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

August 20, 2012

Aircraft Performance Study

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Dennis Crider

A. ACCIDENT: WPR11MA454

Location:	Reno, NV
Date:	September 16, 2011
Time:	Approximately 16:26 PDT
Airplane:	North American P-51D

B. GROUP IDENTIFICATION:

No group was formed for this activity.

C. SUMMARY

On September 16, 2011, about 1626 Pacific daylight time, an experimental North America P-51D, N79111, sustained substantial damage when it impacted an area of box seats in front of the grand stand following a loss of control while maneuvering at the Reno Stead Airport, Reno, Nevada. The airplane was registered to Aero-Trans Corp, Ocala, Florida, and operated by the pilot as Race 177 under the provisions of Title 14 Code of Federal Regulations Part 91. The commercial pilot, sole occupant of the airplane was fatally injured. Ground injuries include 10 people fatally injured and 66 people that sustained serious injuries. Visual meteorological conditions prevailed and no flight plan was filed for the local air race flight which departed from RTS about 10 minutes prior to the accident.

D. DETAILS OF INVESTIGATION

Introduction

The accident occurred on the third lap of a six-lap race, as the airplane was turning around pylon 8 and flying towards the grandstand. The airplane's deviation from the expected flight path (or upset) was initially observable as a roll transient. This study uses telemetry data along with information extracted from photographs and video to evaluate the forces, moments and flying qualities of the airplane throughout the race, and to assess various possible causes of the upset. Photographic evidence (Image Study [1]) indicates that both the left and the right elevator trim tab control rods were fractured at times close to the upset, and this information is also used in evaluating possible accident scenarios. The accident airplane was flying in the race under the name Galloping Ghost, and that term is used throughout the report. Two other airplanes in the race (Strega and Voodoo) are also referred to in the report.

The Galloping Ghost was substantially modified from the original P-51D airframe (see the Airworthiness Group Chairman's report [2] for more details). There was no aerodynamic data from testing or analysis available for the Galloping Ghost. Some historical aerodynamic data for the P-51 was found, and that data was used as the basis for building a model of the airplane that was used in the performance evaluations in this report.

Telemetry Summary

The aircraft was equipped with a telemetry system which was monitored from the ground by the race team. The system recorded time, vertical acceleration, latitude, longitude, Global Positioning System (GPS) altitude, GPS speed, true course, magnetic course, and engine parameters (see Data Recorder Specialist Factual Report [3]) . All channels suffered from episodic loss of data, but at best the resolution of GPS position and speed data was 1 Hz and onboard engine and acceleration data was 3 Hz. The last GPS position recording occurred at 16:24:29.0, more than 4,000 feet away from the final wreckage site. The race flight path of the Galloping Ghost is shown in Figure 1, below.

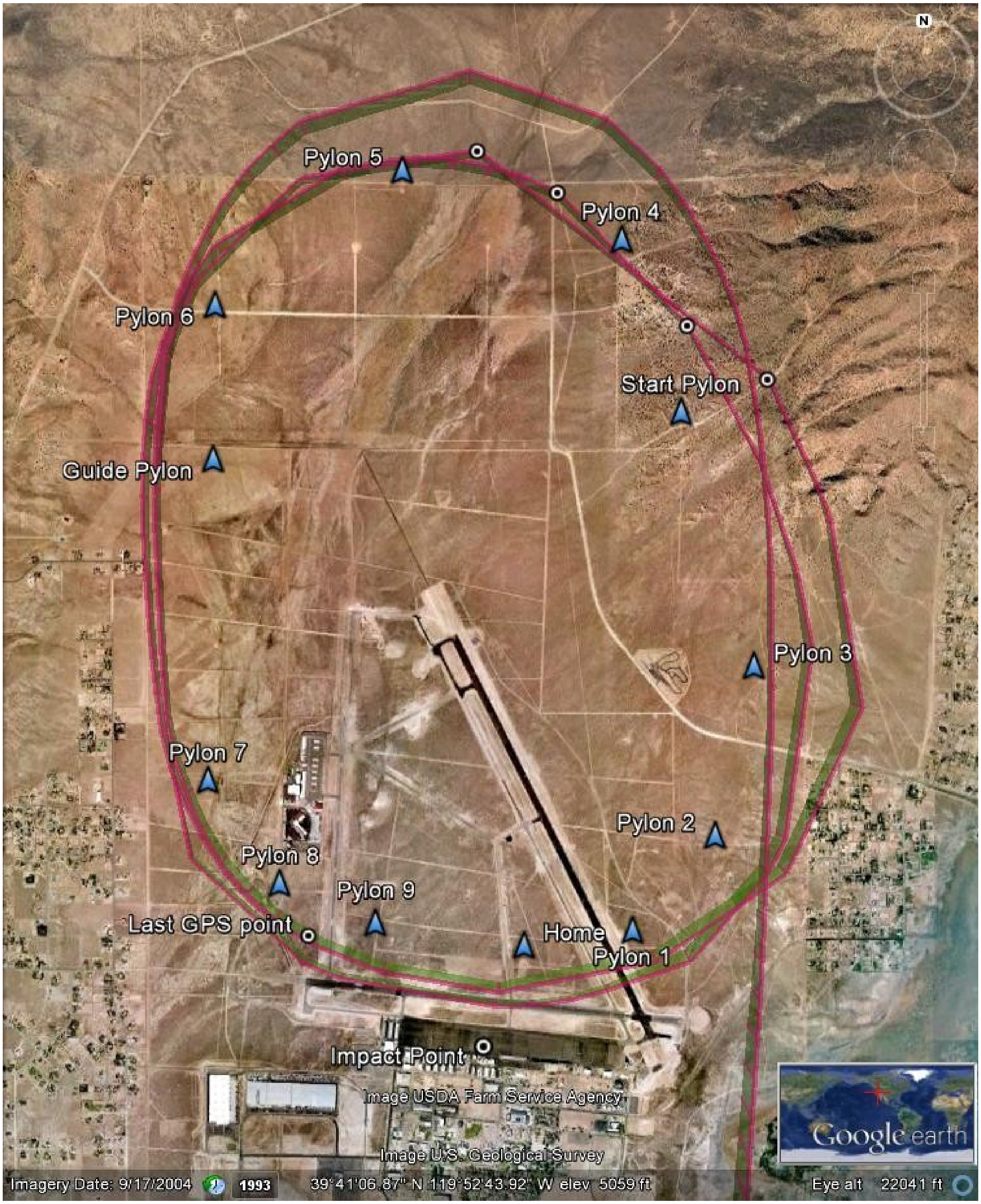

Figure 1. Galloping Ghost race flight path from GPS telemetry latitudes and longitudes.

In Figure 1, the aircraft seems to twice pass to the inside of Pylon 4. The erroneous flight path is due to gaps in telemetry data in this area. The flight path is drawn with straight lines between latitude and longitude points (shown before and after Pylon 4 as black and white circles), so missing points lead to a flight path that appears to miss the turn around the outside of the pylon. However, there were other aspects of the GPS system that contributed to the uncertainty. According to the Data Recorder Specialist Factual Report [3], the quality of the signal degraded during the race due to rapid banking to angles that obscured the antenna's view of the sky and limited access to satellites. Additionally, the manufacturer/designer of the telemetry system has noted issues with the GPS data when the load factor exceeds the operational limits (4 g's).

Gaps in data were common for all telemetry channels. The GPS speed record had a period of no data from 16:22:22 to 16:24:02. To compensate for the two minute loss of data, an inertial speed was calculated from the GPS altitude, latitude, and longitude. This data was then smoothed to account for timing irregularities. During the final lap of the race, the calculated ground speed is higher than the telemetry ground speed despite correlating well during the first lap (see Figure 2). It is unclear what accounts for the discrepancy, since the telemetry ground speed should use the same latitude, longitude, and time data as the NTSB calculation. There was no method available to independently verify which speed was the most accurate. This also makes the aircraft's true airspeed (TAS) (which was calculated using winds of 21 knots from 275°) different depending upon which ground speed was used to derive the airspeed. However, the maximum difference between the speeds is about 10 kts, which is less than a 3% difference from the average recorded speed. For the remainder of this report, the true airspeed determined from the GPS-position-based calculated ground speed will be used, unless otherwise noted. Using the calculated ground speed and true airspeed allowed for analysis of the second lap of the race when no telemetry speeds were available. Note that the magnitudes of the various speeds have some uncertainty, but the trends are consistent.

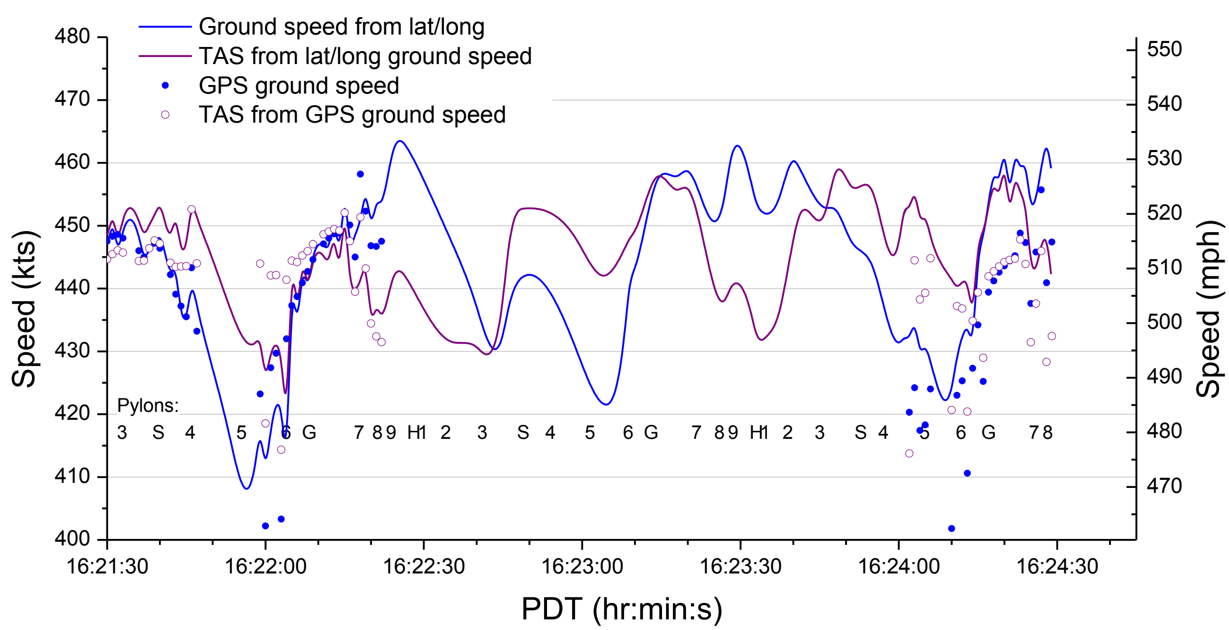

Figure 2. Galloping Ghost race speeds. Symbols indicate the times when the airplane passed the numbered pylons as well as the Start (S), Guide (G) and Home (H) pylons.

The Mach number of the aircraft was calculated using a speed of sound in air of 667 knots and the aircraft's true airspeed and is shown in Figure 3. At some points on the course, these speeds are higher than Reno Air Race Association (RARA) recorded speed values which reflect the average speed calculated from the ideal race course distance divided by the aircraft's lap times. The telemetry data was of much higher resolution recording the variations in speed around the course as well as the actual path the aircraft flew, which extended over a longer distance than the ideal race course.

