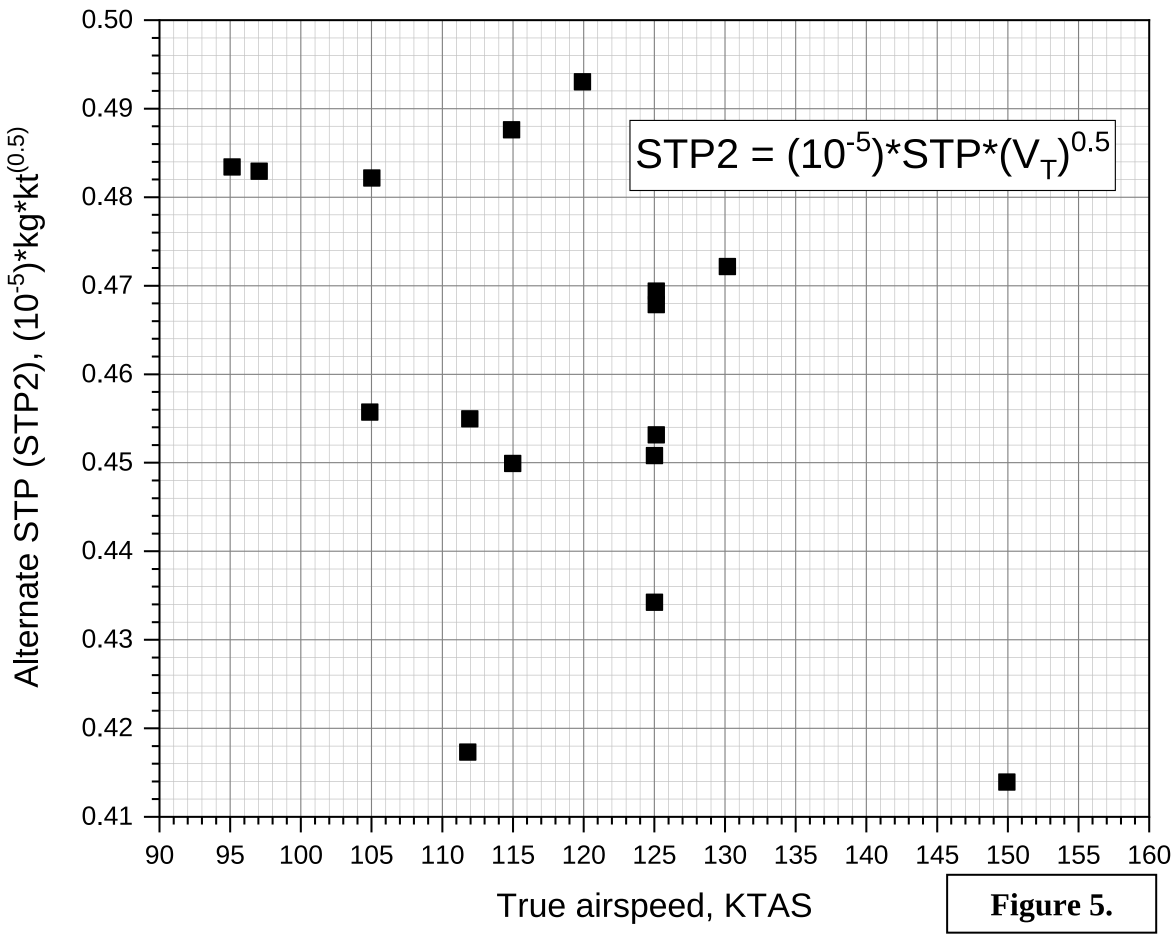

Alternate STP (STP2), (10-5)*kg*kt(0.5)
STP2 = (10-5)*STP*(VT)0.5
True airspeed, KTAS

Figure 5.

