Tamarack Aerospace Group Submission to the National Transportation Safety Board

Regarding

Collision of Cessna 525A (N525EG) With Terrain Near Memphis, IN, November 30, 2018

Accident Number:

CEN19FA036

Accident Date:

November 30, 2018

Report Date:

October 29, 2020

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REFERENCES

[1] Federal Aviation Administration, *Type Certificate Data Sheet No. A1WI, revision 28: Textron Aviation Inc. 525, 525A, 525B, 525C,* FAA, 2020.

[2] M. Moler, *Performance Study,* National Transportation Safety Board.

[3] M. Bauer, *Systems Group Chairman's Factual Report,* National Transportation Safety Board, 2020.

[4] European Aviation Safety Agency, *AMC No. 1 to CS 25.1329 (Amendment 17),* EASA, 2015.

[5] European Aviation Safety Agency, *CRI D-103: Loads Alleviation System,* EASA, 2015.

[6] FAA Flight Standards Service, *FAA-H-8083-3B, Airplane Flying Handbook,* Federal Aviation Administration, 2016.

[7] M. Moler, *RE: Tamarack - more questions re. ADS-B data [email],* 2020.

GLOSSARY

Terms and abbreviations used throughout this submission are presented below, for clarification. Note that references to regulations are made to the amendment level relevant to the certification basis of the 525A, as noted in Type Certificate Data Sheet A1WI [1].

Table 0-1 Glossary of Terms

ACU	ATLAS Control Unit, the component in which the load alleviation logic and primary monitoring functions are implemented
AMC	Acceptable Means of Compliance, a procedure for demonstrating compliance to a particular regulation approved by certification authorities
ATLAS	Active Technology Load Alleviation System, a Tamarack-patented system designed to alleviate aerodynamic loads on a wing
CRI	Certification Review Item, an EASA document which establishes special conditions for certification of new and novel designs.
EASA	European Aviation Safety Authority
INOP	Inoperative
KIAS	Knots Indicated Airspeed, the airspeed presented to the pilot
LH	Left hand
LRU	Line Replaceable Unit, a modular unit installed on an airplane
RH	Right hand
TACS	Tamarack Active Camber Surface, aerodynamic surfaces which deploy to alleviate aerodynamic loads on the wing
TCU	TACS Control Unit, an integrated actuator and control board unit designed to convert ACU commands into TACS actuations
TED	Trailing edge down
TEU	Trailing edge up
VD	Design dive speed, the maximum speed used in the demonstration of flutter and high speed flight characteristics, defined by 14 CFR 23.335 AMDT 23-48

1 INTRODUCTION

On November 30, 2018 at approximately 1628 UTC, A Cessna 525A airplane was involved in an accident near Memphis, Indiana. The airplane, N525EG, was destroyed, and the three occupants were fatally injured. The flight was being operated on an instrument flight rules flight plan as a business flight under provisions of 14 CFR 91. Following the accident, Tamarack Aerospace Group (Tamarack) was invited to be party to investigation CEN19FA036, because the airplane had a Tamarack-designed modification installed at the time of the accident.

1.1 Submission Abstract

- On May 30, 2019, Tamarack Aerospace Group was invited to participate in the investigation as a party due to Tamarack's expertise as manufacturer of the Active Technology Load Alleviation System (ATLAS), a structural modification installed on the airplane at the time of the accident.
- The investigation specifically spent time examining the TACS Control Units (TCUs), integrated linear actuator/controller units developed by Tamarack as a component of ATLAS.
- Witness marks within the actuators of both the left and right TCUs indicate that the actuators were both extended at the time of impact. Similarity in the relative position of witness marks between the left and the right further indicate that the actuators were deployed approximately symmetrically.
- The location of the witness marks within the actuators is consistent with a symmetric deployment to approximately half of the total trailing edge up travel of the surfaces. This is consistent with normal operation in response to a load factor on the airplane of approximately 2g.
- The interruption of signals caused by the bent pins found in the left hand TCU would most likely have interfered with the operation of the system on flights between installation and the accident flight. Physical evidence found within that TCU indicates that the pins were bent during impact.
- There is no evidence of an inflection point in the trace of roll angle near 45°, where the autopilot normally automatically disconnects, indicating that the autopilot did not or could not provide control inputs to counter the roll prior to disconnecting.
- There is evidence of a long delay between the roll onset and the first indication of control inputs to counter the roll, which allowed the roll angle to escalate significantly. There is similar evidence that the throttle position was not reduced from the climb power setting, which allowed the airplane to accelerate significantly.

1.2 Document Scope

This report provides analysis of factual data compiled during the investigation. This report focuses primarily on considering components designed and manufactured by Tamarack, as this is the company's particular expertise. This report also provides a Tamarack interpretation of the available flight data and the Performance Survey [2] compiled by NTSB, from the perspective of extensive company experience with flight testing of various upset conditions assessed during ATLAS certification.

1.3 ATLAS Overview

Tamarack Aerospace Group manufactures a modification for Cessna 525 airplanes, consisting of aluminum wing extensions, composite winglets, and a proprietary load alleviation system known as the Active Technology Load Alleviation System (ATLAS). ATLAS is an analog electromechanical system designed to measure vertical accelerations on the airplane and automatically deploy aerodynamic surfaces to counteract structural loads. The system consists of an ATLAS Control Unit (ACU) mounted near the center of the airplane, which provides command signals which deploy Tamarack Active Camber Surfaces (TACS) at the wingtip via extensions or retractions of linear actuators mounted in TACS Control Units (TCUs). The TCUs are linked to the TACS by conventional linkages. In the event of a fault, the ACU sends a signal to an Annunciator LRU, which illuminates LEDs within an ATLAS INOP Button located in the upper left portion of the pilot's side of the instrument panel. The button functions both as the primary indication of ATLAS fault conditions, and the primary means by which the pilot can reset faults. A view of the four main LRUs involved in the installation is presented in Figure 1-1.

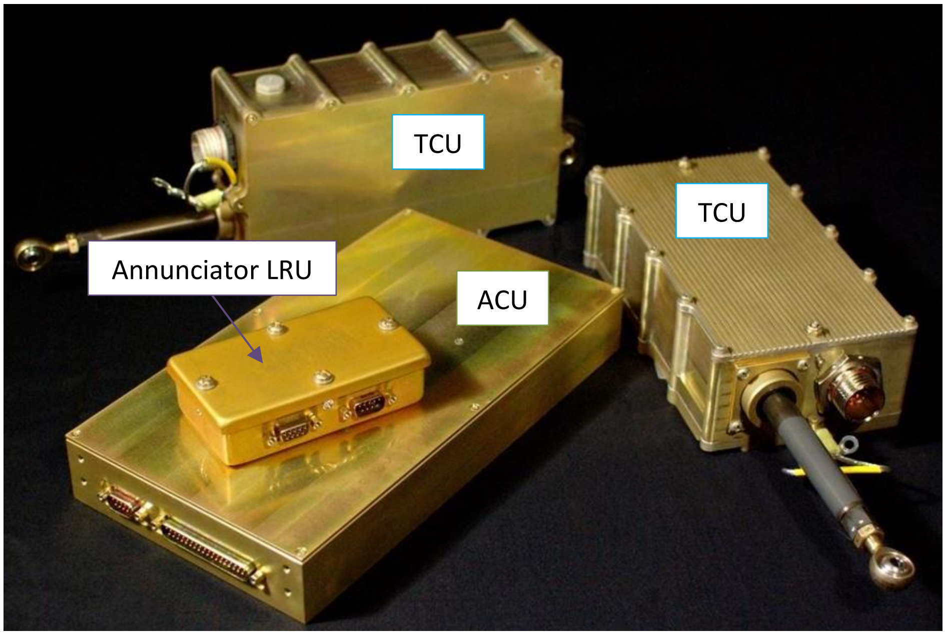


Figure 1-1 ATLAS LRU overview

An overview of the locations of LRUs in the airplane installation is presented in Figure 1-2.

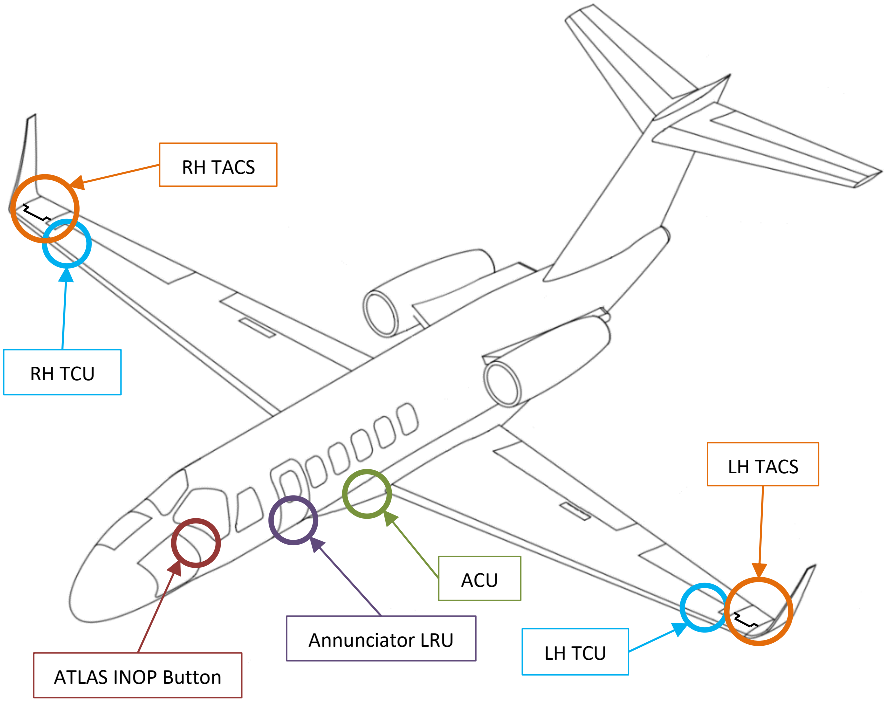


Figure 1-2 LRU locations in 525A installation

For additional reference, a cutaway image of the wing extension and TACS deployment linkages is provided in Figure 1-3.

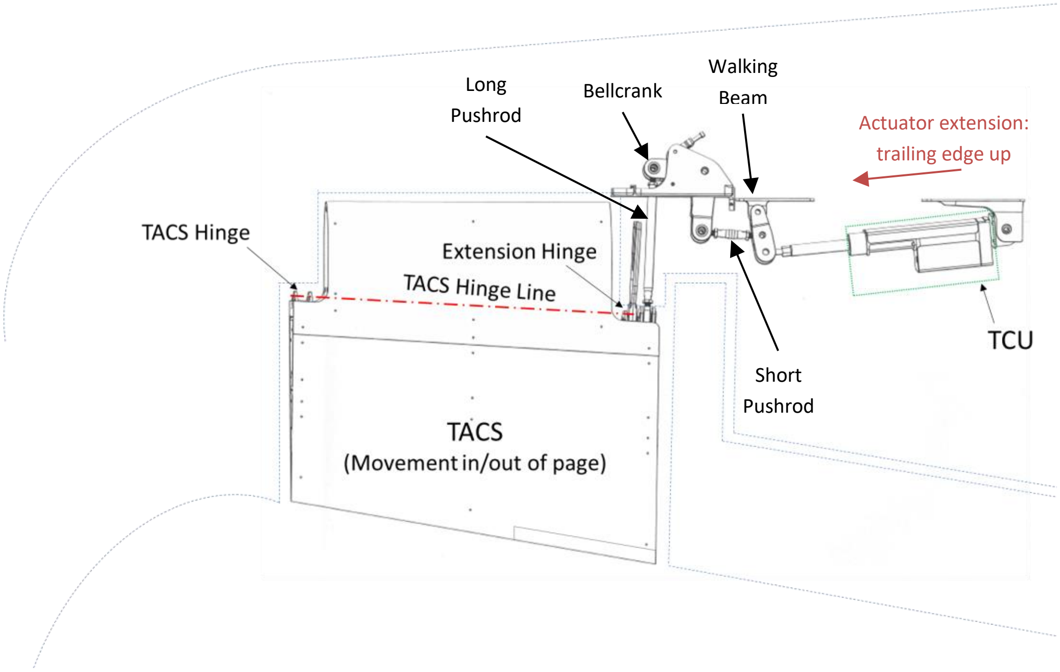


Figure 1-3 TACS deployment linkages detail

2 EXAMINATION OF RECOVERED ATLAS UNITS

The investigation included an examination of the ATLAS-related LRUs recovered from the wreckage. Tamarack personnel directly participated in this effort.

In October of 2019, all parties traveled to the AMF Aviation facility in Springfield, TN to search for components relevant to the investigation. The search focused mainly on data recording devices, flight control systems, autopilot and trim systems, and ATLAS related components. Some elements of data recording devices were discovered during the search, but were of limited value due to extensive damage to the units. Servos related to the autopilot system and trim system were also recovered from the wreckage. Examination of these components did not find any clear indications of malfunction, and damage to the autopilot servos prevented further test. This is consistent with the overall level of damage to the aircraft.

Several ATLAS LRUs were recovered from the collected wreckage, as well as fragments of wing, wing extension, and winglet structure associated with the Tamarack modification.