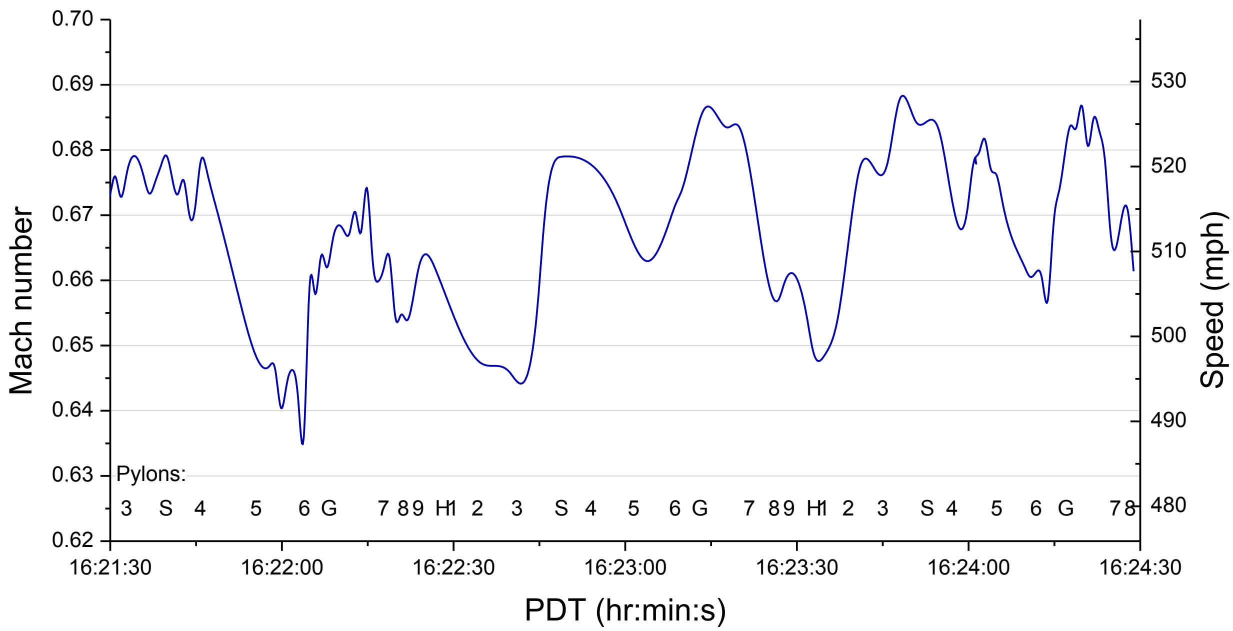

Figure 3. Galloping Ghost race Mach numbers.

The vertical acceleration was recorded using a single axis accelerometer mounted on a circuit board in a chassis that was mounted to the aircraft behind the pilot. The data was noisy due to the strong vibration of the aircraft and flexing of the circuit board. With the 3 Hz sampling rate these high frequency vibrations contaminated the data signal mixing with the lower frequency acceleration due to aircraft motion[1]. Figure 4 shows the telemetry vertical acceleration and the smoothed acceleration for the race. The telemetry vertical acceleration data recorded a number of points greater than 8 g near the end of the recorded data. The accelerometer on the Galloping Ghost was specified as an 8 g gage, but it can measure up to 10 g. However, due to electrical saturation issues as the measurements near 10 g, the data certainty is best below 8 g.

All telemetry data was time correlated to the GPS signal. After the last GPS location, the vertical acceleration and engine parameters continued to record, but did not have times associated with them. For plotting purposes, it was decided to increment the time for each subsequent data point by 1/3 of a second, consistent with the best sampling rate of 3 Hz.

[1] This effect is referred to as aliasing

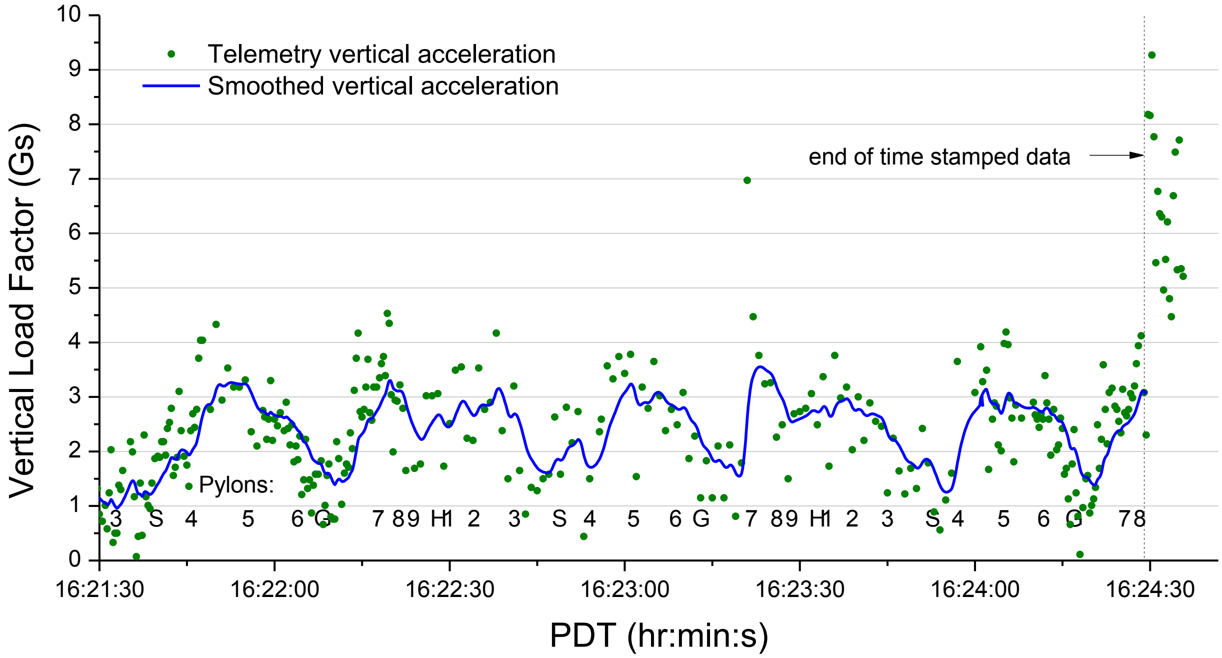

Figure 4. Galloping Ghost race vertical acceleration.

A total of nine telemetry channels were dedicated to engine and cooling system parameters. Engine speed in revolutions per minute (RPM) and engine manifold pressure (MAP) data are shown in Figure 5.

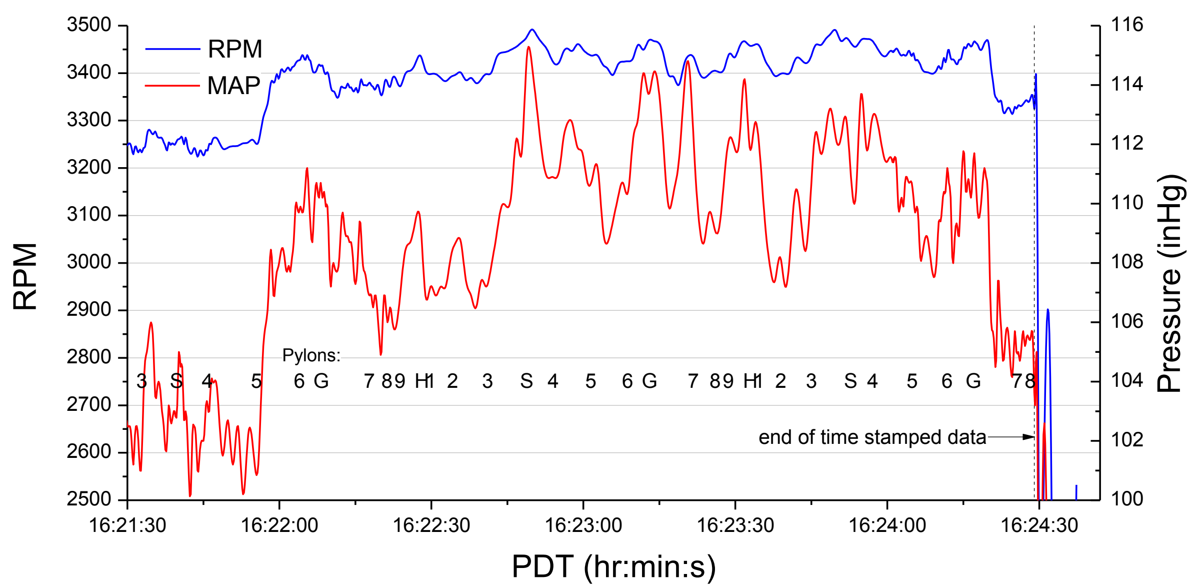

Figure 5. Galloping Ghost race RPM and MAP.

Comparison of Galloping Ghost to Other Racing Aircraft

To determine if the performance of the Galloping Ghost during the race flight prior to the upset was unusual compared to other similar aircraft, the race team from Voodoo, another modified P-51, provided telemetry data from the September 16th race to the NTSB. Voodoo was a few seconds ahead of the Galloping Ghost during the accident race. Figure 6 shows the speeds of both aircraft and Figure 7 compares the vertical load factor throughout the race. Both figures show that the Galloping Ghost speed was close to that of Voodoo and that the two airplanes were experiencing similar vertical load factors.

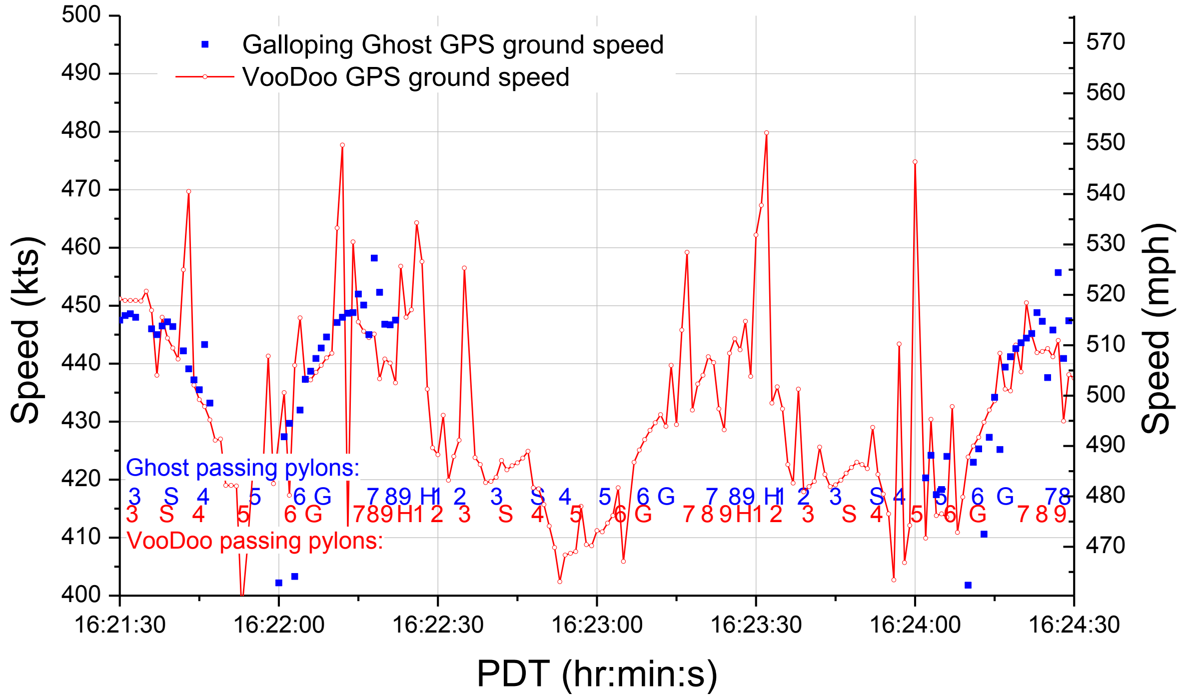

Figure 6. Voodoo and Galloping Ghost GPS recorded ground speed.