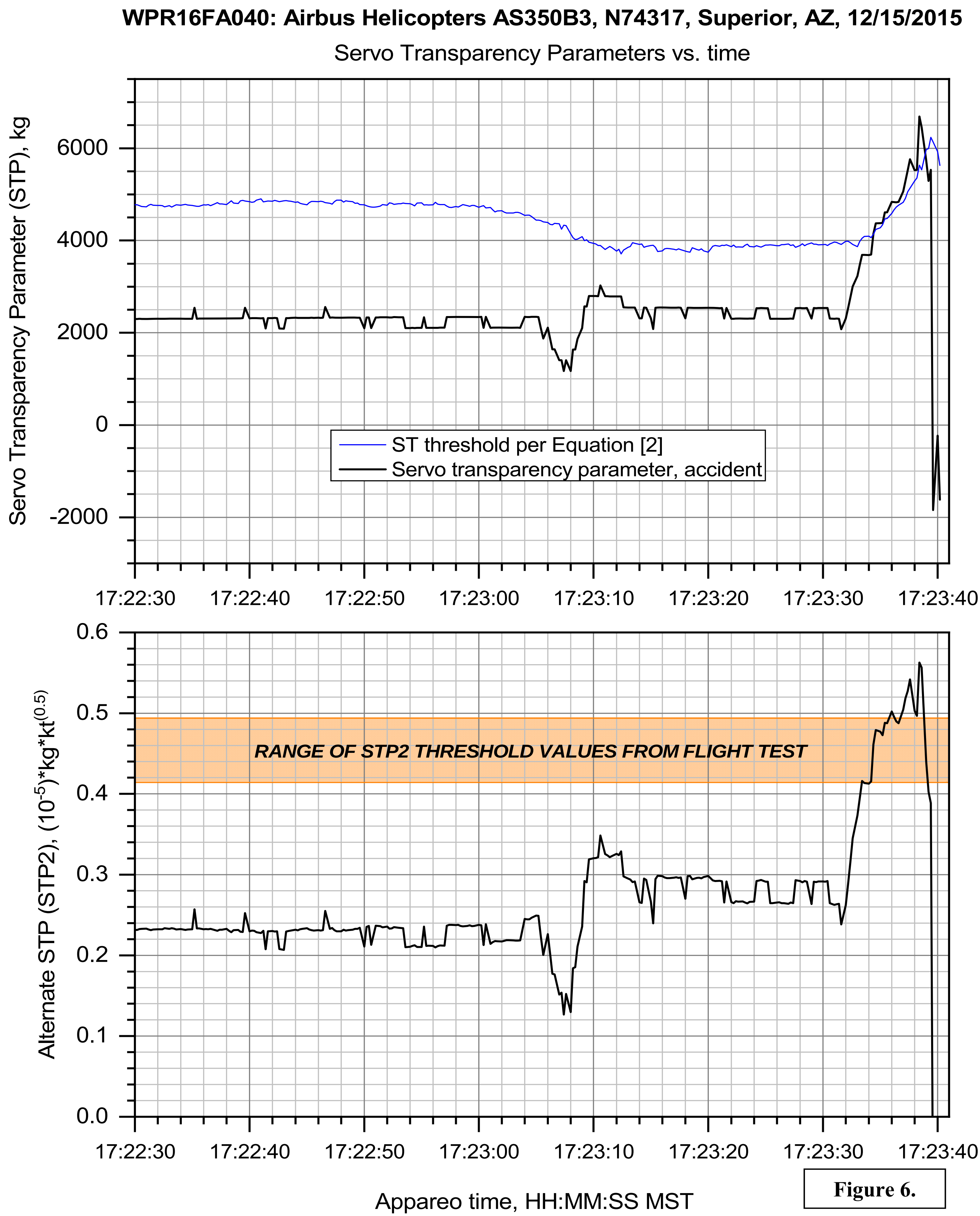

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Servo Transparency Parameters vs. time
Servo Transparency Parameter (STP), kg
6000
4000
2000
0
-2000
ST threshold per Equation [2]
Servo transparency parameter, accident
17:22:30
17:22:40
17:22:50
17:23:00
17:23:10
17:23:20
17:23:30
17:23:40
Alternate STP (STP2), (10^-5)*kg*kt^(0.5)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
RANGE OF STP2 THRESHOLD VALUES FROM FLIGHT TEST
Appareo time, HH:MM:SS MST

Figure 6.