2.1 ATLAS Control Unit

The ACU was found in a severely damaged state, visible in Figure 2-1.

Figure 2-1 ACU as-found condition (external view left, internal view right)

The state of the ACU and the extent of the damage prevented further testing of the unit. The ACU does not have non-volatile memory. The type and extent of the damage is consistent with a severe impact event. The amount of post-impact damage prevents further meaningful investigation into the possibility of in-flight ACU failures. To date, Tamarack has not received any reports of in-flight ACU failures.

2.2 Right Wing TACS and TACS Control Unit

The right hand TCU was found with extensive external and internal damage, similar to the ACU.

A preliminary external examination of the RH TCU found that the actuator ram tube, which ordinarily connects to the TACS deployment linkages via a self-aligning bearing rod end, was broken off from the actuator. A mounting bracket normally installed on the aft end of the TCU box had been broken off as well. The TCU case was also breached, with leaves and other debris found inside the normally sealed box.

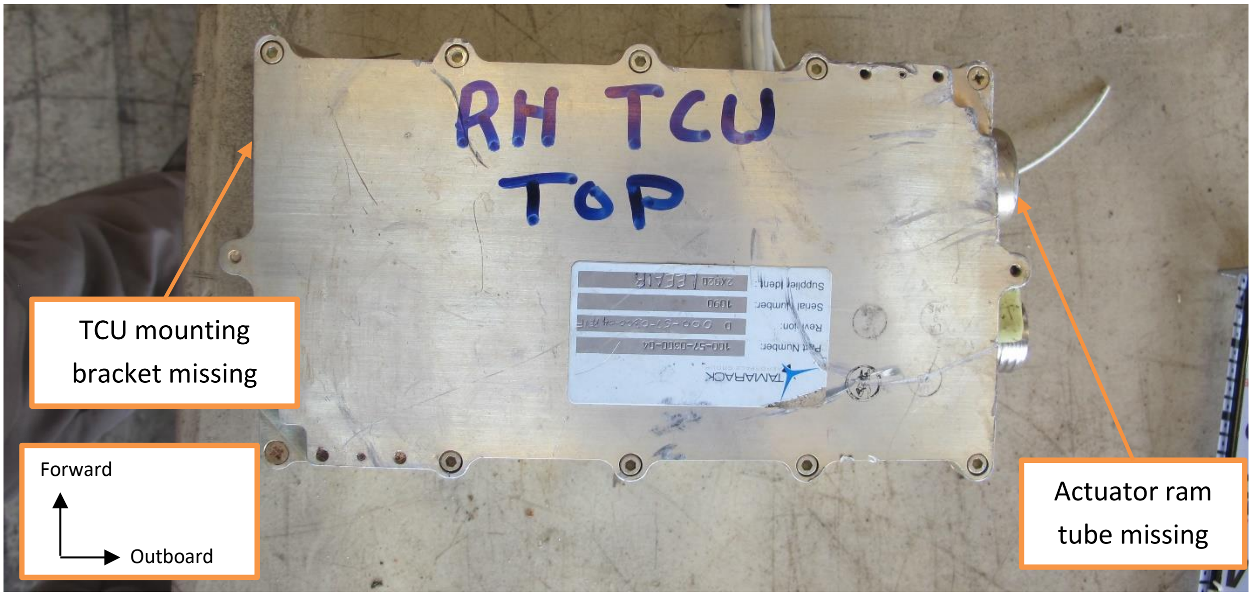


Figure 2-2 RH TCU as-found state (top-down view)

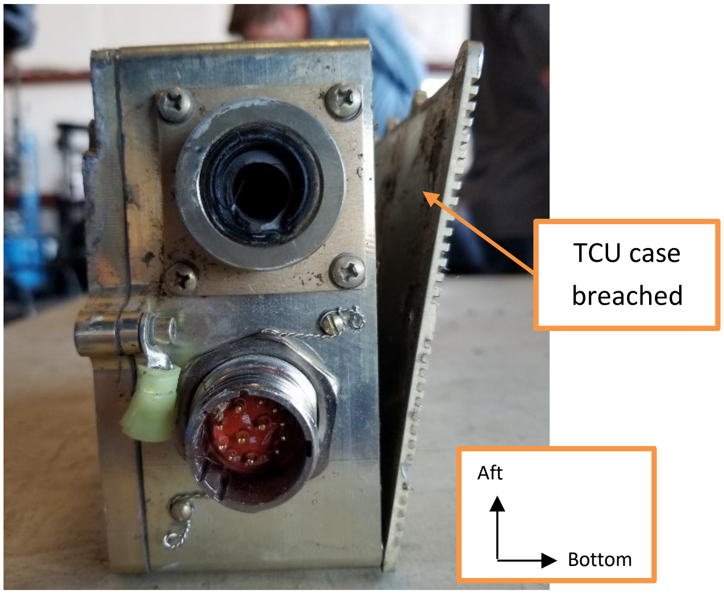


Figure 2-3 RH TCU as-found condition (looking inboard at connector and remnant of actuator ram tube)

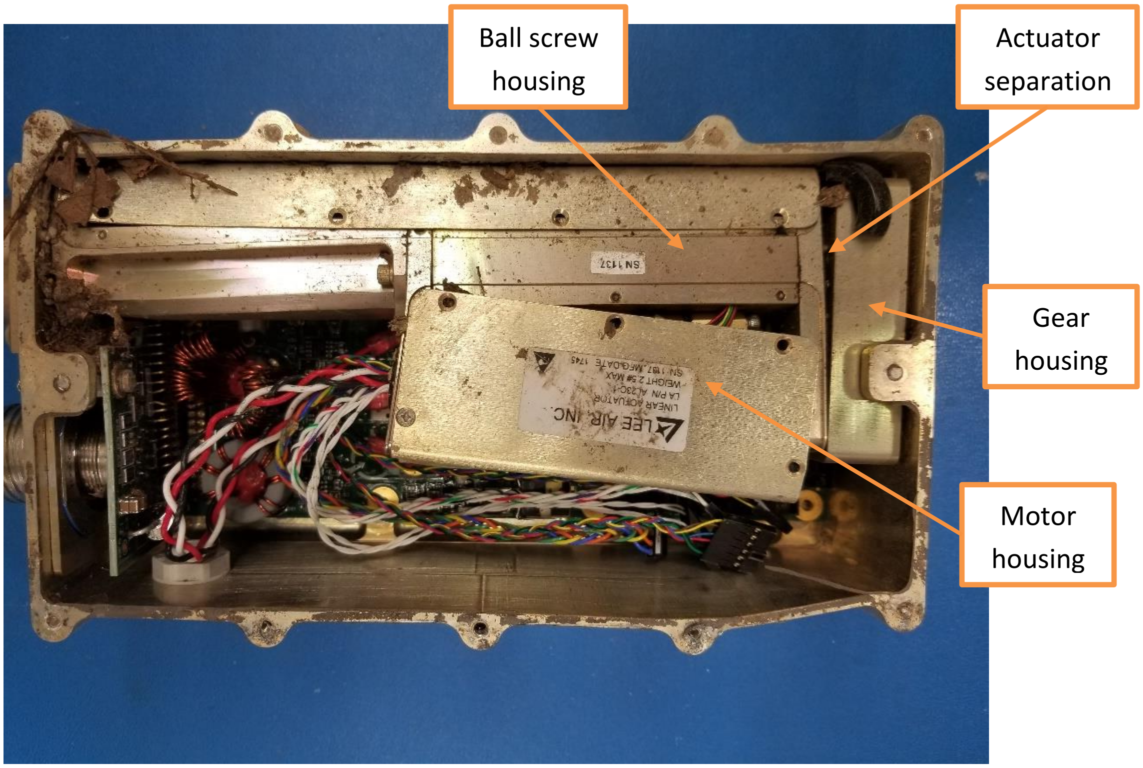


Figure 2-4 RH TCU as-found condition (internal view)

A preliminary internal examination of the RH TCU found that the actuator itself had failed structurally, visible in Figure 2-4 as a separation of the gear housing from the motor and ball screw housings. The gear housing is attached to the motor and ball screw housings by six screws, which were found failed on further inspection. The type of failure was consistent with a tensile overload of the screws. Tamarack notes that the actuator is not capable of developing the static force required to fail these screws in tension, and the separation is thus most likely due to the high energy impact.

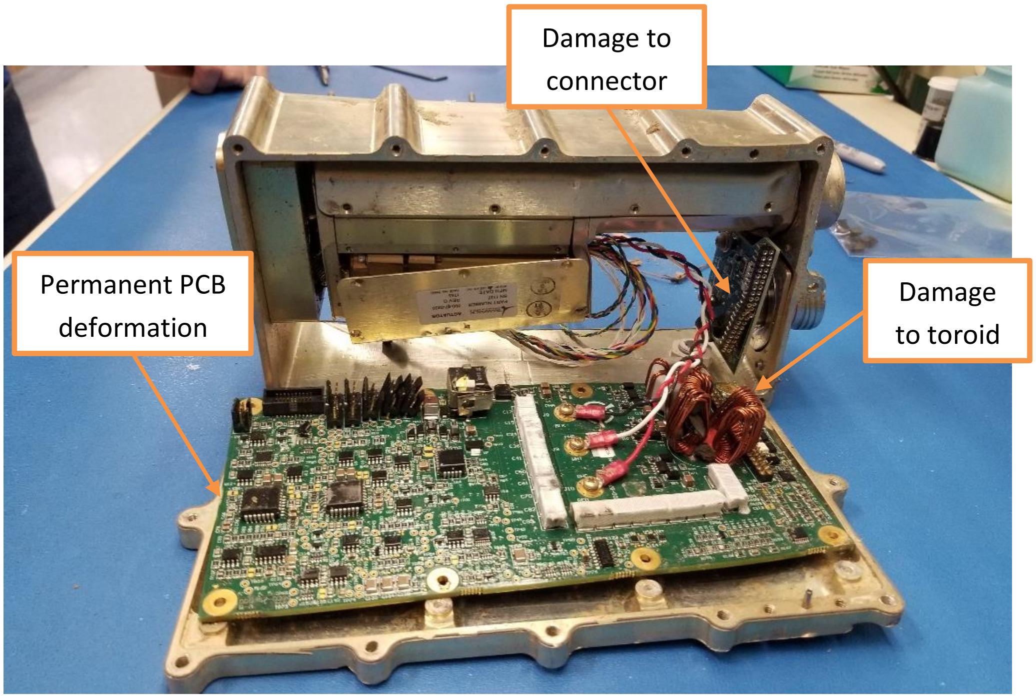


Figure 2-5 RH TCU as-found condition (PCB view)

Extensive damage to the TCU PCB assembly prevented any electrical testing.

A computerized tomography (CT) scan of the RH TCU was performed to determine the position of the ball screw within the actuator, as the actuator position could not be determined externally and the process of tearing the actuator down would likely require disturbing the ball screw. An image from the CT results is included in Figure 2-6.

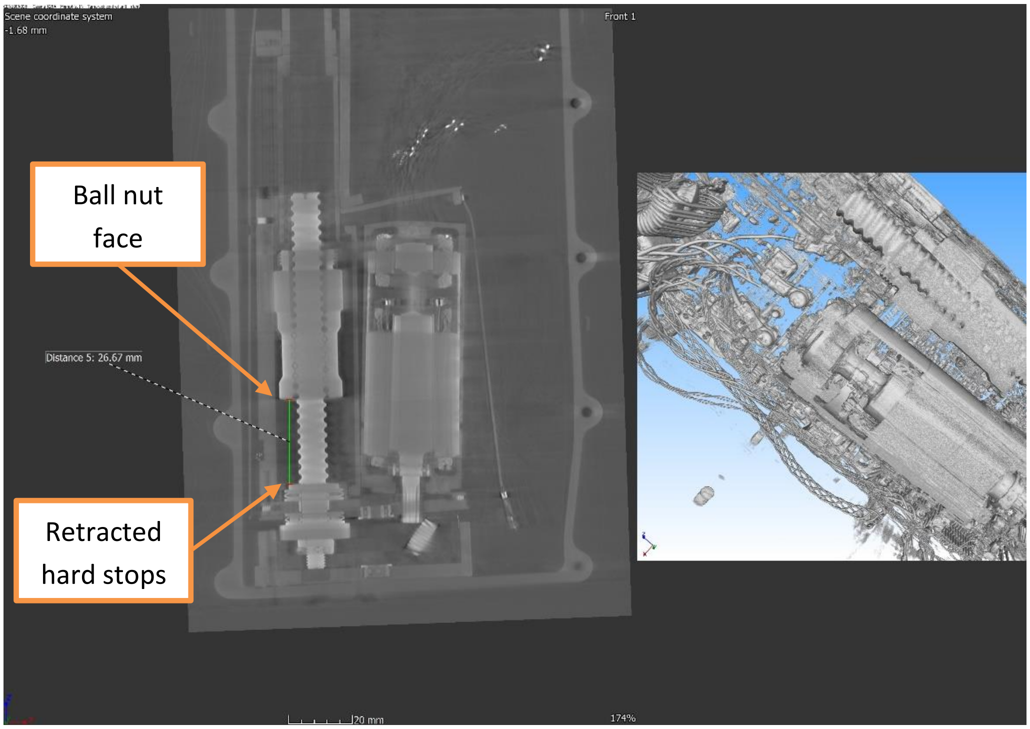


Figure 2-6 RH TCU CT scan results, showing as-found position of ball screw

The CT revealed that the distance from the retracted hard stop of the actuator to the ball screw face was approximately 26.7 mm (1.05 in). When the actuator is in its neutral position (*i.e.*, the TCU is not responding to any gust), the distance between these two faces would nominally be approximately 0.5 in. The distance would be slightly greater than 1.5 in if the actuator were fully extended.