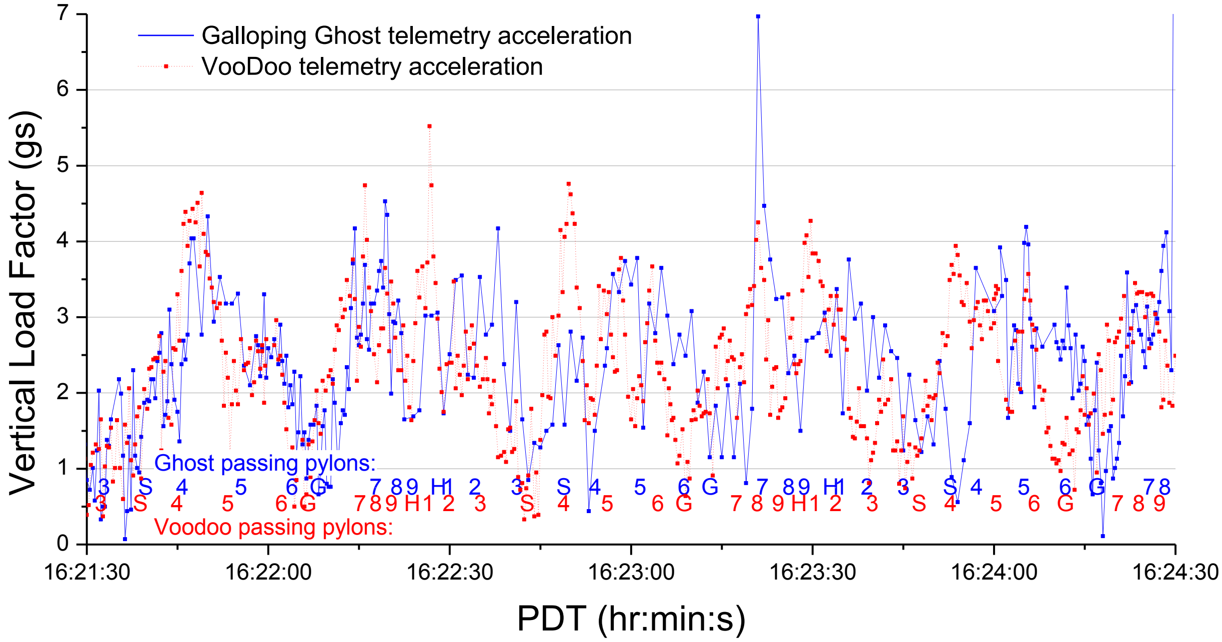

Figure 7. Voodoo and Galloping Ghost vertical load factors.

Comparison of Accident Flight Laps

To determine if the performance of the Galloping Ghost during the portion of the flight immediately prior to the upset was unusual, the aircraft's speed, vertical acceleration, MAP, and RPM for each lap in the location of the upset were compared. The roll transient event occurred as the aircraft passed pylon 8 during the third lap of the race. Figure 8 and Figure 9 show comparisons of the first and second laps of the race to the accident lap for speed, vertical acceleration, and engine performance. The pylon numbers reflect the third lap. Figure 8 shows that the aircraft's speed and acceleration on the third lap of the race were not significantly different from those during its first two turns past Pylon 8.

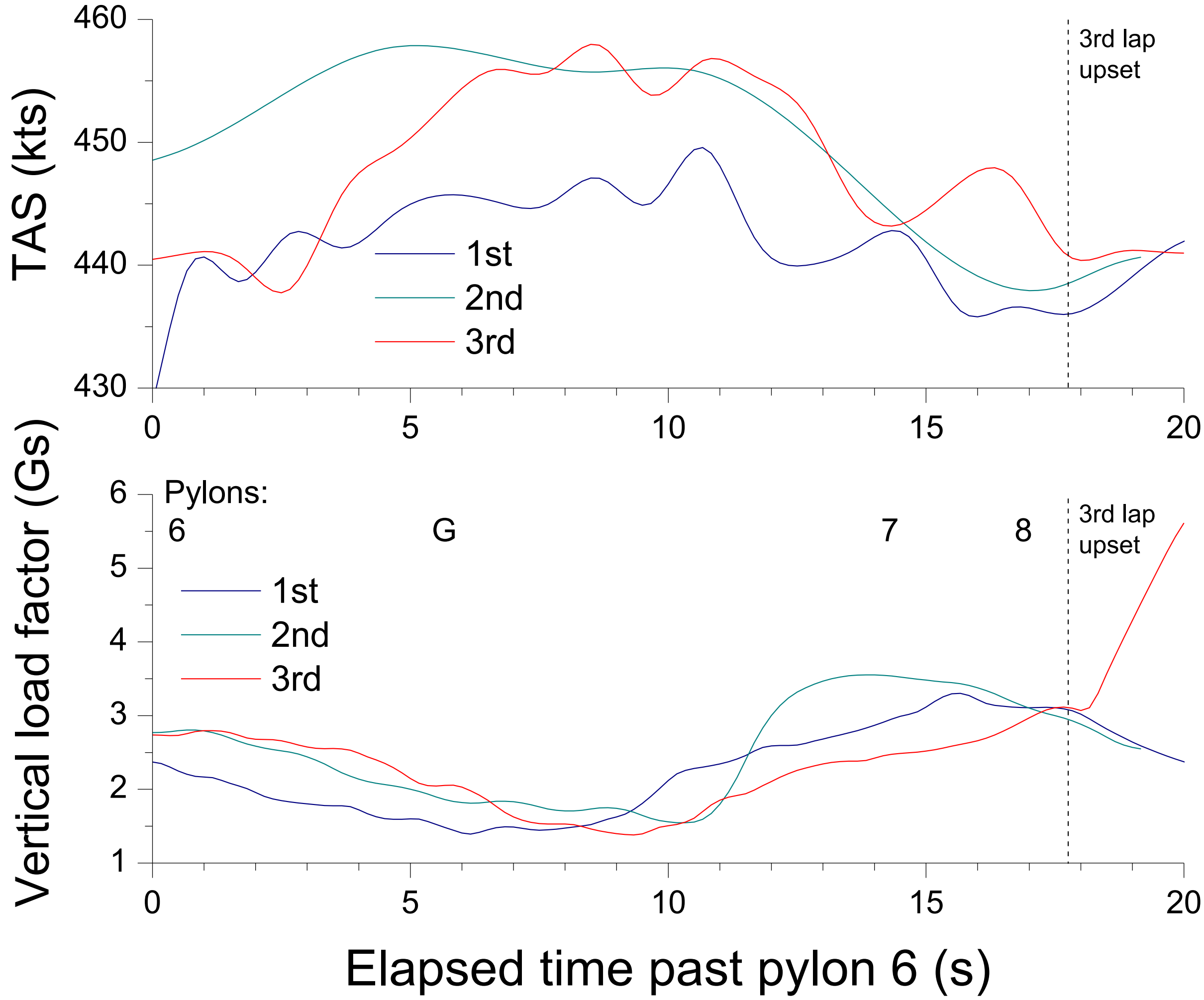

Figure 8. True airspeed and vertical load factor leading into the turn round Pylon 8 on laps 1, 2, and 3.

Figure 9 shows RPM and MAP for the laps. About 8 seconds before the beginning of the upset, the engine was cut back.

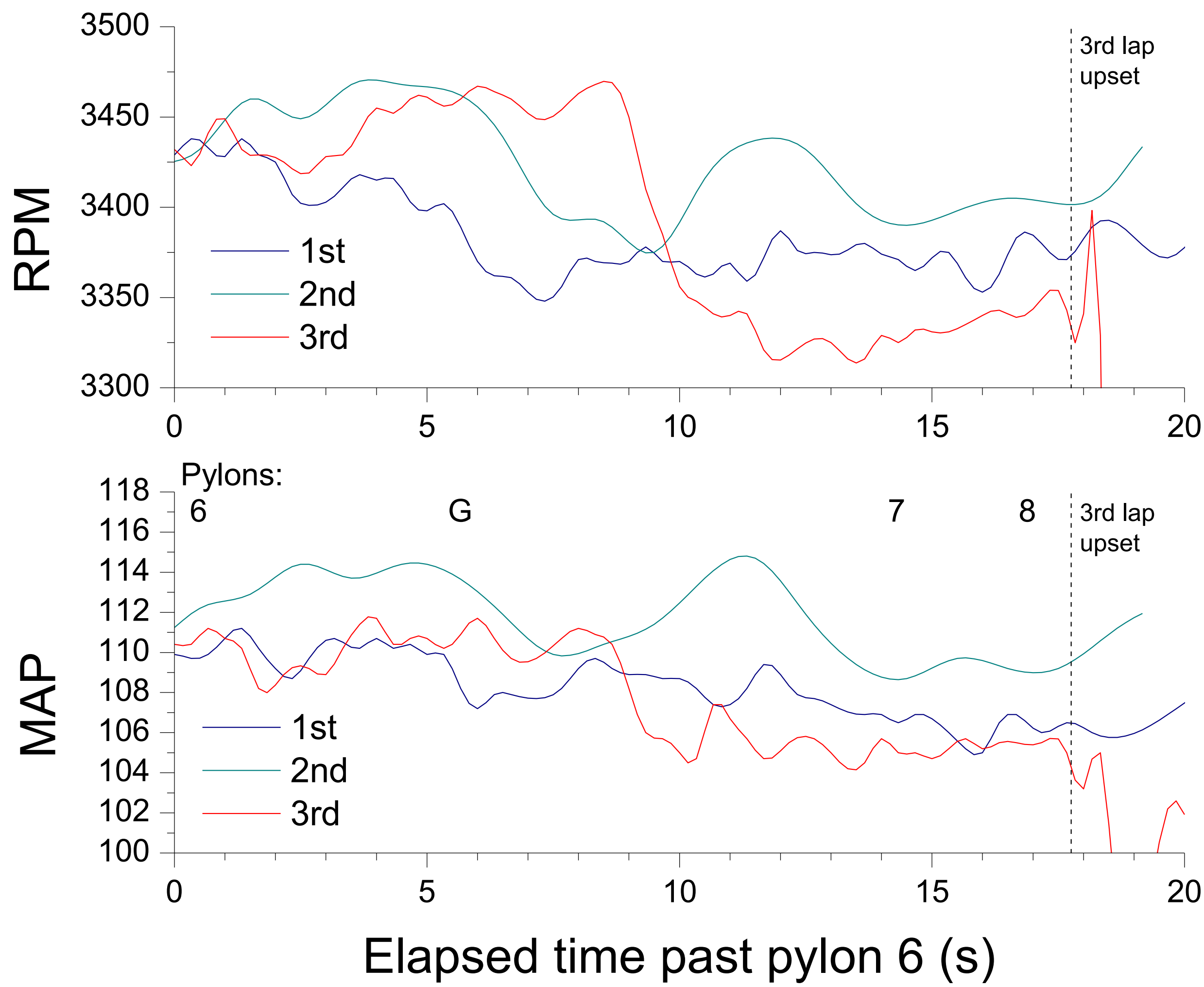

Figure 9. RPM and MAP leading into the turn round Pylon 8 on laps 1, 2, and 3.