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015

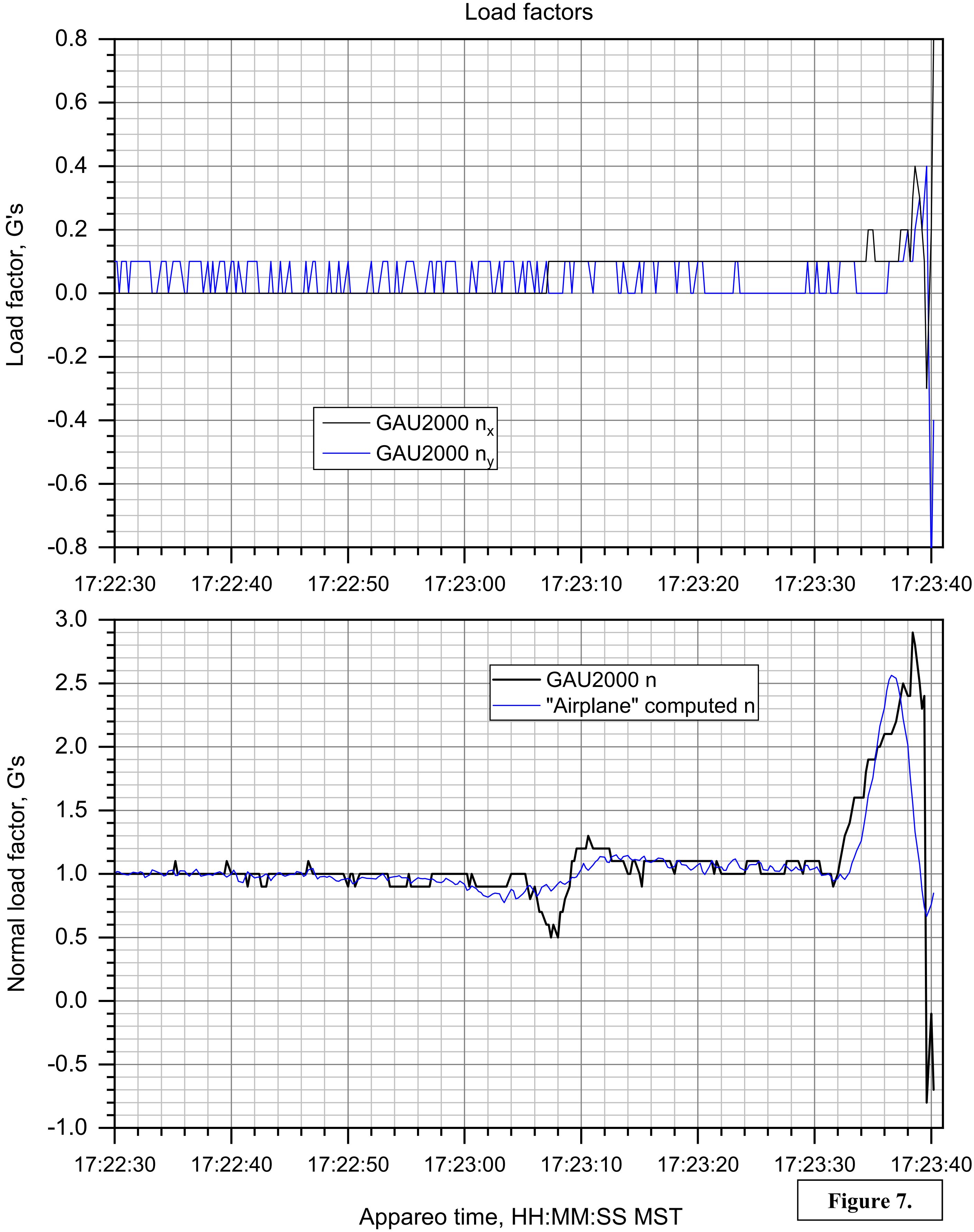


Figure 7.