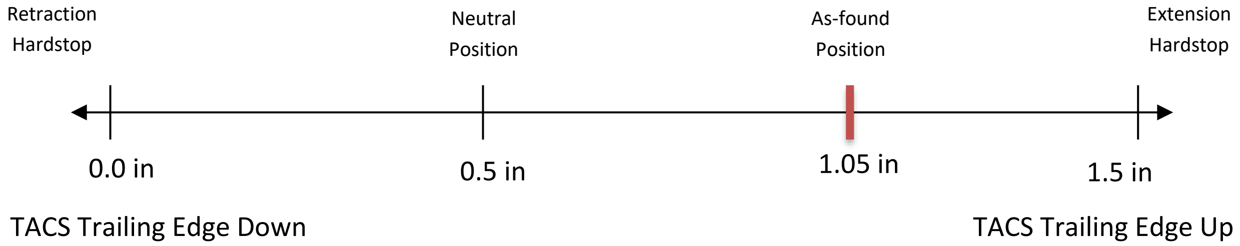


Figure 2-7 Distance from ball nut to retracted hard stop (nominal)

Further teardown of the actuator found witness marks on the upper and lower ball screw guides within the actuator, corresponding to the ball screw position recorded by the CT scan.

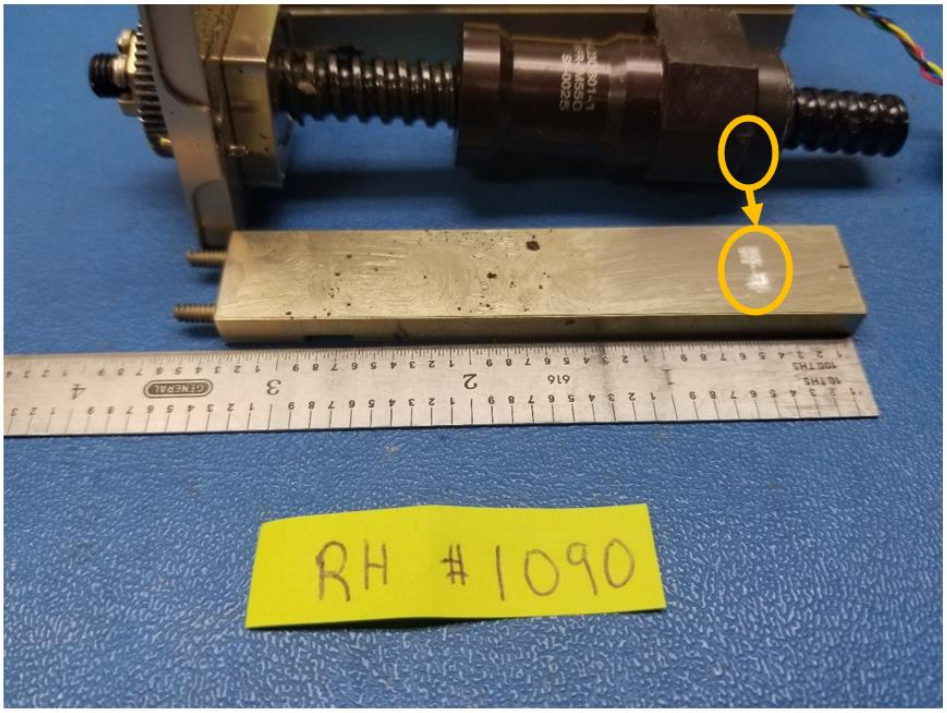


Figure 2-8 RH TCU actuator ball nut lower guide witness marks (excerpt from [3])

It is worth noting that the clearance between the ball nut lower guide and the ball nut is nominally 0.025in, and the travel of the ball nut along the axis of the ball screw does not allow the two components to come into contact. The witness marks observed in this TCU (and in the LH TCU as described later) have not been observed in any other actuator teardown by the manufacturer. Therefore, it is likely that these witness marks were caused by deflection of the ball nut under impact loads, rather than normal operation.

The as-found position of the ball nut after the actuator ram tube was sheared off and the witness marks on the lower ball nut guide strongly suggest that the actuator was in this position, deploying the TACS approximately 10° trailing edge up, at the time of impact. A deployment of this type would be expected during an attempted recovery from a dive, as the airplane would experience elevated positive load factor and thus would cause ATLAS to deploy TACS to alleviate resulting aerodynamic loads.

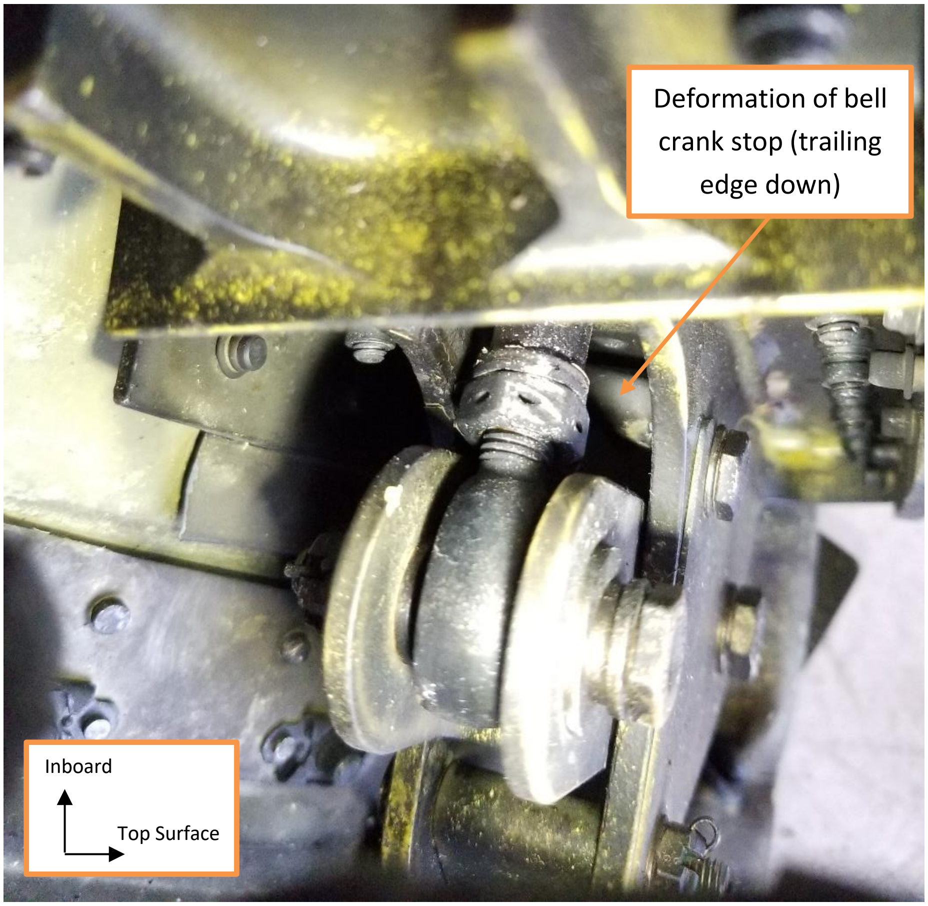


Figure 2-9 RH wing extension bell crank damage

Damage to the right wing extension, specifically the bell crank and the hinge bracket, presents a disparity between the witness marks within the actuator and witness marks on the hinge hardware. The bell crank bracket contains stops, to prevent overdeployment of the TACS. A simplified CAD view of the bell crank bracket assembly is presented in Figure 2-10 for context.

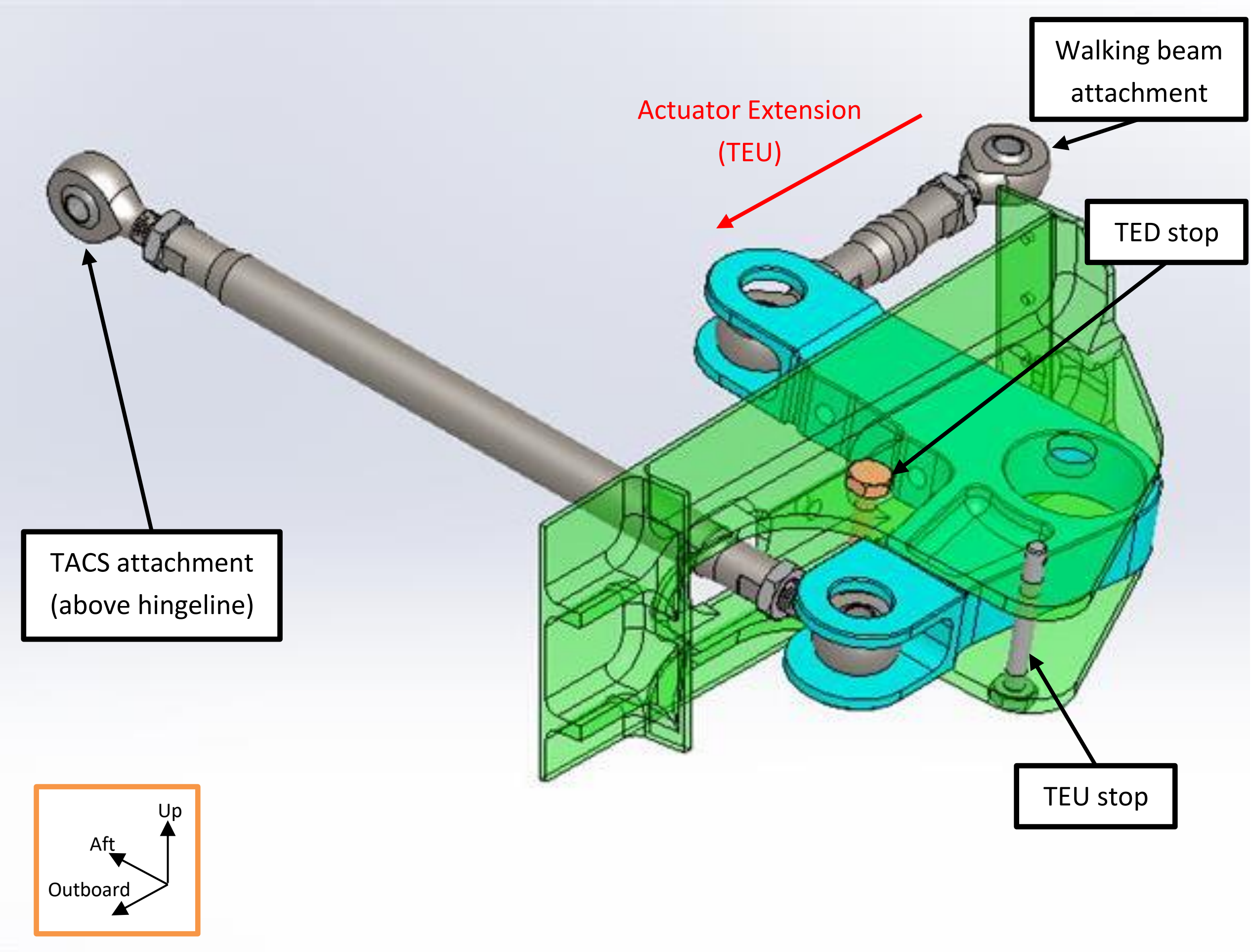


Figure 2-10 Bell crank assembly view (simplified, RH shown)

The stop corresponding to a trailing edge down deployment is a sleeved AN3-14A bolt installed through the bell crank bracket. The trailing edge down stop was severely deformed the as-found condition of the right wing extension. This does not match the position of the ball nut and the witness marks found within the actuator, which indicate an extended condition (corresponding to a trailing edge up deployment). The deformation of the trailing edge down bell crank stop most likely happened during impact after the actuator ram tube was separated from the TCU, as the actuator is not capable of producing the force required to deform this bolt to the extent it was found.