Effect of modifications on stability

The maneuvering stability of the stock P-51 was just over 20 lb/g at normal flight speeds, which was somewhat higher than the maneuvering stability for other fighters of the time [4]. However, the P-51 pilot training manual mentions control reversal in high speed dives when there was fuel in the fuselage and states that these reversibility characteristics were improved by the addition of a 20 lb bob weight on the P-51D. However, the weight and center of gravity of a stock P-51D would have been different from the Galloping Ghost due to armament, fuel, and structural modifications. Additionally, the bob weight of the Galloping Ghost had been cut down to an estimated weight of 8⅔ lbs. The modifications to the Galloping Ghost also included elevator counterweights that were added which also reduced the stability benefit of the bob weight. For the Galloping Ghost weight and center of gravity at the time of the accident, there would have been approximately an 8½ lb/g reduction in maneuvering stability compared to a stock P-51.

Roll Transient/Beginning of Upset

Photographs and video of the Galloping Ghost during the race and subsequent upset and accident were analyzed by the NTSB. The Video Study [5] used available video to evaluate the motion of the aircraft's flight over approximately 4 seconds. The Galloping Ghost was in a coordinated left turn at a 73º bank when it abruptly rolled to a greater than 90º bank. The aircraft then rolled back right and pitched up into a climb. The motion results of video analysis, shown in Figure 10, were time correlated to the telemetry data. Because of the difficulty in determining the motion of the aircraft with respect to the motion of the camera when the aircraft was coming towards the camera, especially for heading and pitch, the data before 16:24:28.90 is less accurate than later data. The estimation of the bank of the aircraft is dependent upon pitch and heading for transformation from camera to earth axis and is therefore also slightly less accurate during this period before the upset.

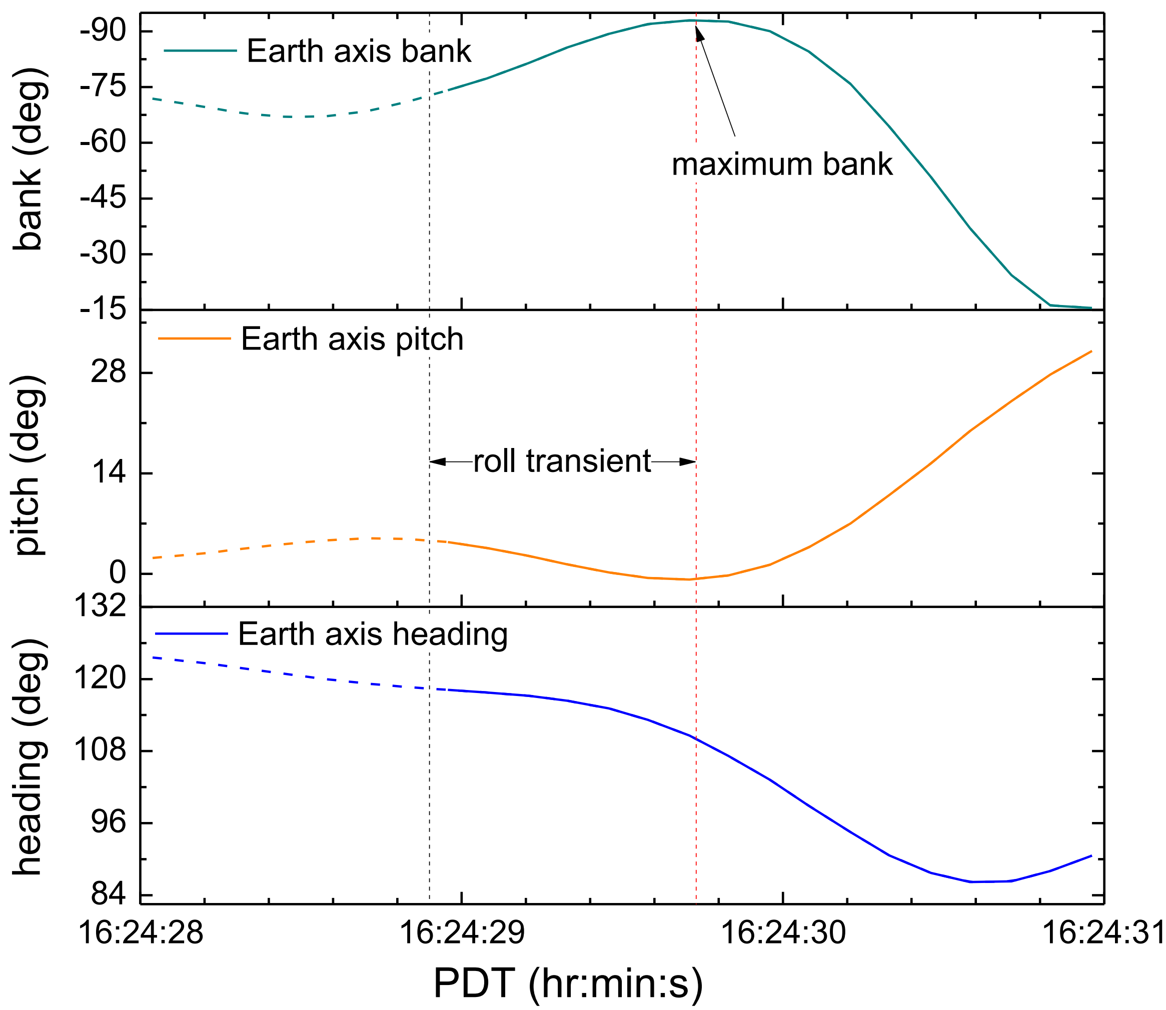

Figure 10. Motion of Galloping Ghost from video analysis of final portion of the accident flight.

Figure 11, below, shows the vertical acceleration leading up to, during, and after the roll transient identified in photographs and videos of the accident. During the roll transient, the onboard accelerometer recorded a greater than 5 g jump in vertical acceleration in 1/3 of a second. The departure from the flight path and the sudden increase in vertical acceleration indicate that the roll transient was at the beginning of the upset that led to the accident. Figure 11 also locates when, in the photographic evidence (Image Study [1]), the right and left trim tab control rods were first definitively recorded as being visibly broken.

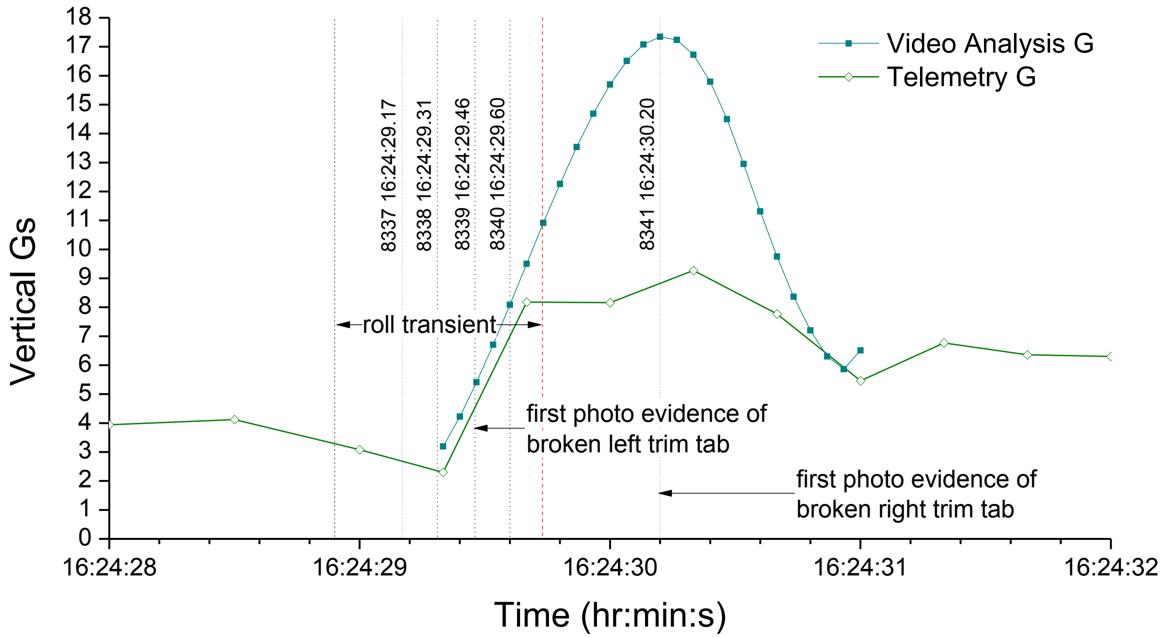

Figure 11. Galloping Ghost vertical acceleration during upset. Dashed blue lines mark the time of Apfelbaum photographs. Further information on the content of each photo is in the Image Study [1].

The photographic evidence showed the trim tab to be in the trailing edge up position throughout the race and into the upset. The measured trim tab setting was between -5º and -8° (negative numbers indicate a trailing edge up position). Through the upset, the photographs showed definitive movement of the left trim tab at 16:24:29.46, about 0.56 seconds after the onset of the left roll transient. The tab position during the pre-upset and upset period could not be determined before this time. The inboard section of the left trim tab did not detach until 4.3 seconds after the beginning of the left roll transient.

Aerodynamics and Kinematic Extraction Method

An aerodynamic model of the Galloping Ghost was developed from historical P-51 data ([6],[7],[8]) and modified for the structural and power changes made to the accident aircraft (discussed in depth in the Airworthiness Factual Report [2] and illustrated briefly in Section G).

Longitudinal data was obtained largely from wind tunnel data and NACA reports of the time and adjusted to match available flight test information. Hinge moment data was particularly sparse. No data was found on hinge moment due to tab deflection so this hinge moment coefficient term was estimated using the method outlined in the text by Perkins and Hage [9]. Hinge moments are usually not as precise as other parameters derived in a wind tunnel and analytical estimates are likewise of lower accuracy than other aerodynamic parameters. Accordingly, due to low accuracy, parameters involving hinge moments are not included in this report. No lateral directional data was found so lateral directional aerodynamic parameters were also analytical estimates (though much more reliable estimates than hinge moments). No flight test data was found for validation of lateral directional aerodynamics. The relative accuracy of the parameters derived with the aerodynamic model included in this report is given in Table 1.

Table 1. Confidence levels of various aerodynamic parameters.

Parameter	Confidence level	Comments
Lift coefficient, C_L	Very precise	Aerodynamics required for motion description are model independent
Pitching moment, C_m	Very precise	Aerodynamics required for motion description are model independent
Rolling moment, C_{roll}	Very precise	Aerodynamics required for motion description are model independent
Angle of attack (AoA) wing	Sub degree	Dependent on $C_{L\ alpha}$ which is precisely known
Elevator deflection, δ_e	+/- 1 deg	Basic longitudinal aerodynamics validated to match elevator deflection
AoA of the horizontal stabilizer	+/- 1 deg	Basic longitudinal aerodynamics validated
Tail force	+/- 10%	Basic longitudinal aerodynamics validated
ΔC_m	+/- 5%	Basic longitudinal aerodynamics validated
$\Delta\ C_{roll}$	+/- 20%	Analytical lateral directional model
Aileron deflection	+/- 20%	Analytical lateral directional model

A kinematics extraction technique was applied to the data to determine the moments and control inputs required for the aircraft during the race and to perform the roll transient maneuver prior to the accident. Aircraft speed, vertical acceleration, and engine parameters were required for the extraction. Additionally, a number of parameters had to be calculated or estimated using the limited existing telemetry data before the kinematic extraction could be performed. The vertical acceleration of the aircraft was corrected using an offset determined from data recorded when the aircraft was on the ramp and when the aircraft was in steady level flight. It was then converted into vertical force using the weight of a full aircraft from the Galloping Ghost's weight and balance sheet.