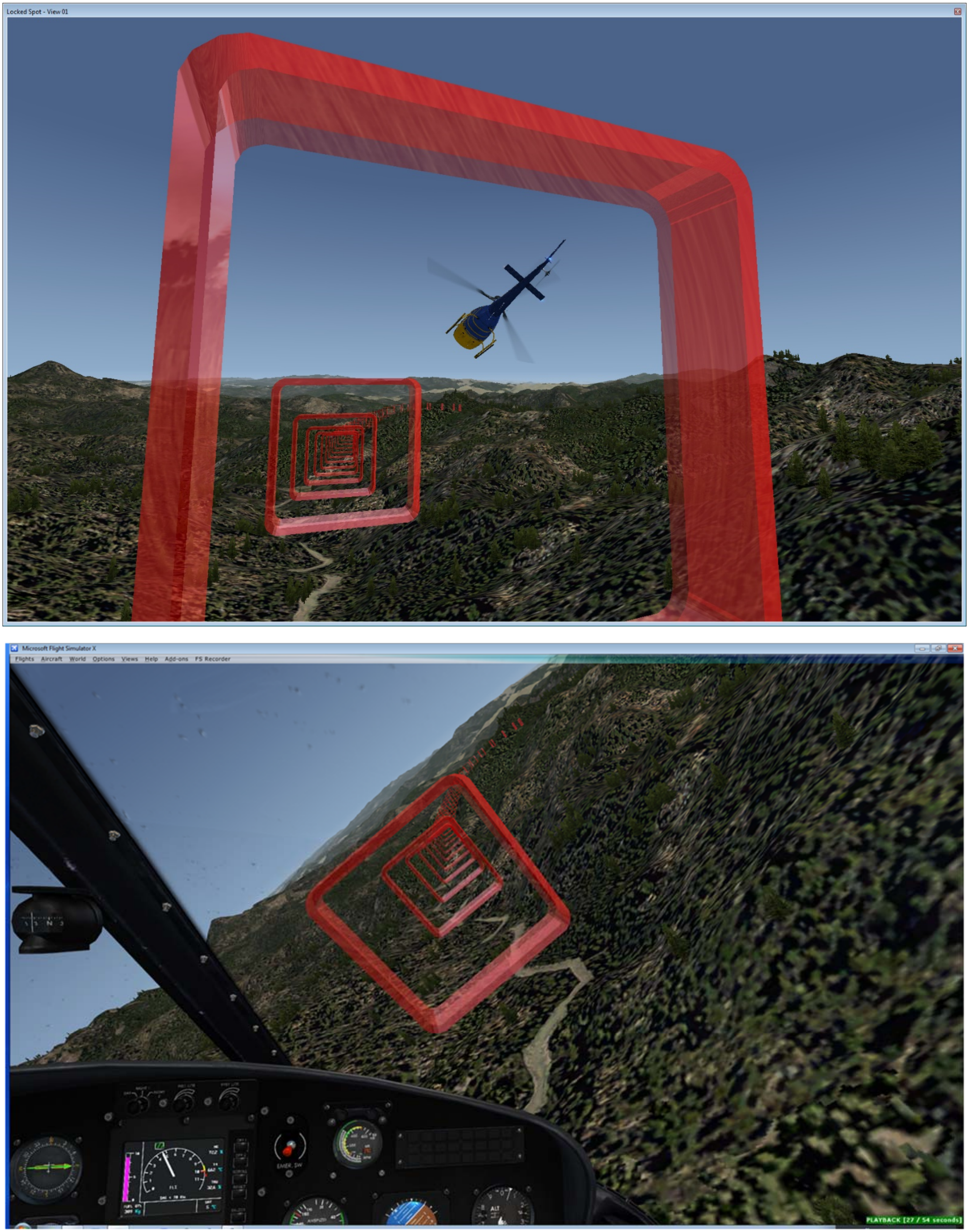


Figure 8. Screenshots of manual flight through GPS "targets" in *FSX*. Top image: external view. Bottom image: cockpit view.