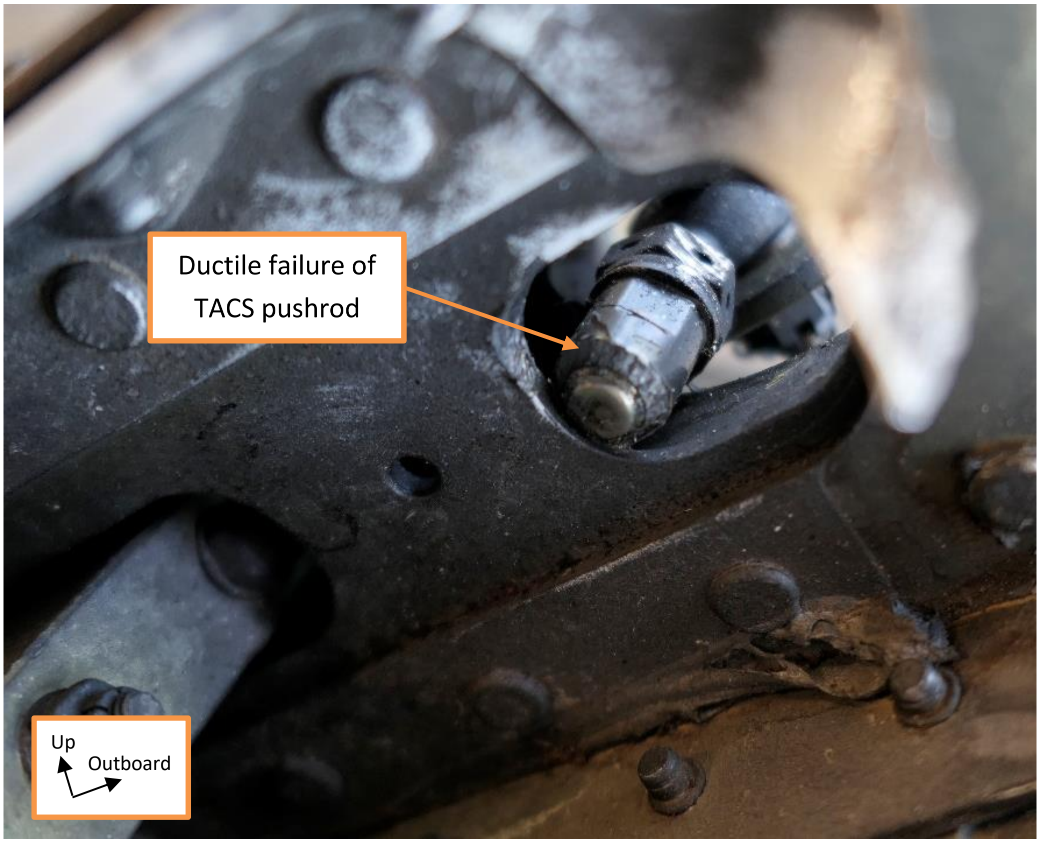


Figure 2-11 RH TACS pushrod damage

2.3 Left Wing TACS and TACS Control Unit

The left hand TCU was recovered installed in a mostly intact section of the outboard wing, and the external damage to the unit was less severe than that of the RH TCU, but was still significant. The wing section in which the LH TCU was mounted had sustained significant impact damage, specifically such that the TCU imprinted itself in the access panel below its installed position.

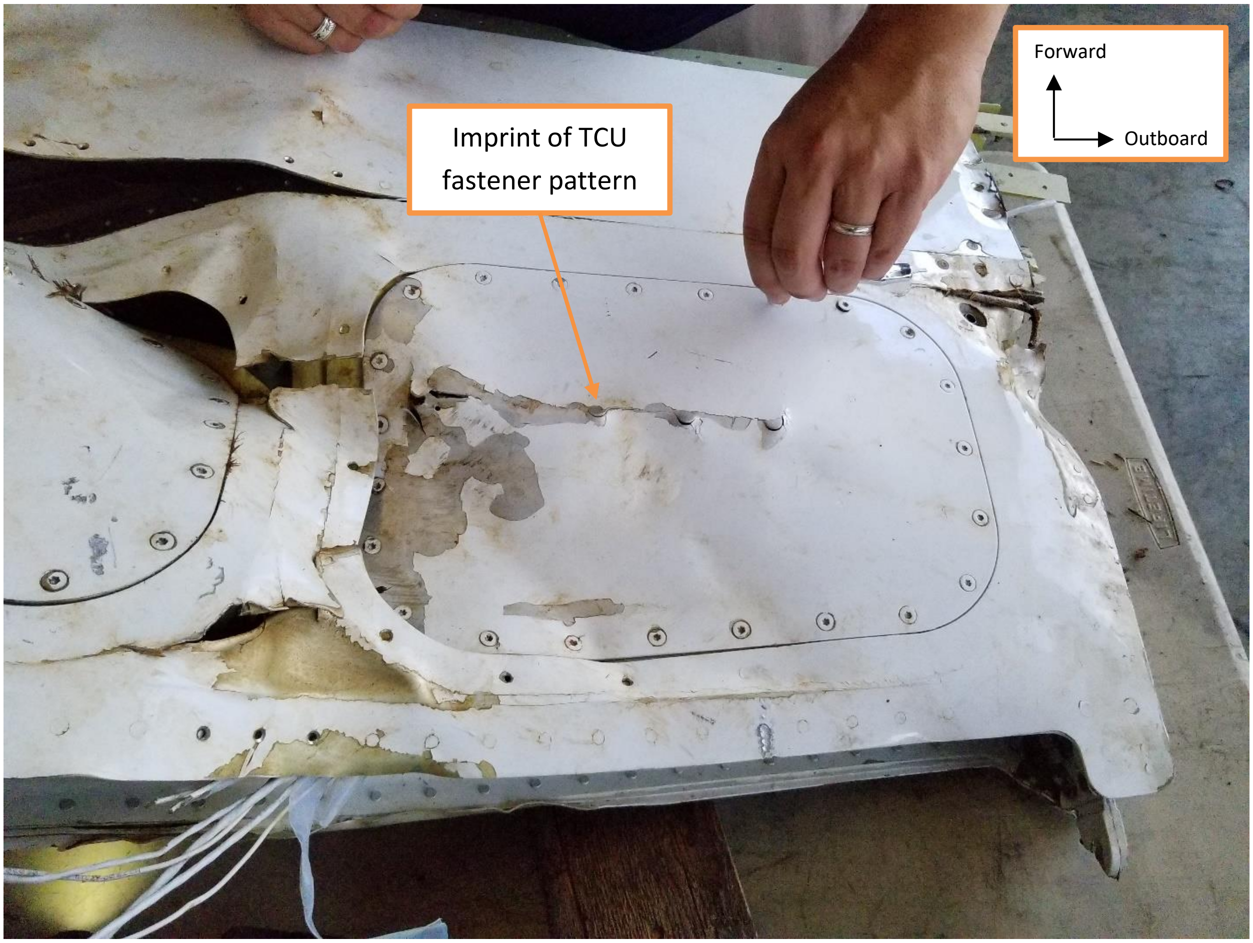


Figure 2-12 LH wing extension (lower surface shown) showing imprint of TCU

The LH TCU case was not breached, as the RH TCU was, and the ram tube was present in the actuator as found. However, the rod end was found rotated 90° from nominal with the safety wire still in place, suggesting the possibility of internal damage to the actuator. This is visible in Figure 2-13.

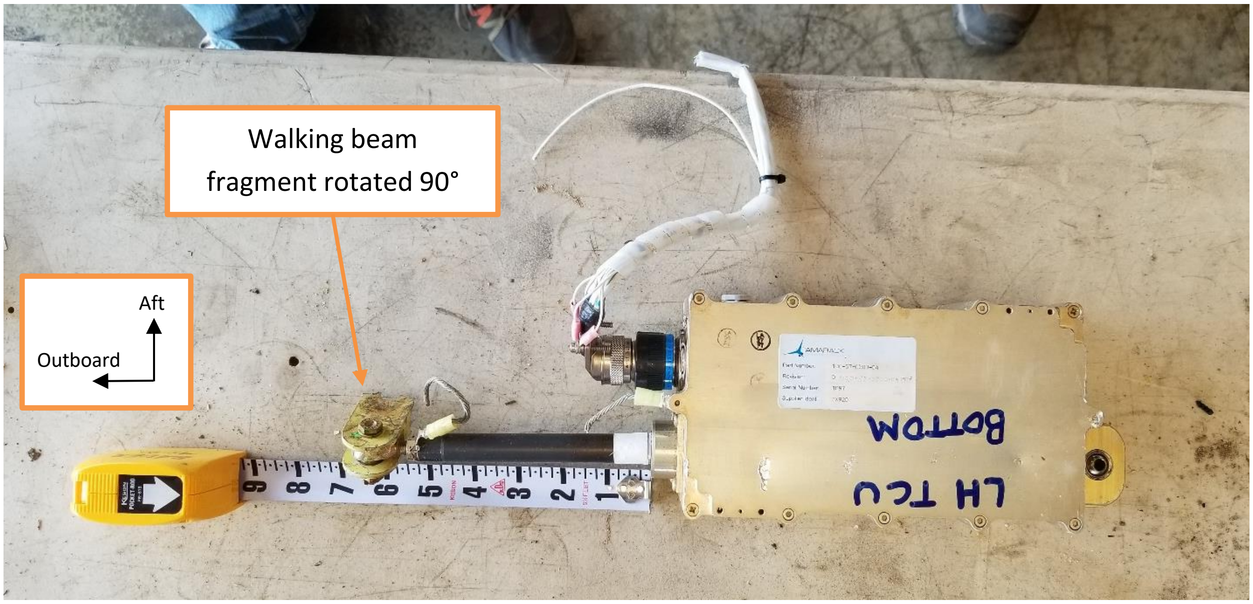


Figure 2-13 LH TCU as-found condition (external view)

CT scanning confirmed this, revealing broken screws between the motor and gear housing, similar to the type of damage found in the actuator of the RH TCU.

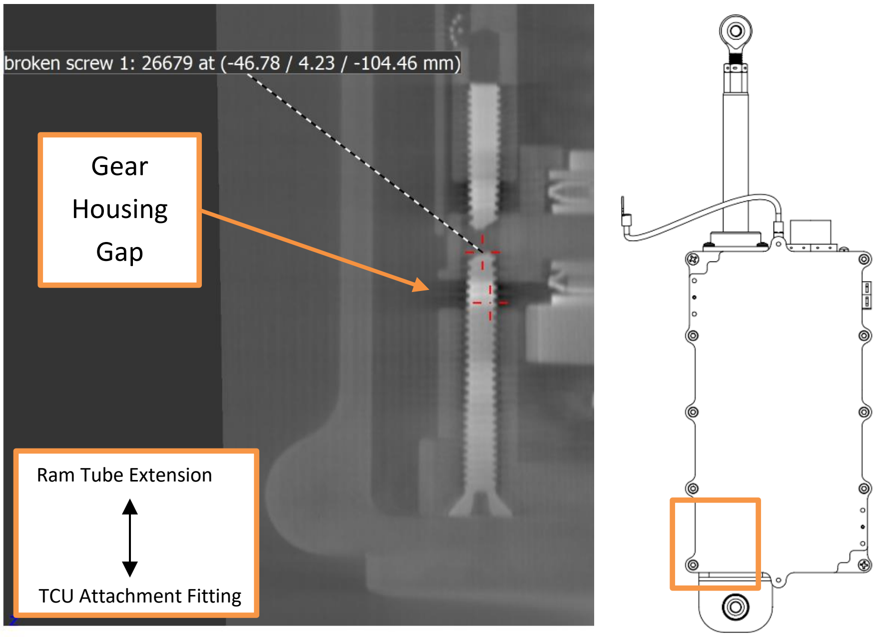


Figure 2-14 LH TCU actuator as-found condition showing broken screws (view from bottom)

Teardown of the actuator also revealed witness marks on the lower ball nut guide similar to those found in the RH TCU actuator. An image of these witness marks is provided below, excerpted from the Systems Group Chairman's Report [3]. Note that the colors only indicate that there are two sets of marks.

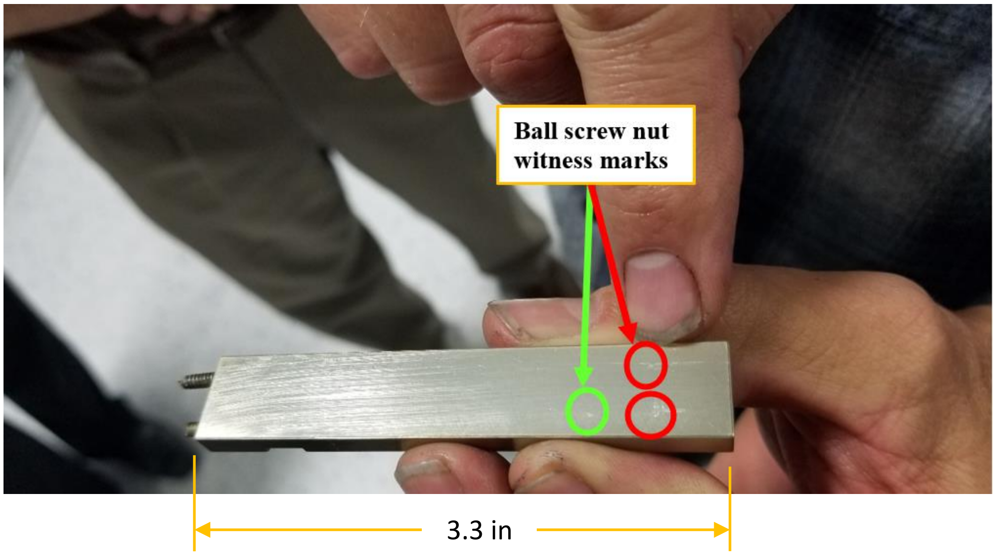


Figure 2-15 LH TCU actuator lower ball nut guide witness marks (excerpt from [3])

The left hand TACS inboard hinge bracket demonstrated evidence of overdeployment of the surface, trailing edge up. This was in the form of damage to a web in the bracket itself, most likely caused by contact with the TACS hinge itself. See Figure 2-16 for reference. The TACS pushrod rod end was found still installed on the TACS hinge, but the rod itself was sheared off approximately at the threads of the rod end.