For the flight prior to the roll transient, the kinematic extraction technique required an estimate of the roll, pitch, and yaw of the aircraft during the race leading up to the roll transient. These parameters require an angle of attack of the aircraft which was calculated using the C_N of

$$C_N = \frac{F_N}{q\,S_W}$$

Where F_N is the vertical force determined from the telemetry vertical acceleration and aircraft weight, q is the dynamic pressure from the calculated true airspeed, and S_W the area of the wing. C_N was then used to calculate a first estimate of the aircraft angle of attack using the aerodynamic model of the Galloping Ghost.

The telemetry data plus the angle of attack were used to estimate the earth-axis roll and pitch of the aircraft during the race. Yaw was determined from the change in heading of the aircraft. Roll, ø, was calculated as

$$\emptyset = \cos^{-1} \frac{N_{Zearth}}{N_{Zaircraft}}$$

and pitch, θ, from

$$\theta = \gamma + \alpha$$

Where γ is the flight path angle and α is the angle of attack. Flight path angle was determined using the difference in latitude, longitude, and altitude between points. The vertical load factor, altitude, airspeed, roll, pitch, yaw, RPM, MAP, and weight of the aircraft were input into the kinematic extraction tool which used a math model of the aircraft to extract control positions. Figure 12 shows the lift coefficient and angle of attack of the aircraft for the accident race.

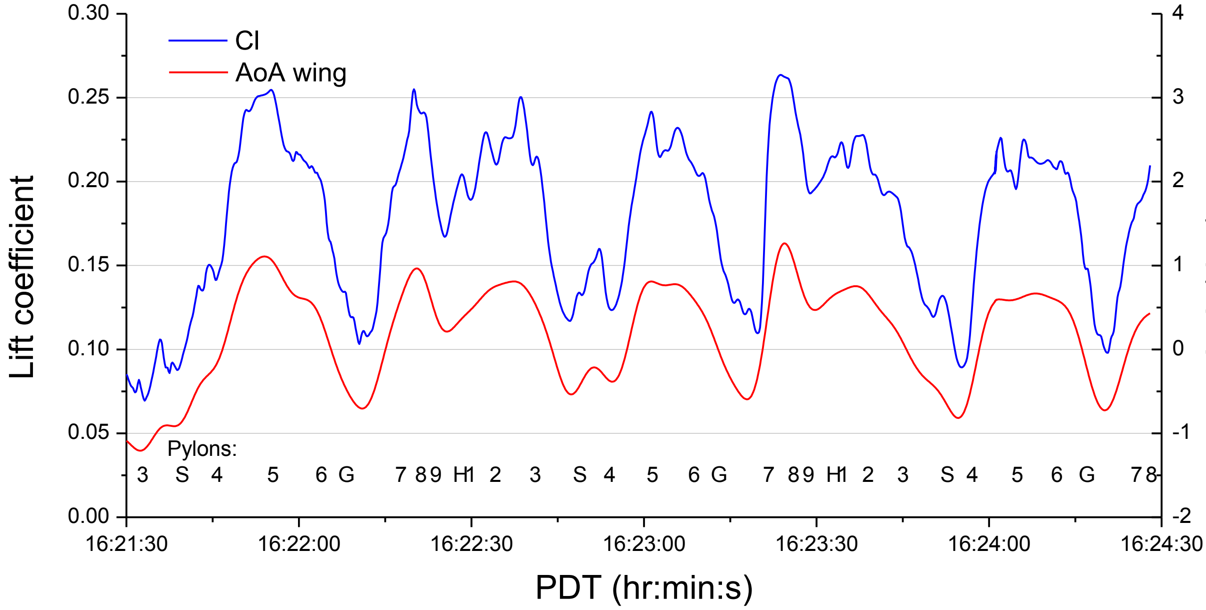

Figure 12. Calculated lift coefficient and angle of attack of the wing.

Figure 13 shows the angle of attack of the tail, the elevator deflection, and the load on the tail. Note that a negative elevator deflection equates to a trailing edge up condition, which is consistent with the photographic evidence from the race. The negative load on the tail equates to a download which is consistent with photographs showing fuselage wrinkling discussed in the Image Study [1].

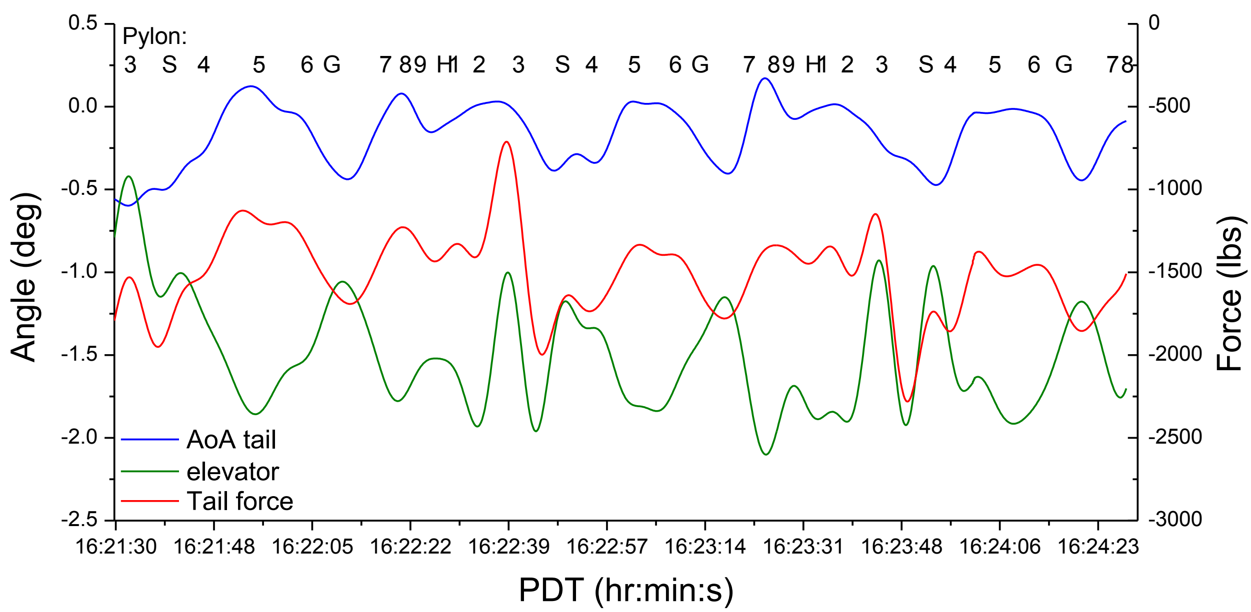

Figure 13. Angle of attack of the tail, elevator deflection, and load on the tail for the accident race from the kinematic extraction.

It is of note that during the race the Galloping Ghost maintained a slight trailing edge up elevator deflection consistent between the photographic evidence and the kinematic extraction.

The kinematic extraction method was applied to the video data (shown earlier in Figure 10) and Figure 14 shows the pitching and rolling moments required for the aircraft to complete the roll upset. As the data before 16:24:29 has larger uncertainty, especially in pitch and heading, the rolling moment is shown as a dashed line, the pitching moment is not shown before 19:24:29, and the yawing moment is not presented at all. The change in aerodynamic moment for the initiation of roll began before 16:24:28.90, but due to inertial lags, the roll was not visible until 16:24:28.90.

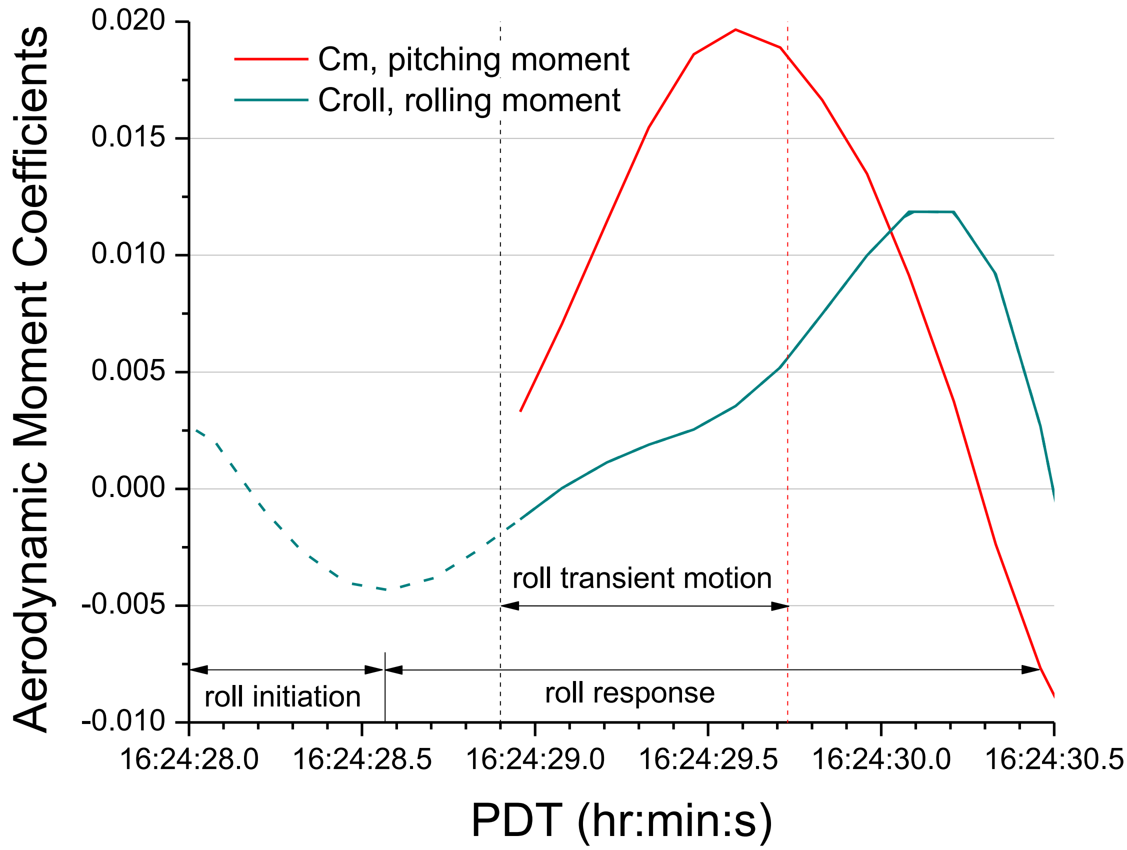

Figure 14. Pitching and rolling moment aerodynamic coefficients required for roll transient. Dashed lines indicate less reliable data.

Additionally, it was determined what control inputs would be required for the aircraft to complete the roll transient maneuver. Assuming an intact airplane and no wake or wind encounters, the elevator and aileron deflections required to complete the roll transient motion are shown in Figure 15. During the roll initiation a change in aileron input of about 3° (± 30% due to uncertainty) would be necessary for the aircraft to complete the roll transient motion. The photographs of the aircraft during the roll initiation period were at such an angle that measuring the deflection of the ailerons to the necessary degree of accuracy was not possible. Therefore it was not possible to use the photographs to either confirm or rule out that a change in control inputs initiated the roll transient.