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015

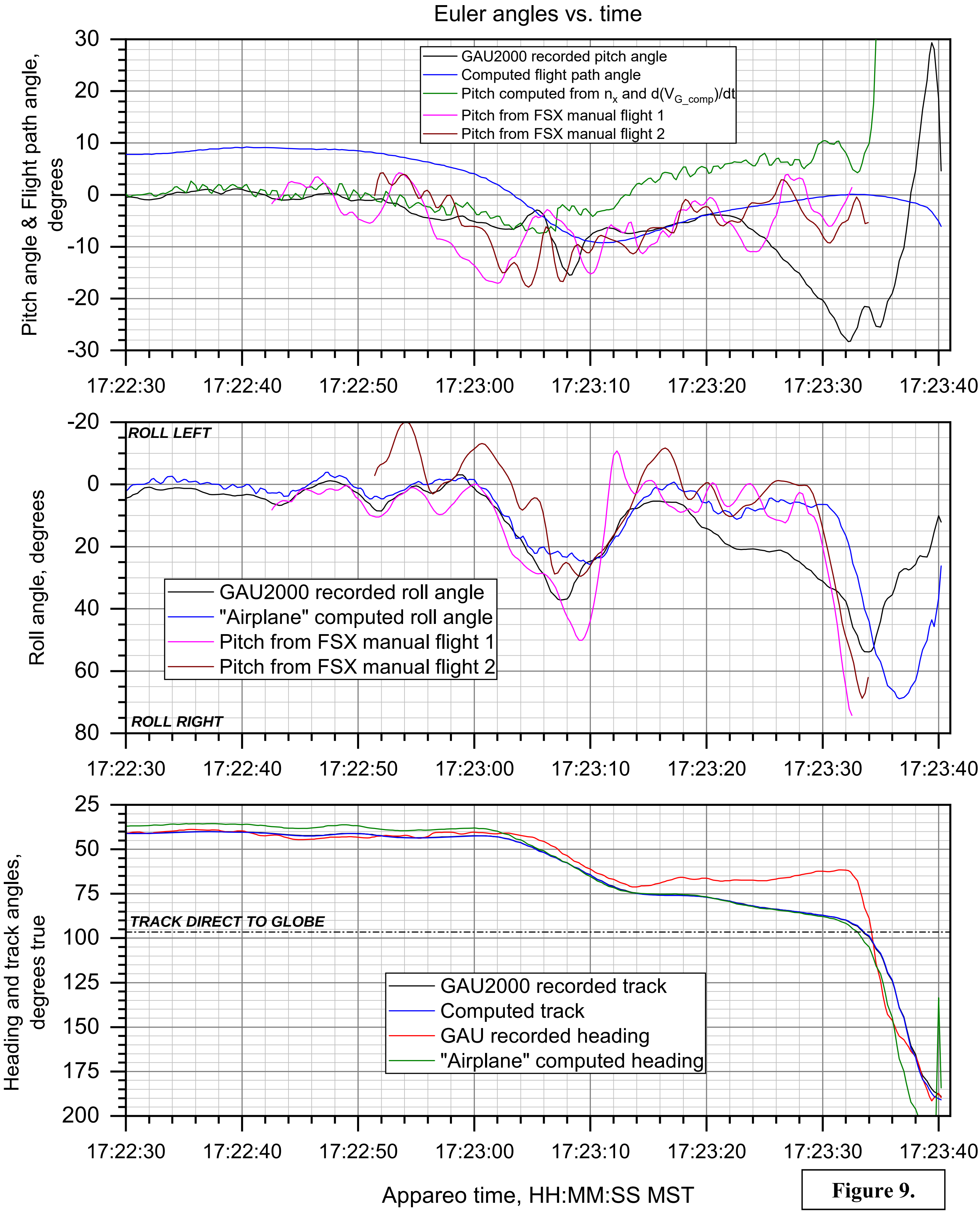