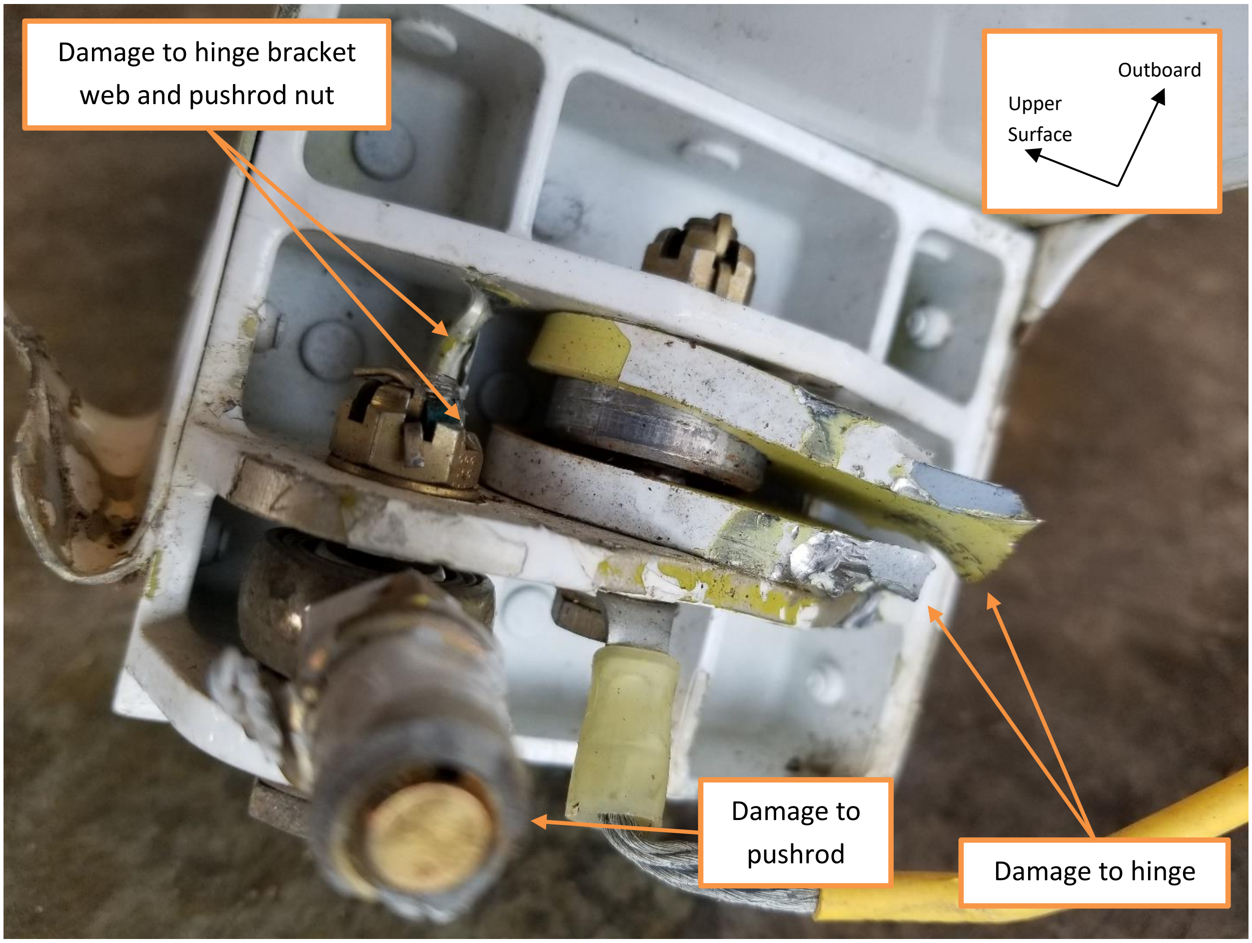


Figure 2-16 LH inboard TACS hinge bracket (view looking aft)

The TACS deployment angle required to cause this type of deformation is approximately 55°, more than twice the maximum angle permitted by either the hard stops internal to the actuator or the stops installed in the bell crank.

The pushrod exhibits the cup-and-cone shape consistent with ductile failure, without evidence of fatigue areas. A slight lateral deformation of the failure area indicates an eccentric tensile load, likely caused as the hinge failed and the TACS separated from the wing extension.

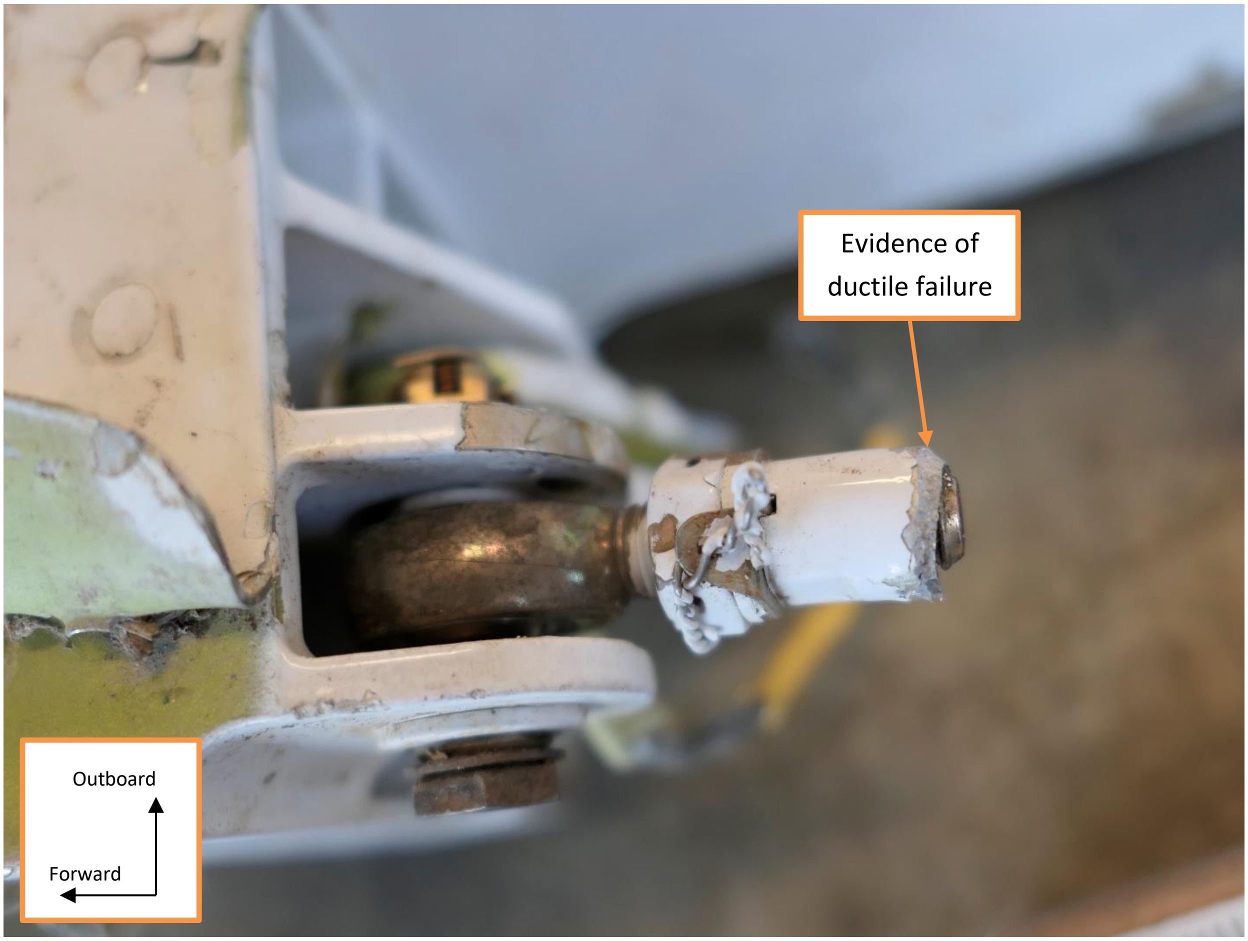


Figure 2-17 LH TACS pushrod failure

2.3.1 LH TCU Bent Pins

An inspection of the LH TCU PCBA found several key indications of damage. Most noticeably, six pins on a 40-pin connector between the main TCU control board and a smaller board providing an external connector interface were found bent and not seated as expected. Pins 29, 31, 33, 35, 37, and 39 were affected. The bent pins are visible in Figure 2-18, with the start and end range of the affected pins noted in the image.

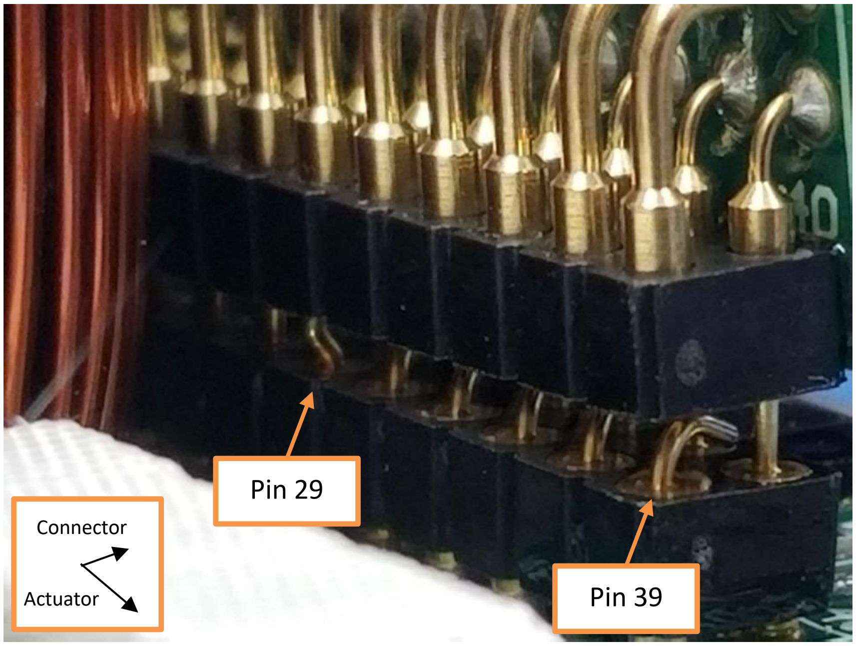


Figure 2-18 LH TCU bent connector pins

Initial electrical testing of the LH TCU found that pins 33 and 35 were open. Pin 33 connects to pin A of the external connector, carrying a discrete enable signal from the ACU. Pin 35 connects to pin D of the external connector, carrying the analog actuator command signal.

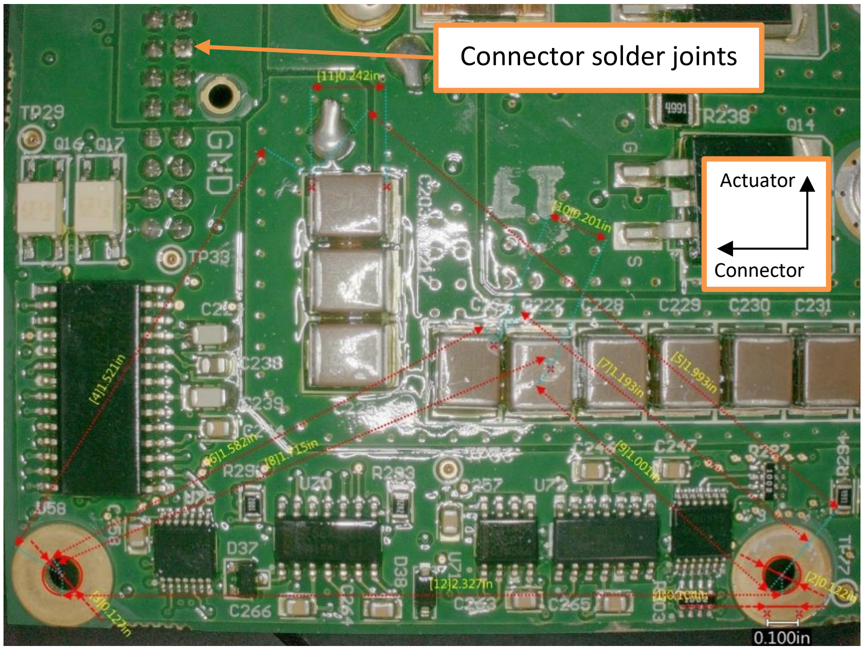


Figure 2-19 TCU control board lower surface view with key features annotated

There is evidence to suggest that the pins were bent by a substantial flexure of the PCBA during the impact event. The lower surface of the PCBA is populated in part with two rows of capacitors, visible in

Figure 2-19. Witness marks were discovered on the interior of the lower TCU housing, corresponding to the positions of the capacitors installed on the PCBA. These witness marks are visible in Figure 2-20.