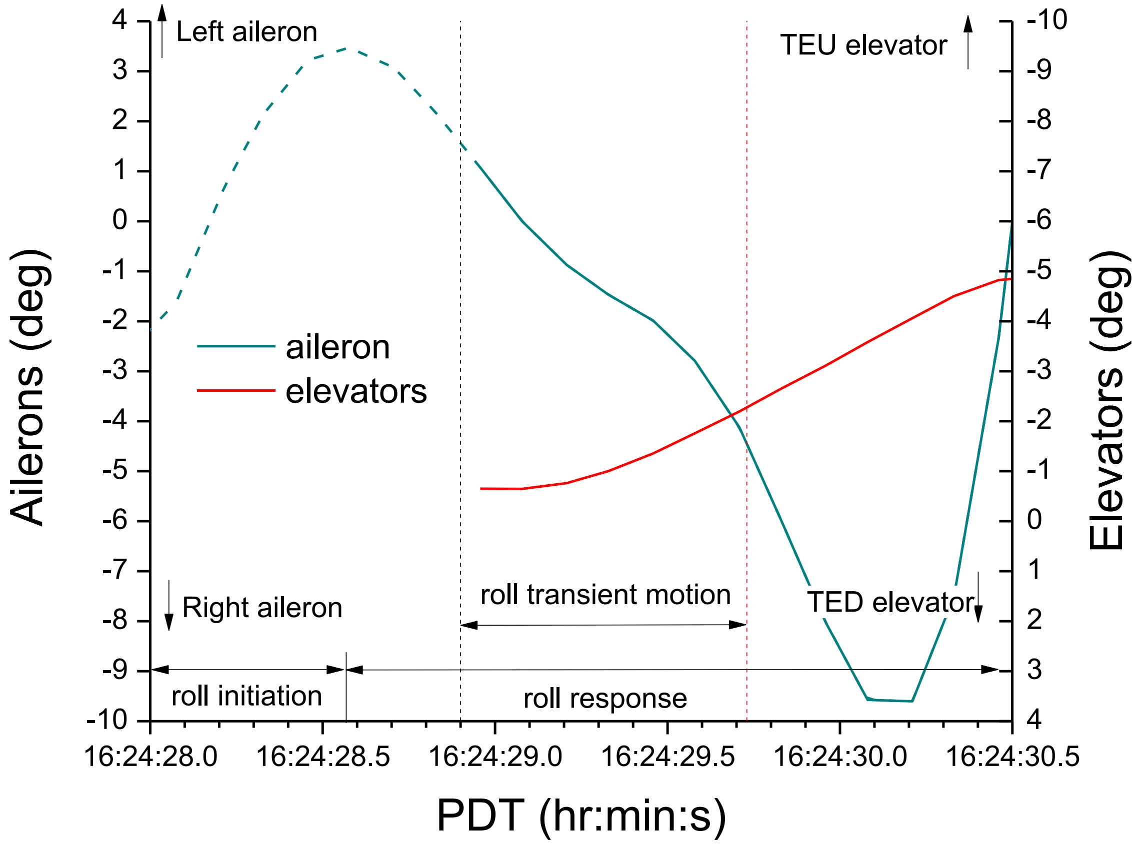

Figure 15. Elevator and aileron required for roll transient motion.

Accident Scenarios

Roll transient initiators can be broadly divided into two categories: (1) an outside force acted upon the aircraft or (2) the aircraft itself changed, due to a structural or mechanical failure or pilot input. The transient event was left roll and all of the scenarios considered in this study require that the right roll which follows the maximum left bank was pilot initiated.

Roll Initiated by External Force

Wind Gust

A sudden gust of wind of sufficient magnitude could have initiated the left roll transient. However, the Meteorological Factual Report [10] stated that the winds above the surface at Reno Stead Airport during the race were laminar and not gusty. It is unlikely that a wind gust initiated the roll transient.

Mach Buffet

Mach buffet could have caused separation on the left wing, causing it to lose lift, and initiate the left roll. The Mach number where Mach buffet occurs is inversely related to the lift coefficient. Figure 16, below, shows the NACA defined lift coefficient marking the Mach buffet boundary (Reference [11]) for the P-51D modified for the reduced wing area of the Galloping Ghost, as calculated using the aircraft's Mach number during the race. The accident aircraft's lift coefficient (first presented in Figure 12) stays well below the buffet boundary throughout the race. Additionally, the aircraft lift coefficient was higher and closer to Mach buffet earlier in the race than at the time of the upset. It is unlikely that Mach buffet instigated the roll transient.

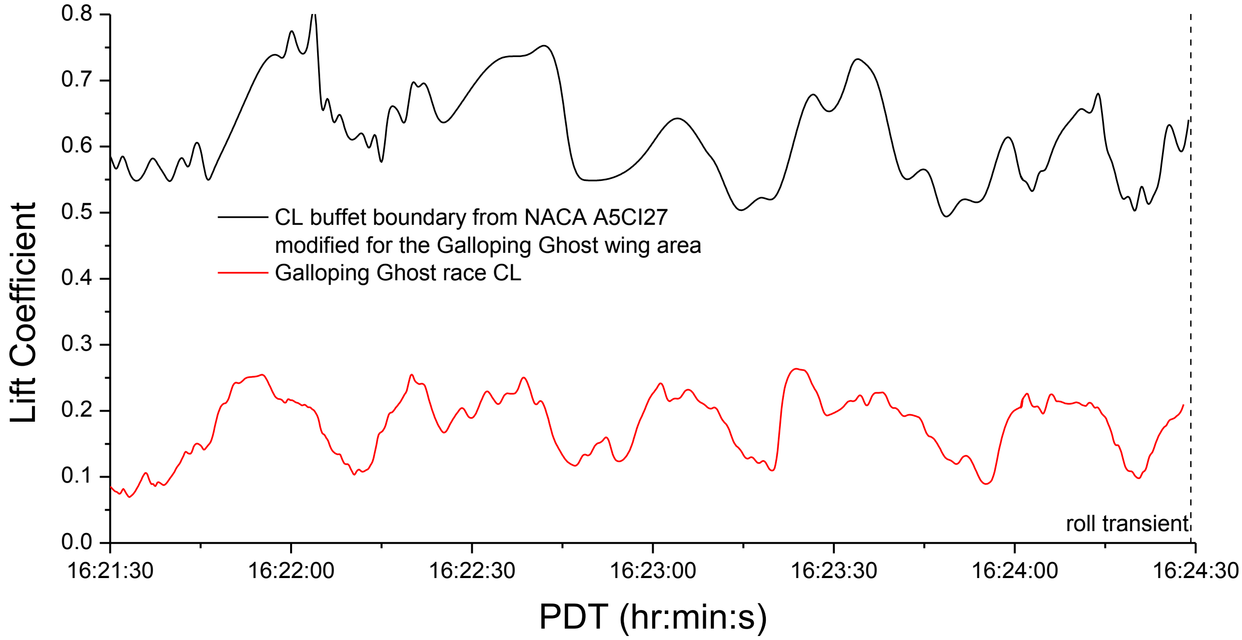

Figure 16. Comparison of Galloping Ghost lift coefficient with modified P-51D Mach buffet boundary data.

Wake Encounter

Wake encounters are not uncommon during race events. The possibility of a wake encounter was evaluated for the two aircraft immediately ahead of the Galloping Ghost. A vortex is generated from each wing tip of an aircraft. Initially these vortices will pair and for aircraft with this weight and load factor should move perpendicular to the aircraft wings at 200 to 300 fpm. The Meteorological Factual Report [10] showed that the environment was neutral vertically and descending vortices would be expected to continue to descend.

At the time of the upset, Voodoo was about 4.5 seconds ahead and Strega was about 8.8 seconds ahead of the accident aircraft. Voodoo was at a bank angle of about 70º (nominally 2.9 g's) when it was at the point of the Galloping Ghost upset. Strega's left bank angle was assumed to be 70° for calculation purposes. Image analysis determined that Voodoo and the Galloping Ghost were at about the same altitude near the point of the upset (see Image Study [1]). A wake generated by either airplane would be pushed along a heading 275° by the 21 kts wind. Using the GPS ground tracks of Voodoo and the Galloping Ghost it was determined that at 16:24:24.45 Voodoo would have been aligned in such a way that the wind would carry its wake towards the upset point (see Figure 17). The 21 kts (35.4 ft/s) wind could have only carried the wake 157 ft in 4.5 s, 176 ft short of the accident aircraft's location at the time of the upset. Accounting for possible increases in wind due to altitude and uncertainties in GPS locations, a second estimate was made using 4.8 s of separation and a 25 kts (42.2 ft/s) wind and it yielded a travel distance of 202 ft, still short of the distance to the Galloping Ghost. However, the GPS data for Voodoo showed a number of inconsistencies during the race, so the exact path of the airplane was not able to be determined. Therefore, it is not possible to conclude definitively whether the Galloping Ghost could or could not have encountered a wake from Voodoo.

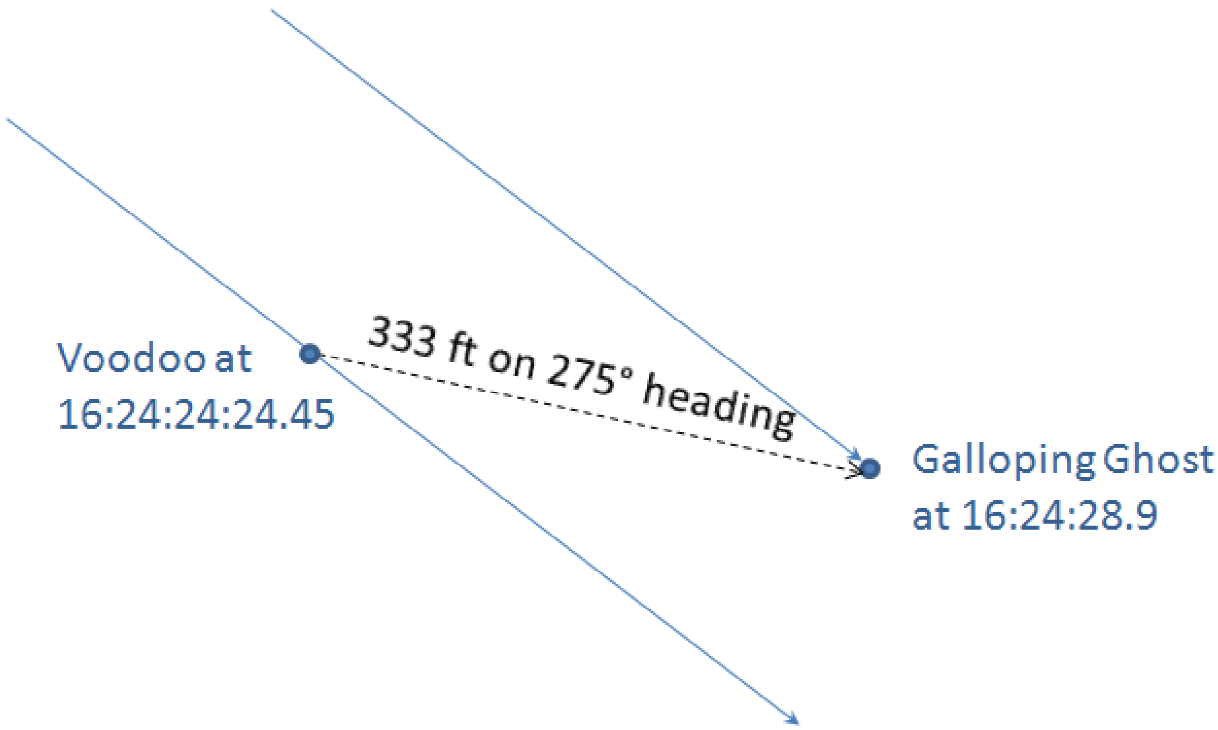

Figure 17. Distance between Galloping Ghost and Voodoo GPS ground paths along wind heading.