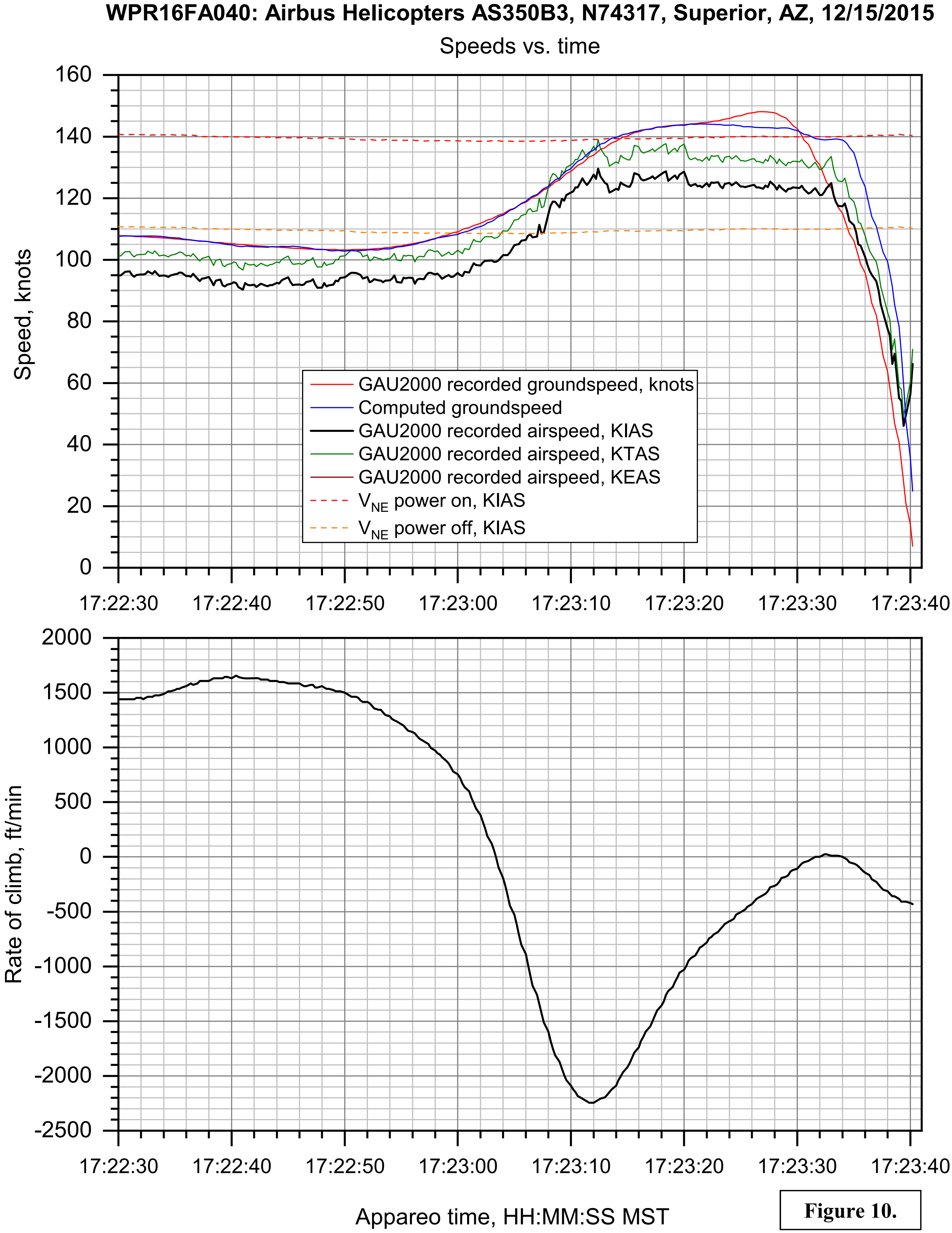
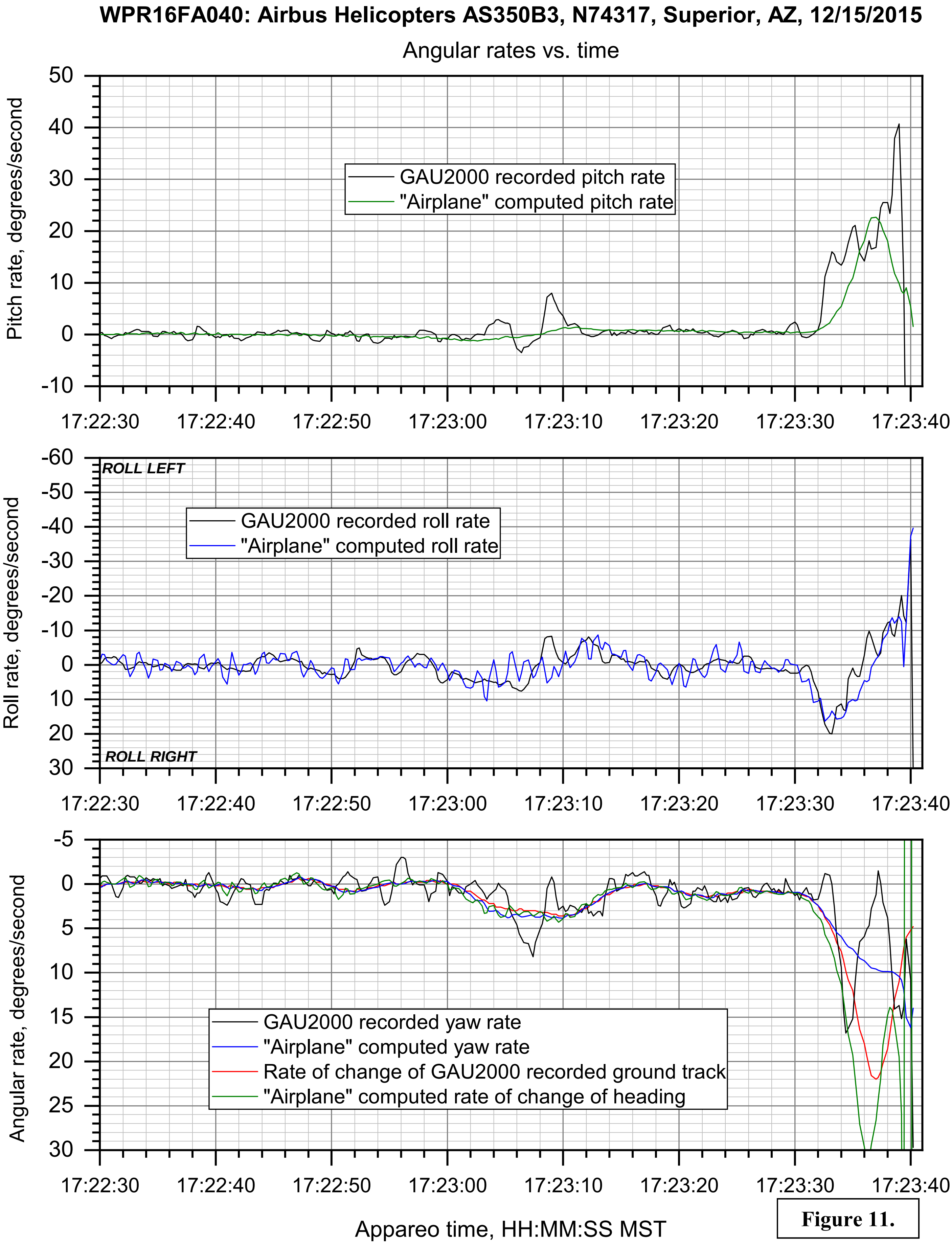