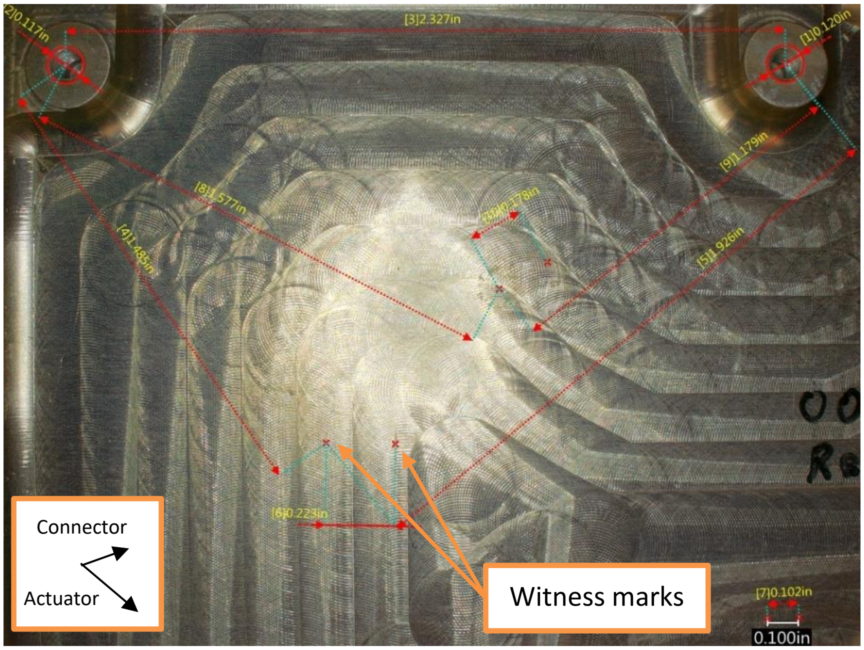


Figure 2-20 Witness marks below PCBA on TCU lower case

A detail view of one of the marks in Figure 2-21 shows that it is an impact mark caused by an object with a thin, rectangular cross section. The capacitor bank above the marks in the lower case is populated by capacitors assembled from two smaller capacitors, joined on each end by a small metal plate, which is soldered to the board's solder pads. The plate has a thin, rectangular cross section.

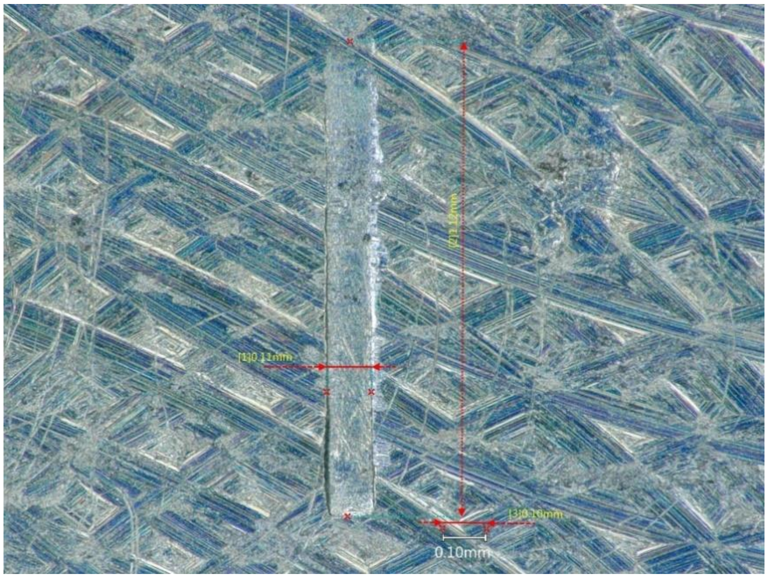


Figure 2-21 Detail view of witness mark on TCU lower case

It is likely that during the impact, extreme impact forces on the TCU caused the control PCBA to flex downward, contacting the interior face of the TCU housing below the PCBA and causing the witness marks described above. This partially disconnected the 40-pin connector between the control PCBA and the smaller connector PCBA. As the control PCBA returned to normal position, six of the pins failed to re-seat properly and were bent to the positions in which they were found.

Tamarack notes that the signals affected by the bent pins (enable and command voltage) are critical to the proper function and powerup of the TCU. This type of extensive damage to those pins, if it had been caused during manufacturing or handling, would most likely have been indicated by faulting or system unavailability on flights prior to the accident flight, especially since the LH TCU was found with fully open circuits on these two signals. Tamarack has no such reports of nuisance failures on this airplane prior to the accident.

2.4 Actuator Witness Marks

Tamarack concludes that the witness marks left on the upper and lower ram guides in the TCUs were caused by the large impulse force of the impact acting normally to the axis of the ball screw, causing the ball screw to deflect enough to allow the ball nut to contact the ram guides. Images of the two components are presented below in Figure 2-22 for comparison.

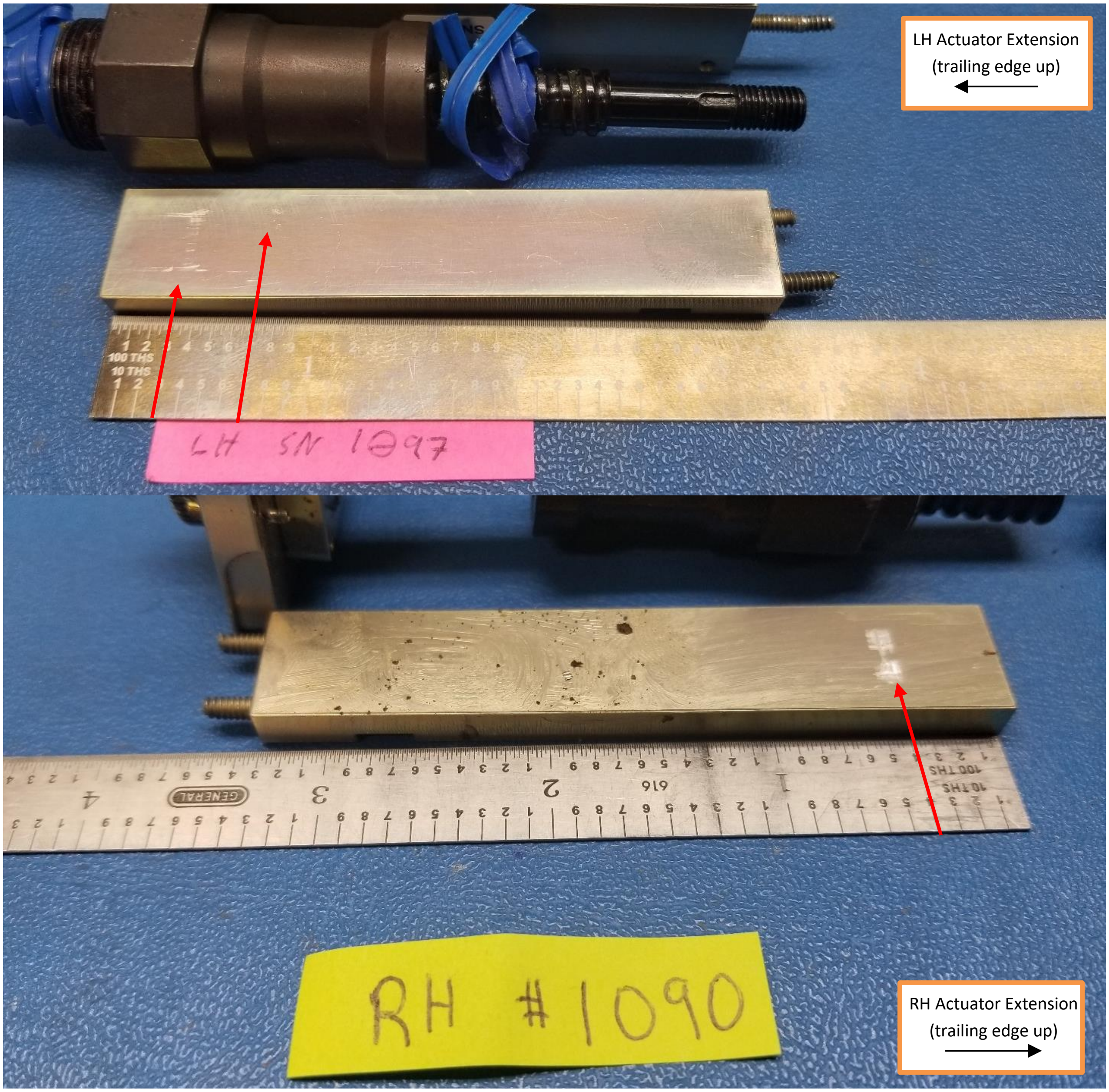


Figure 2-22 LH and RH actuator witness marks comparison

The overall length of the ball screw guide section is 3.35 in. The retraction hard stop extends into the ball nut guide 0.20 in, and the extension hard stop provides an additional 0.15. The distance between hard stops is 3.30 in. The length of the ball screw is approximately 1.8 in. This leaves approximately 1.5 in of ball nut travel. In normal operation, the actuator allows approximately 1.0 in of extension and approximately 0.5 in of retraction.

The left hand actuator has two sets of witness marks. One set is very faint and appears approximately 0.7 in from the extension end of the ball nut guide, or 0.85 in from the extension hard stop. The other set is more pronounced and appears at approximately 0.3 in from the extension end of the ball nut guide, or 0.45 in from the extended hard stop. Apparent scratches extend from the witness marks to the extension end of the ball nut guide. Scratches from the more extended marks to the end are more visible than scratches between the two sets of marks. The ball nut flat feature is approximately 0.5 in long. It is possible that the two sets of marks represent both corners of the ball nut flat feature contacting the lower ball nut guide.

The right hand actuator witness marks appear at approximately 0.40 in from the extension end of the lower ball nut guide, or approximately 0.55 in from the extension hard stop, close to halfway between the nominal neutral position and the full physical extension of the actuator. The RH actuator does not exhibit the same scratch marks that the LH actuator does.

The witness marks in the actuators are important to understanding the most likely state of the system at the moment of impact. The short time scale of the impact event makes is likely that the witness marks were left by the actuator ball nuts in or near the positions they were in at the time of impact. The LH TCU shows evidence of the ball nut dragging for a short distance along the lower ram guide. This is consistent with evidence that the TACS trailing edge was displaced upward on the left wing, as the scratch marks appear to be moving in the direction of an actuator extension. Note that the presence of scratch marks in the LH TCU suggests that there would be evidence if the ball nut position had changed dramatically during the impact. The length of the markings indicates that the ball nut was positioned consistently with an approximately half-scale extension of the actuator.

A TACS deployment schedule relating the nominal TACS deployments to actuator positions and load factors for ATLAS as installed on the 525A is presented in Figure 2-23 for reference.

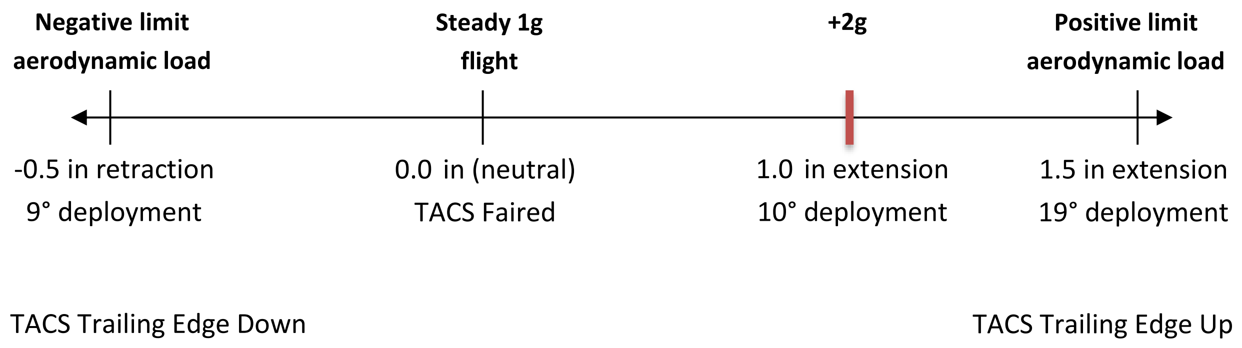


Figure 2-23 525A simplified TACS deployment schedule

A ball nut position of 0.45 in from the extended hard stop on the LH actuator corresponds with approximately a 0.55 in extension from the TACS faired position. Similarly, the RH actuator position of 0.55 in from the extended hard stop corresponds to an approximate extension of 0.45 in from the TACS faired position. These positions nominally correspond to TACS deployments of 9° (LH) and 10° (RH). This is within tolerance for symmetry of TACS deployments, especially considering the extreme aerodynamic and impact loads applied to the TACS just prior to and during the impact event and tolerances to account for measurements of severely damaged units. In terms of load factor, the LH and RH TACS positions would indicate a response to a load factor of approximately 2g in normal operation.

2.5 Maintenance Considerations

The TCUs installed on the airplane at the time of the accident were installed on July 12, 2018, at an airframe total time of 3,113.8 hours. The TCUs had been removed for compliance with a service bulletin at the unit manufacturer's facility, and were returned to the airplane for reinstallation. The last maintenance on the airplane occurred on November 20, 2018, at an airframe total time of 3,296.7 hours. Tamarack received no reports of faults or failures in the 182.9 hours of flight between the last maintenance on the unit and maintenance performed shortly before the accident on November 20. Tamarack was consulted for guidance on minor cosmetic repairs to the winglet paint during the November 20 maintenance, but does not have information on what other maintenance was performed at the time.