The position or altitude time history of Strega was not known from telemetry or GPS. Nominally, the position required for Strega to generate a wake to upset the Galloping Ghost is shown in Figure 18 and Figure 19. Since there are multiple encounter geometries and wake descent rates that could produce a left roll, this nominal point grows to a region about the size of the Galloping Ghost. Strega's flight path would have had to be just inside Voodoo's and its height would have to be level or just above the Galloping Ghost for the wake to intersect the accident aircraft. The tendency for wakes to depart from straight lines due to the possibility of developing Crow instability[2] widens the region further.

[2] Crow instability is a mechanism which causes vortices shed from the wingtips to curve away from the path of the airplane, in some cases eventually developing into rings before dissipating.

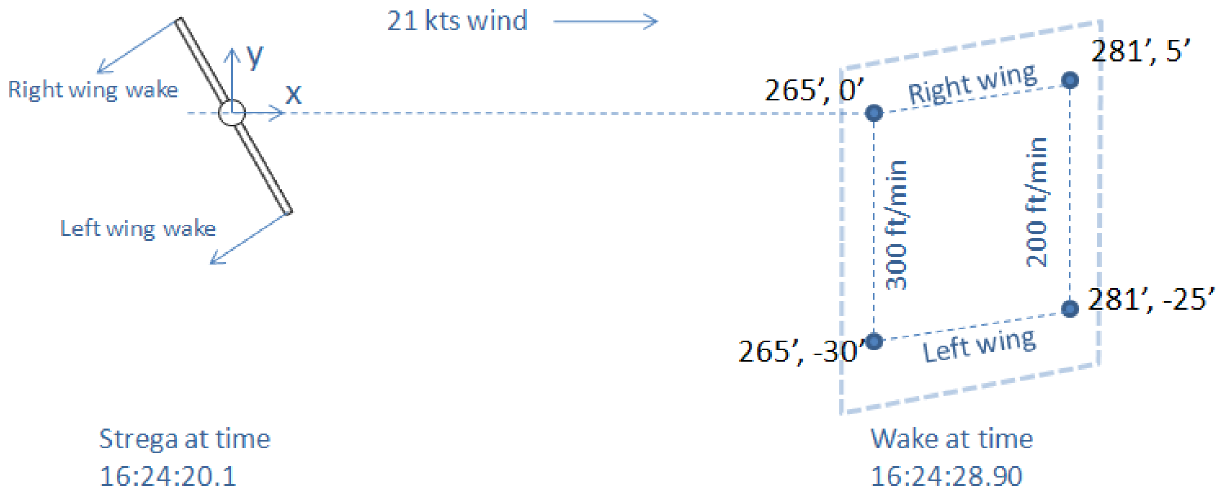

Figure 18. Horizontal and vertical distance the wake from Strega’s right and left wing could move over 8.8 s.

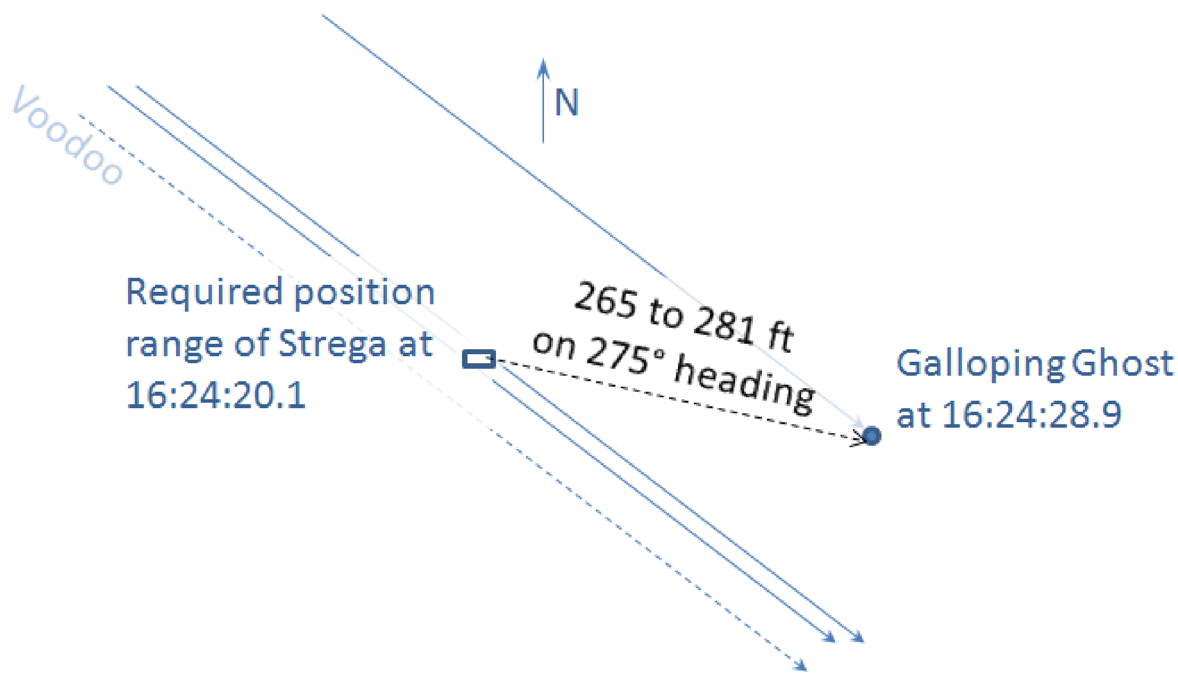

Figure 19. Required distance between Galloping Ghost and Strega ground paths along wind heading for Galloping Ghost to encounter Strega’s wake.

To be responsible for an upset, a wake vortex encounter must produce the roll coefficient time history shown in Figure 14. However, due to the uncertainty of the data during the initiation of the roll in the kinematics analysis, it is not possible to separate out the effects of a wake encounter versus a different roll initiator. It can be concluded that a wake would only have to induce a small change in the rolling moment coefficient (less than 0.005) to begin the roll transient.

Roll Initiated by a Faiure of the Left Trim Tab

The purpose of the elevator trim tabs is to reduce the stick force required for a given elevator deflection, making the aircraft more manageable for the pilot flying. The Galloping Ghost was trimmed using only the left trim tab. The right trim tab was locked in a faired position with the right elevator. Throughout the race the accident aircraft flew with the left trim tab trailing edge up.

Failure of the Trim Tab Control Rods

The earliest photographic evidence of the failure of the left trim tab control rod is at 16:24:29.46, 0.56 s after the beginning of the roll transient as shown in Figure 11. However, the quality or angle of the other photographs of the aircraft leading into and at beginning of the upset made it not possible to definitively determine if the tab was broken earlier. In the 16:24:29.46 photograph, the trim tab was deflected trailing edge up at an angle past the design constraints of the system. For a loss of trim tab effectiveness to have induced the left roll transient, it would have had to occur before the onset of the roll at 16:24:28.9.

An increase in aerodynamic load could have overloaded the left trim tab and caused a failure of the control rod, leading to the extreme deflection of the trim tab seen in the photographs. Static loads on the trim tab control rods are calculated using hinge moments unique to each type of aircraft. Unfortunately due to the age of the P-51, the data for the hinge moments were not available. However, the tab loads are a function of dynamic pressure (q) multiplied by both the angle of attack of the horizontal tail and the elevator deflection. These quantities are shown in Figure 20. From this plot it can be seen that the values for $q*AoA_{tail}$ and $q*\delta_{elevator}$, terms which are multiplied by constants and added together to yield the load on the trim tab control rod, are both lower at the point leading into the upset than they were at earlier points during the race. The deflection of the tab itself is also a factor, but is not included since the deflection is unknown and assumed to be near-constant throughout the race. Regardless of the actual hinge moment values, the combination of these two values could not have produced a greater static aerodynamic load on the trim tab leading into the upset than at points earlier. Therefore, it is not possible that a flight induced increase in static aerodynamic loads on the tab was able to break the left trim tab control system.

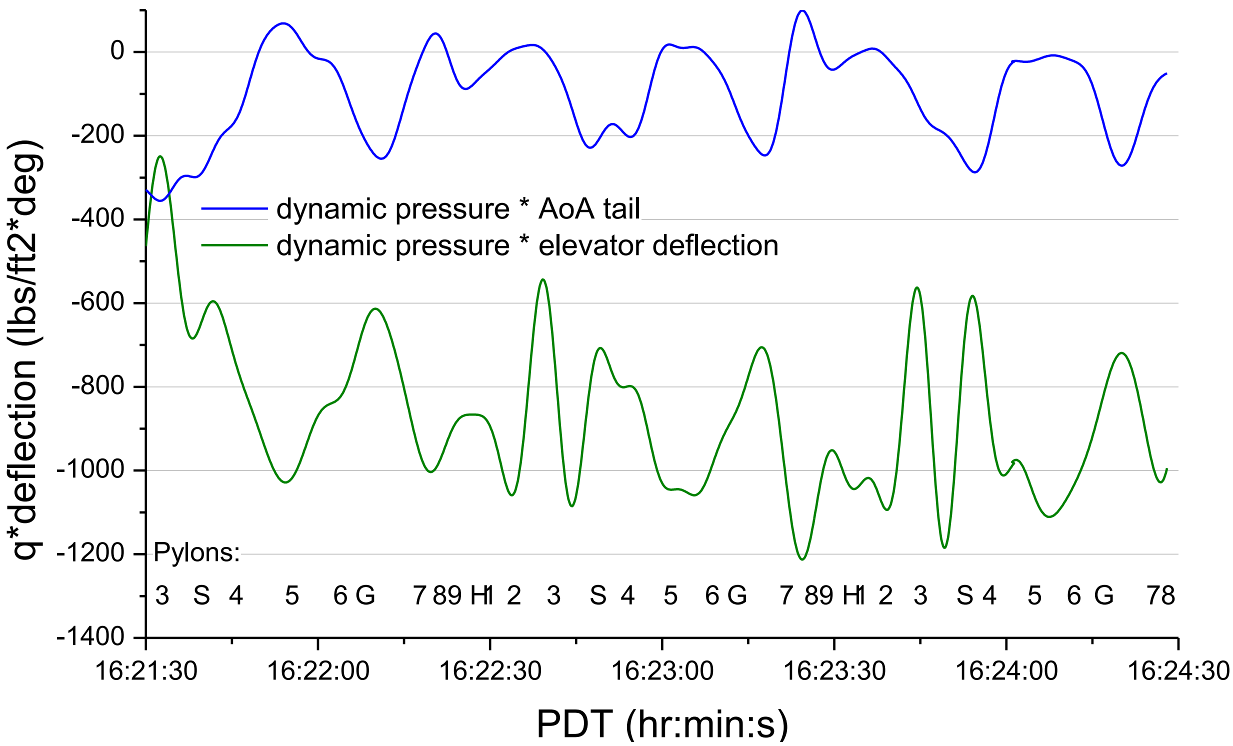

Figure 20. Dynamic pressure (q) multiplied by the angle of attack of the horizontal tail and the elevator deflection.