Figure 9.



WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Speeds vs. time
Speed, knots
GAU2000 recorded groundspeed, knots
Computed groundspeed
GAU2000 recorded airspeed, KIAS
GAU2000 recorded airspeed, KTAS
GAU2000 recorded airspeed, KEAS
V_NE power on, KIAS
V_NE power off, KIAS
Rate of climb, ft/min
17:22:30
17:22:40
17:22:50
17:23:00
17:23:10
17:23:20
17:23:30
17:23:40
Appareo time, HH:MM:SS MST

Figure 10.



WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015
Angular rates vs. time
Pitch rate, degrees/second
GAU2000 recorded pitch rate
"Airplane" computed pitch rate
50
40
30
20
10
0
-10
17:22:30
17:22:40
17:22:50
17:23:00
17:23:10
17:23:20
17:23:30
17:23:40
Roll rate, degrees/second
ROLL LEFT
ROLL RIGHT
GAU2000 recorded roll rate
"Airplane" computed roll rate
-60
-50
-40
-30
-20
-10
0
10
20
30
Angular rate, degrees/second
GAU2000 recorded yaw rate
"Airplane" computed yaw rate
Rate of change of GAU2000 recorded ground track
"Airplane" computed rate of change of heading
-5
0
5
10
15
20
25
30
Appareo time, HH:MM:SS MST

Figure 11.

Figure 12. Overview of flight from KIWA to intended destination of Globe, AZ, showing distance and bearing of Globe from the crash site.

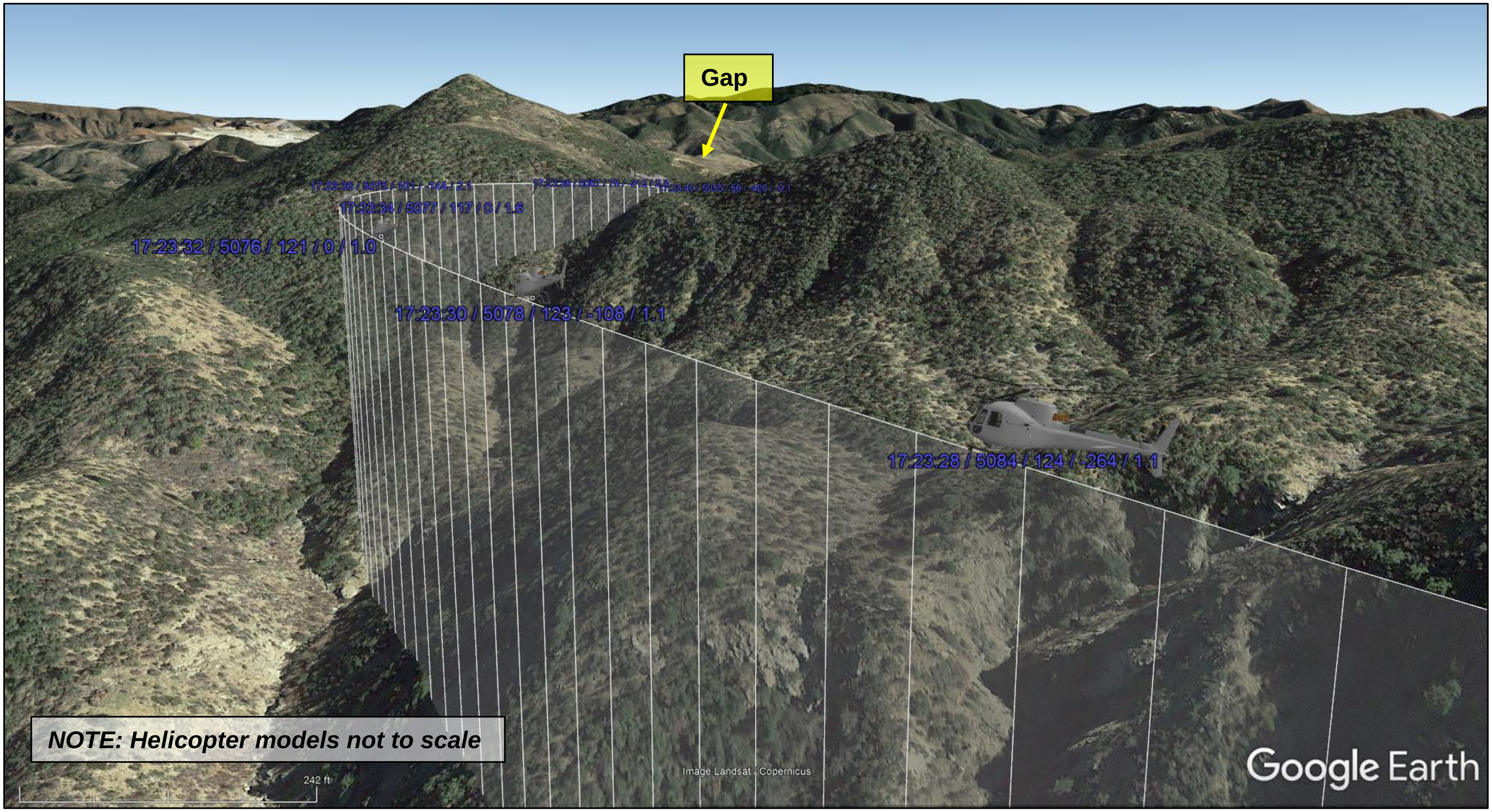


Figure 13. Image from *Google Earth* computer program depicting helicopter attitude and flightpath approaching accident site.