3 PERFORMANCE ANALYSIS

3.1 Roll Event

Tamarack has examined the Performance Study [2] prepared by Marie Moler in support of this investigation. Of particular interest is the time history of speed, altitude, and roll data (Figure 2 in the report) presented on p. 3 of that report. In this time history, the roll angle of the airplane is presented as a purple line, with the corresponding calculated roll rate presented as an orange line. An excerpt from the performance study is presented below.

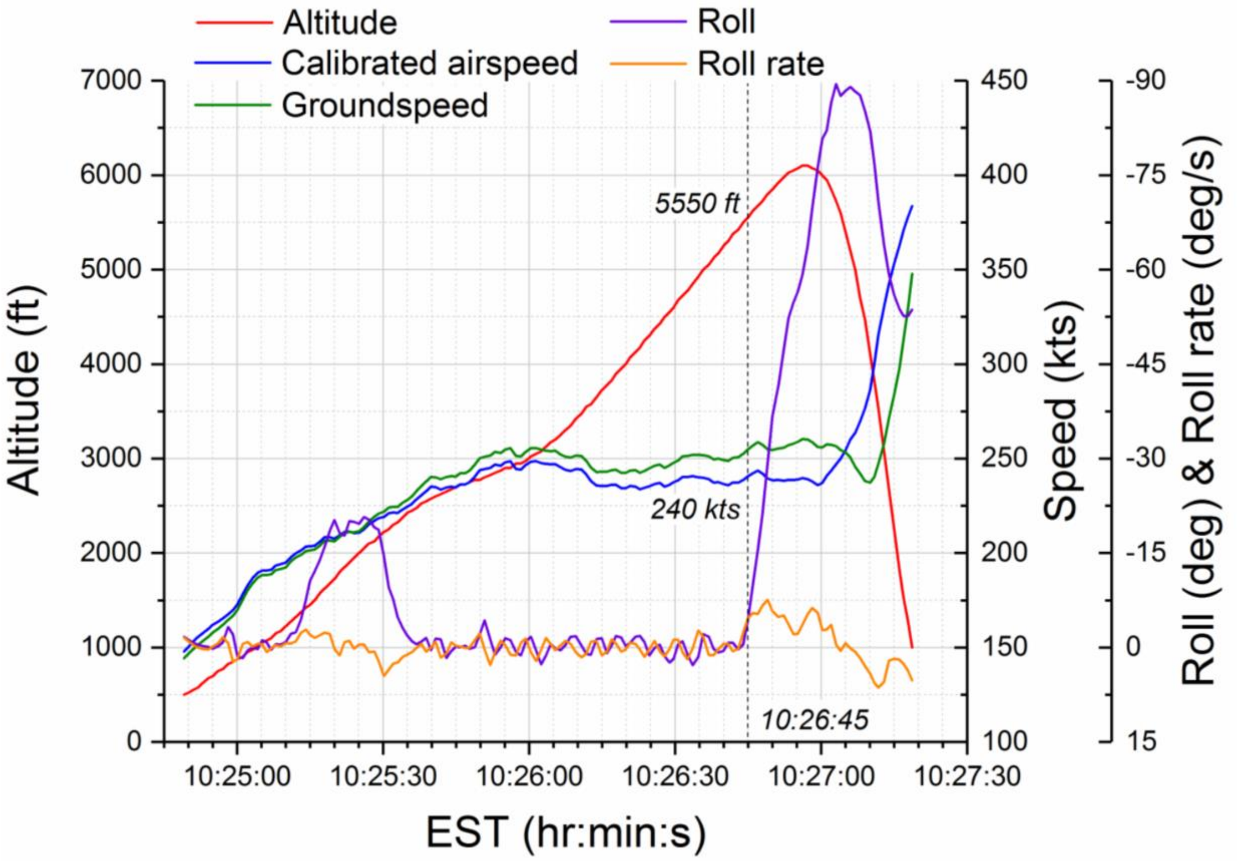


Figure 3-1 Flight condition time history (excerpt from Performance Study)

After the onset of roll at approximately 10:26:45, the rate of roll fluctuates, appearing to average approximately 5 degree/second for approximately fifteen seconds, with a brief dip approximately ten seconds after the onset of the roll.

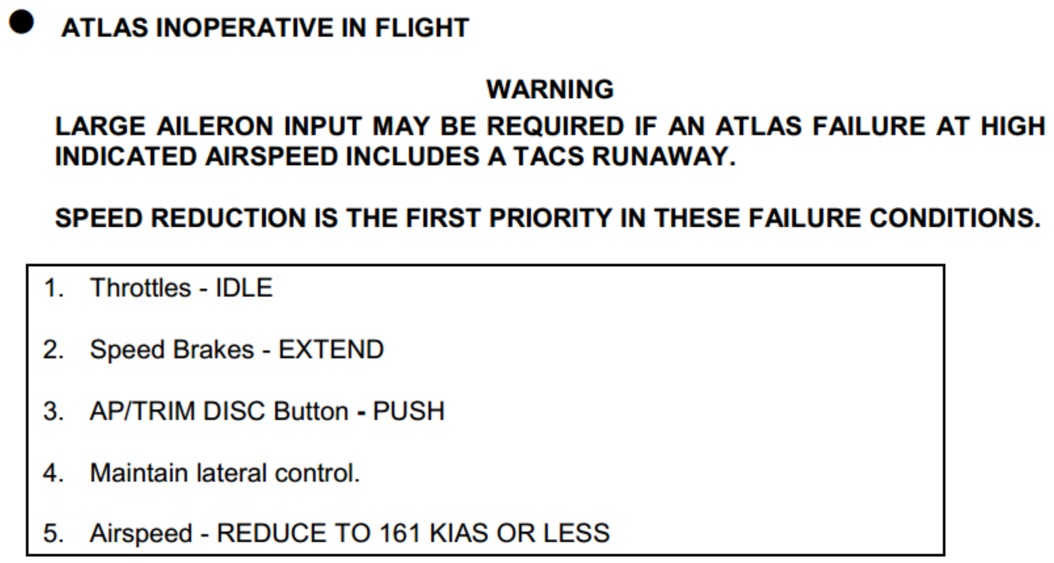
3.2 Comparison to Flight Test

Certification flight testing conducted with EASA flight test personnel involved extensive tests of forced asymmetric TACS deployments. The intent of this testing was to fully characterize and understand the airplane response to a variety of combinations of asymmetric TACS deployments in support of Tamarack's system safety analysis work. All failure conditions were found during certification to be controllable and recoverable by a pilot of average skill and strength. These flight tests used a pilot recognition time of three seconds, based on section 14.2.1.3 of an Acceptable Means of Compliance (AMC) for EASA CS 25.1329 [4]. This AMC typically applies to larger Part 25 Transport category airplanes (the 525 is a Normal category airplane, certified under Part 23), but was approved as a means of compliance for a special condition formalized for the 525 certification (and carried through the subsequent 525B and 525A certification) in EASA CRI D-103 [5].

The initial conditions used for flight tests of asymmetric TACS deployments varied depending on specific phase of flight. Tests simulating the cruise phase of flight assumed an initial airspeed of 240 KIAS, at a thrust setting as required to maintain this high airspeed, with autopilot active and the pilot's hands not directly on the flight controls. In these regards, the flight test initial conditions are similar to the flight conditions which existed prior to the roll onset in this case. Notably, however, flight testing also included more critical conditions in which an asymmetric deployment was suddenly introduced when the test airplane was already established in a 30° banked turn with the maximum allowable fuel imbalance. There is no evidence that a significant fuel imbalance existed in this case, and the data indicates that the airplane was not established in a turn at the onset of the roll upset.

During EASA-conducted flight test, several flight conditions involving an asymmetric deployment of a single TACS produced an initial roll rate of approximately 3 degrees per second. In some asymmetric deployment test conditions starting from an established 30° banked turn, the airplane did not reach a maximum bank angle greater than 45° before the test pilot initiated recovery procedures, even including a three second delay per the AMC. In these cases, the autopilot did not automatically disconnect, and the test pilot manually disconnected the autopilot as part of the recovery procedure. The critical dual asymmetric condition, in which both TACS were fully deployed in opposite directions, resulted in roll rate of slightly more than 20 degrees per second.

EASA-conducted flight tests were used to develop the ATLAS fault emergency procedures, the first five steps of which are presented in Figure 3-2.



● **ATLAS INOPERATIVE IN FLIGHT**

WARNING

LARGE AILERON INPUT MAY BE REQUIRED IF AN ATLAS FAILURE AT HIGH INDICATED AIRSPEED INCLUDES A TACS RUNAWAY.

SPEED REDUCTION IS THE FIRST PRIORITY IN THESE FAILURE CONDITIONS.

1. Throttles - IDLE
2. Speed Brakes - EXTEND
3. AP/TRIM DISC Button - PUSH
4. Maintain lateral control.
5. Airspeed - REDUCE TO 161 KIAS OR LESS

Figure 3-2 First five steps, ATLAS Inoperative In Flight procedures, excerpt from CAS/AFM0003 rev A(R1)

The excerpt above is from CAS/AFM0003, revision A(R1), the revision which was in effect at the time of the accident. The box around the first five steps of the procedure indicates that these are memory items; response procedures intended to be executed from memory without requiring reference to the checklist.

Tamarack notes that the ATLAS Inoperative In Flight procedures were developed to address the full range of fault and failure conditions considered during the system safety analysis in certification, including faults classified as extremely improbable which would result in asymmetric deployment. The procedures were developed partly to resemble the guidance in the FAA Airplane Flying Handbook [6] for responding to nose low unusual attitudes. The general response to a spiral dive as presented in the AFH consists of five steps:

1. Reduce Power (Throttle) to Idle
2. Apply Some Forward Elevator
3. Roll Wings Level
4. Gently Raise the Nose to Level Flight
5. Increase Power to Climb Power

Throttle reduction is key to responding to nose-low upsets to avoid accelerating beyond airspeed limitations. This is true both of the failure conditions which Tamarack directly tested during certification, and of nose-low attitudes in general. Tamarack again notes that all combinations of TACS asymmetric deployments were found to be recoverable with average piloting skill and strength during EASA-conducted certification flight tests, particularly when throttle reduction was prioritized.

3.3 Response to Roll Event

Tamarack notes two important contributing factors evident in the data which directly affected the flight condition of the airplane: the amount of time between the onset of the roll event, and the likely throttle position during recovery. A time history of the airplane performance data collected in the Performance Study [2] is presented in Figure 3-3 for reference.

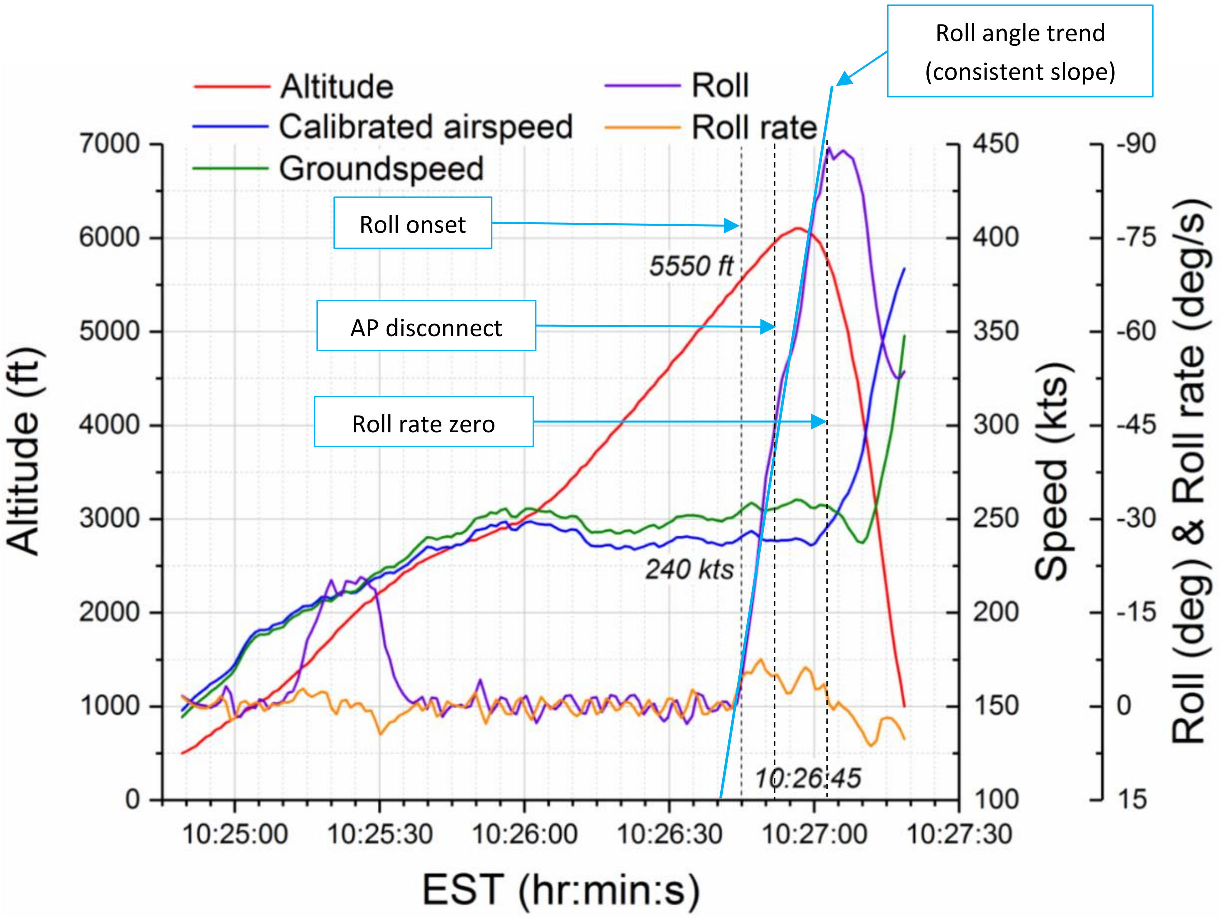


Figure 3-3 Annotated performance survey excerpt

The onset of the roll event occurred just before 10:26:45, indicated in Figure 3-3. The roll onset is easily identified by the start of a steady increase in roll angle. Based on the performance survey, it is apparent that the roll angle increased for approximately twenty seconds, until approximately 10:27:04. At this point, the bank angle stabilized for 3-5 seconds before starting to reverse.