A wake encounter itself is unlikely to have overloaded the trim tab control rod enough to cause it to fail. Wake encounters are common occurrences during air races and are not expected to cause structural failures. However, a wake encounter may trigger flutter in an already loosened trim tab system.

Exacerbated by the loose screws and growing screw fatigue crack in the trim tab system discussed in the Materials Laboratory Factual Report [12], a low amplitude flutter could have developed on the left trim tab that would not be visible in the photos. Such a low amplitude flutter motion would disrupt the flow alternatively on the top and bottom of the tab resulting in cyclic loads into the tab rod. These cyclic loads could have grown and overloaded the left tab rod. Alternatively, once a certain level of structural degradation had occurred a wake could act as a trigger for flutter. With the tab rod buckled and fractured, the flutter mode would have transitioned to the full deflection flutter of both the right and left trim tabs seen at 16:24:30.2 in Figure 11. Flutter is further discussed in the Airworthiness Group Chairman's Study [13].

Effect of Trim Tab Failure on Roll and Pitch

To hold the right wing down aileron input seen throughout the race, the pilot had to hold the control stick to the right of center. The loss of the trim tab effectiveness would produce a sudden and large stick force directed aft. At the sudden application of the aftward force, the pilot would lose his ability to precisely hold the stick out to the right at least temporarily resulting in the onset of the left roll transient. A change in aileron input of 3º (± 30% due to aerodynamic uncertainty) would be necessary for the aircraft to complete the roll transient motion as shown in Figure 15. It was not possible to determine if these changes were present during the roll initiation from the photographs.

Since the pilot would be unable to hold the control stick as far forward as with an intact trim tab, the elevator would deflect slightly trailing edge up, which would pitch the aircraft upward and increase its angle of attack (pitch onset would be slightly later than roll onset due to the higher inertia about the pitching axis). The increased angle of attack would in turn increase the forces on the elevator surface and control stick according to

$$F_{controlstick} = F_{bobweight} + F_{counterweight} + qGS_eC_e \ \ C_{h\delta e}\delta_e + C_{h\alpha t}\alpha_t$$

Where F is force, q is the dynamic pressure, G is gearing, S_e and C_e are the area and chord of the elevator, δ_e is the deflection of the elevator, α_t is the angle of attack of the tail, and C_{h_α} and $C_{h_{d_e}}$ are hinge moment coefficients due to α_t and δ_e respectively. As the elevator deflection and tail angle of attack increase, so does the force required to hold the control stick in place. The pilot, already unable to hold the control stick in its original position due to the broken trim tab, would be unable to resist as the increased angle of attack of the tail induced the elevator to deflect even further trailing edge up, pushing the stick further aft. Stick force, elevator deflection, and tail angle of attack will increase together, with the stick force becoming too large to be counteracted by the pilot. The continued increase in elevator deflection with angle of attack of the tail, shown in Figure 21, is consistent with how the loss of the elevator trim tab would be expected to affect the aircraft. The data in Figure 21 is derived from the kinematic extraction shown earlier in Figure 15.

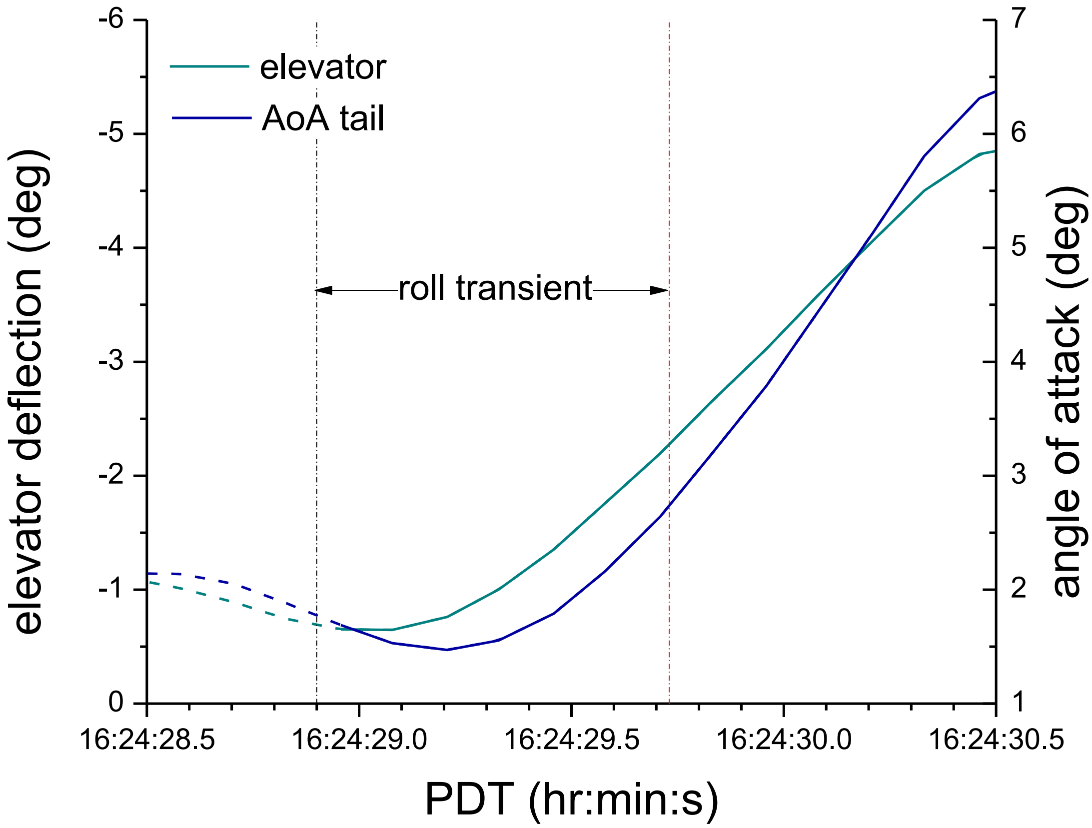

Figure 21. Elevator and angle of attack of the tail during the roll transient and pitch-up.

Loss of Tail Asymmetry and an Increase in Stick Force Initiate Left Roll Transient

Photo evidence shows that both sides of the aircraft experienced skin buckling during the race before the upset signifying that the aircraft was bending. Power and asymmetries on the airframe resulted in a net left rolling moment that the pilot was balancing throughout the race with right aileron. Direct forces due to the left tab trailing edge up deflection would have produced left rolling moment. This would be countered to some degree by the torque the tab load produces about the stabilizer which would twist the left side of the tail leading edge up relative to the right side, rolling the airplane right. Additionally, the hinge moment due to the left tab deflection would be expected to move the left elevator slightly more trailing edge down than the right elevator due to the spring effect of the elevator torque tube. Again, this would roll the aircraft to the right. The right roll would be partially countered due to the slightly more trailing edge down left elevator twisting the stabilizer leading edge down. In summary the failure of the left tab will produce an unknown change in rolling moment which is likely to be small (classically, tab forces are usually ignored when calculating forces causing motion of the airplane).

E. CONCLUSIONS

During the race the speed and vertical loading of the Galloping Ghost was comparable to other racing P-51s. Its flight leading into the upset was similar to its performance during the previous two laps. The speed, vertical loading, and calculated static loads on the airplane were higher during the race before the upset and there was no indication that an increase in static aerodynamic forces overloaded to cause the failure of the left trim tab control rod.

The aircraft loss of control began at 16:24:28.90 with a left roll and pitch up transient. Photographs confirm that the failure of the left trim tab control rod occurred sometime before 16:24:29.46. The motion of the aircraft during the transient is consistent with a failure of the left trim tab and its effect on the pilot. A low amplitude flutter of the left trim tab due to loosening screws and a growing fatigue crack in one of the screws attaching the trim tabs could have increased in amplitude and cyclically loaded the control rod until it failed, causing the left roll and pitch up. It is also possible that the aircraft encountered a wake that initiated the roll transient and excited the flutter in the already loosened trim tab system which caused the tab control rod to break. It is not possible for the kinematic extraction to differentiate the effects of a wake encounter from the effects of a trim tab failure alone since the two events would have occurred at the same time. Both mechanisms for initiating the left roll transient require that the aircraft trim tab structure be compromised by looseness of the screws because a wake encounter alone would not be expected to break the trim tab of another race aircraft.

F. REFERENCES

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G. GALLOPING GHOST SPECIFICATIONS

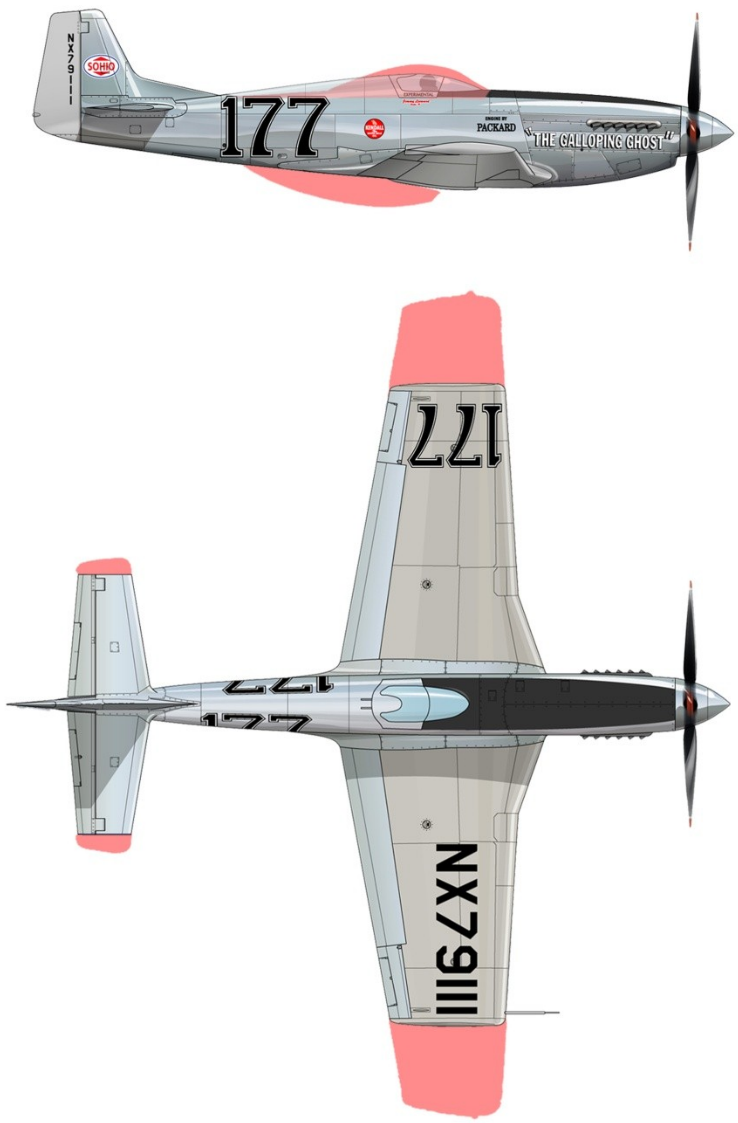

Figure 22. Galloping Ghost drawing with stock P-51D area shown in red. The aircraft featured shorted wings and tail, a low profile racing canopy, and had the fuselage scoop removed.

Table 2. Galloping Ghost Geometery.

Wing span	28’ 11”
Tail span	12’ 1”
MAC	7’ 2"
Weight from pre-race weight and balance sheet	8695 lbs
C.G. from pre-race weight and balance sheet	142.6” from reference line
Calculated weight at upset	7763 lbs
Calculated C.G. at upset	140.2” from reference line