WPR16FA040: Airbus Helicopters AS350B3, N74317, Superior, AZ, 12/15/2015

Plan view of final 40 seconds of flight

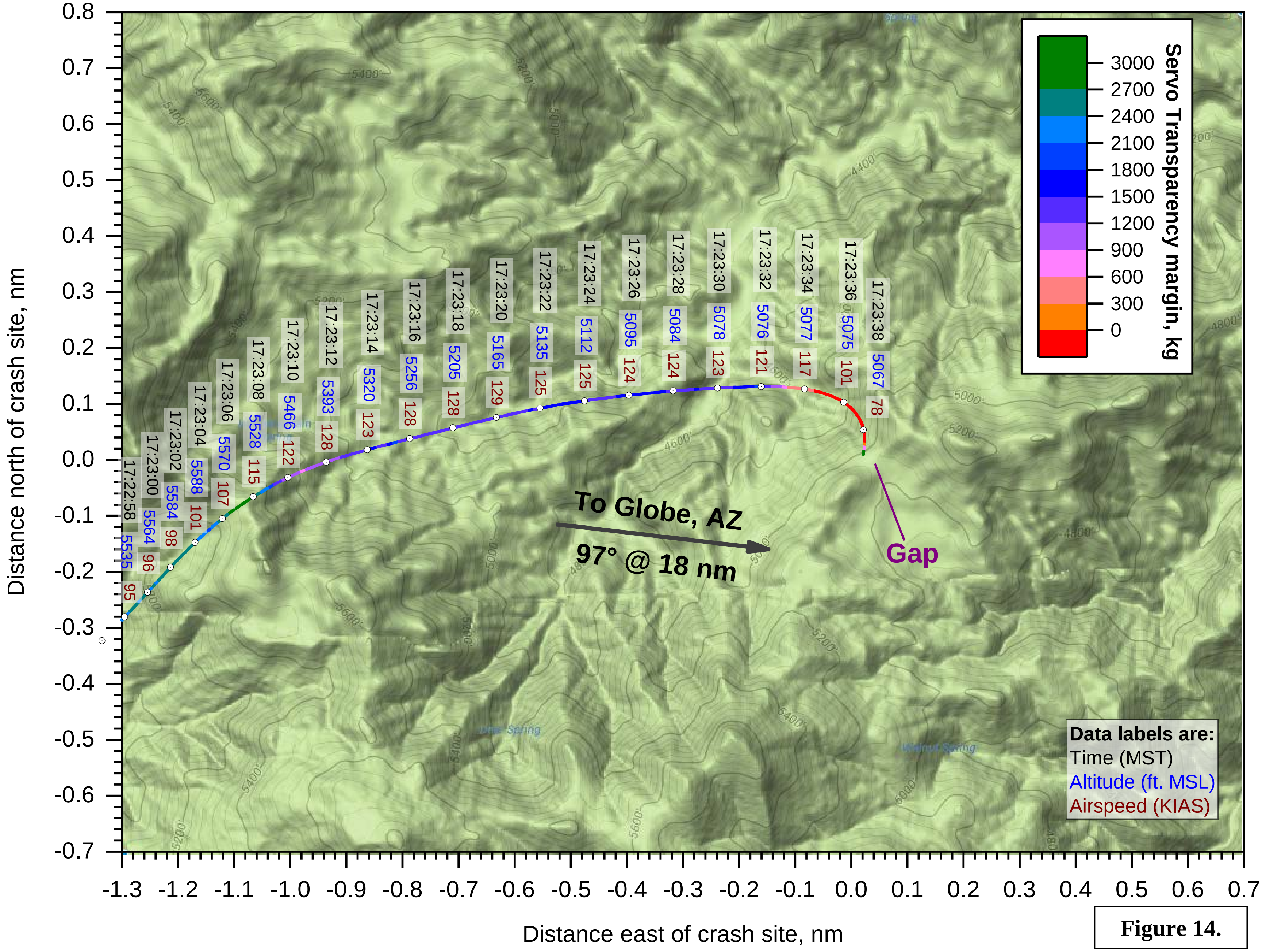


Figure 14.