Of particular importance in the figure above is the trend of roll angle. Specifically, note the lack of clear inflection point in the trend of roll angle vs. time. EASA certification flight testing found that when the TACS were forced to any asymmetric deployment during flight testing, the autopilot did not immediately disconnect, and would attempt to compensate for the roll rate caused by the forced TACS asymmetry. If the roll was allowed to continue past 45°, the autopilot would automatically disconnect (per normal operation), and the sudden removal of lateral control inputs from the autopilot would cause the roll rate to increase. In this performance survey, the roll rate does not appear to distinctly change as the airplane passes the 45° roll angle. Thus, there is no evidence of any control inputs by the autopilot to counter a roll upset. There is also no evidence of pilot intervention at the point of autopilot disconnection, in the form of discontinuities in any data trace, which would indicate sudden reassertion of human control.

Over the same timeframe (10:26:45-10:27:04), the airplane continued to climb for 10-12 seconds before the altitude peaked and the airplane began to descend. As the airplane began descending, the airspeed rapidly increased and continued to increase until the data ended. The final recorded airspeed was 380 KCAS. For reference, the VD used during ATLAS certification was 310 KCAS (selected in accordance with 14 CFR 23.335, amendment 23-48). During flutter and high speed flight characteristics testing, Tamarack flew instrumented 525 and 525B flight test airplanes to this speed under experimental flight test plans. To achieve this speed in flight test required the throttles to be set at the maximum continuous thrust setting and for the airplane to be in a significant nose-down attitude. These factors indicate that, for the time between 10:26:45 and 10:27:04, the pilot did not or could not provide control inputs to the airplane, including throttle reduction.

After 10:27:04, approximately 19 seconds after the roll onset, the roll angle stabilized at approximately 90 degrees. 3-5 seconds after that, the roll angle began to reduce. This may indicate the beginning of pilot response to the roll event. Importantly, the airspeed continued to increase as the roll angle began to decrease. Based on flight test experience, this level of airspeed increase suggests that the thrust setting was not reduced at any time after the initial onset of the roll.

A supplemental Tamarack analysis of the time history of altitude and vertical speed recovered from the ADS-B data indicates that an attempt to raise the nose of the airplane was initiated just before 10:27:13, nearly 30 seconds after the roll onset. At 10:27:13, the trend of the vertical speed reverses, reaching a peak descent rate of 24,000 fpm. The rate of descent was reduced to approximately 14,000 fpm in the final seconds before impact. A section of the altitude and vertical speed data is presented in Figure 3-4.

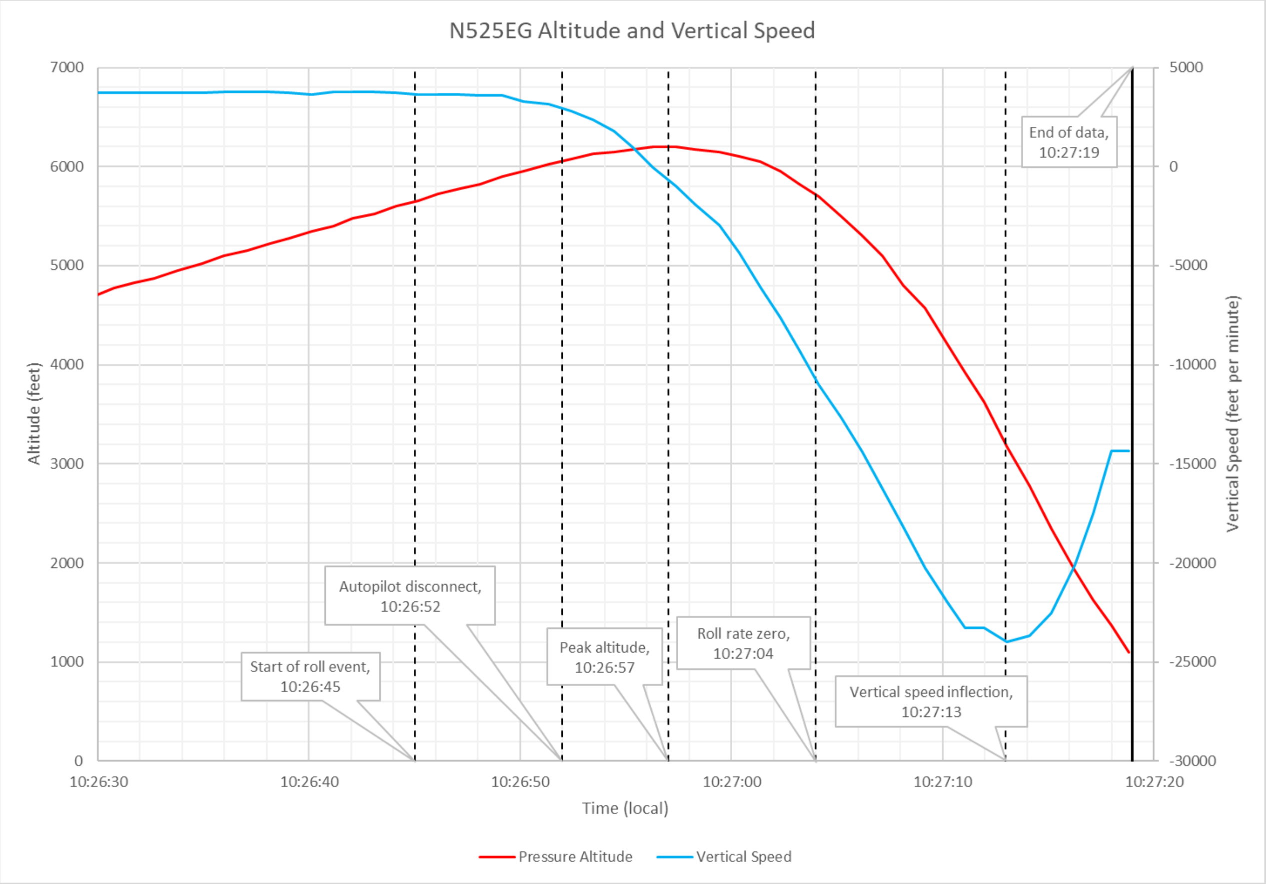


Figure 3-4 Altitude and vertical speed time history, detail view

A flight condition of this type is generally an elevated load factor maneuver due to the elevated aerodynamic forces required to cause a significant rate of change of heading and change in vertical speed. An email exchange with Marie Moler [7] subsequent to the initial release of the Performance Survey provided additional clarification on the calculated load factor underlying the NTSB analysis of the event.

This data is provided in Figure 3-5, described as “NLF” and presented as the orange trace in the middle chart.

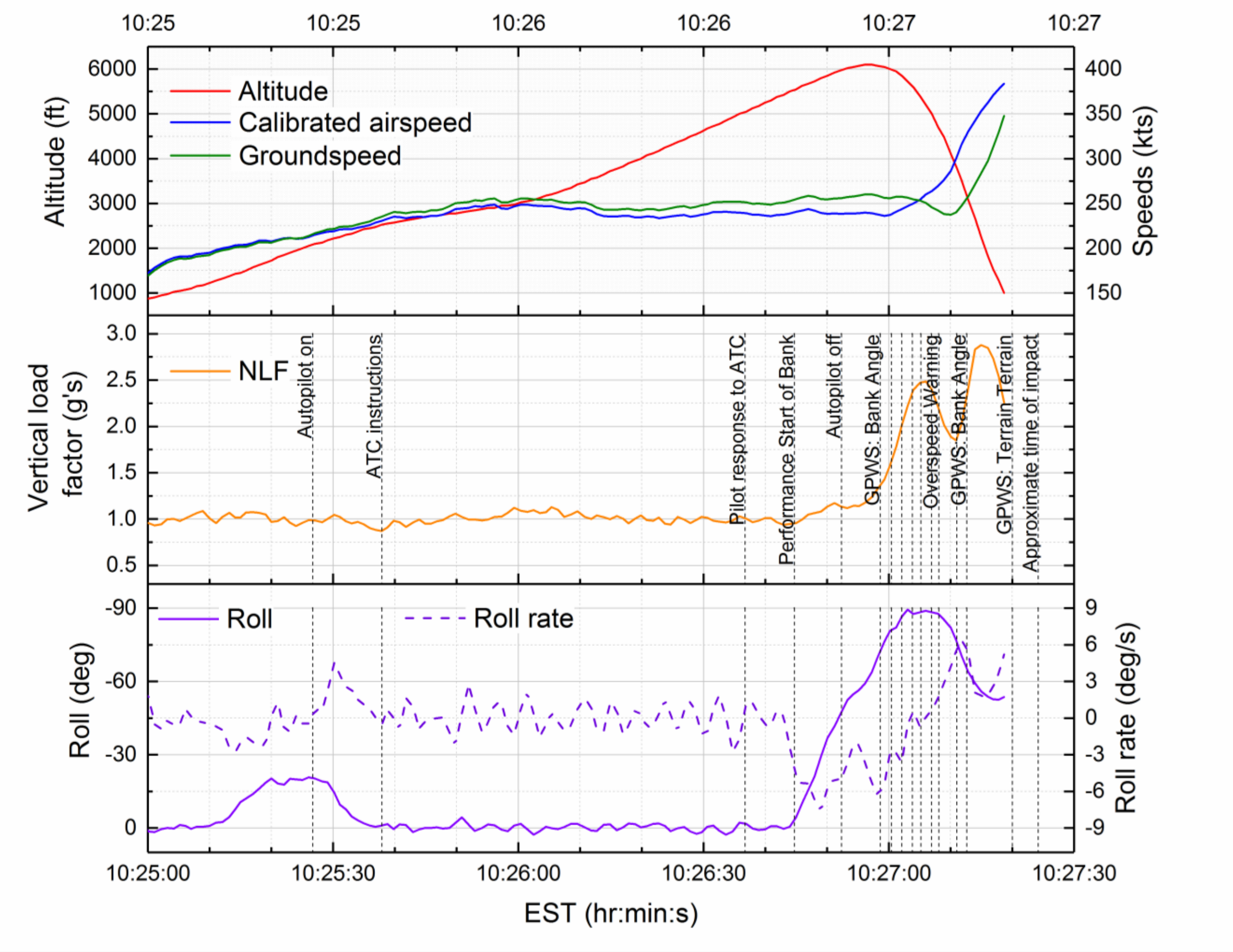


Figure 3-5 Comprehensive view of NTSB performance survey data

It is important to note that this data is based on ADS-B data, taken at one second intervals. Therefore, transient load factors acting on the airplane on very short timeframes would not be calculable. The trend of load factor indicates a peak at approximately 3g at a timestamp of 10:27:13, corresponding to the minimum vertical speed. This is expected, as this is the point at which the largest forces would be acting on the airplane to reverse the rate of change of vertical speed while still at a large bank angle.

At timestamp 10:27:19, the last available data point, the calculated load factor is approximately 2g. Tamarack notes that this is consistent with the load factor expected by the position of the witness marks on the lower ball nut guides within both actuators.

4 TAMARACK CONCLUSIONS

Tamarack has considered the factual data gathered during the investigation, and FAA/EASA certification data provided to NTSB during the investigation, and draws two primary conclusions.

First, there is not sufficient data currently available to determine the reason for the onset of the roll event; however, there is evidence that ATLAS was functioning normally at the time of impact. Markings within the actuators in each TCU on the upper and lower ball nut guides were caused by the impact. The relative positions of the markings indicate that the actuators were deployed symmetrically at the time of impact, at a position consistent with an elevated positive load factor. Other damage to the TCUs, particularly bent pins within the left hand TCU, was also caused by impact. There is no evidence available to Tamarack or indicated in NTSB factual data to indicate that Tamarack equipment failed in flight.

Additionally, Tamarack concludes that the initial roll event most likely escalated into an accelerating descending steep turn due to the nineteen second delay between the onset of the roll event and the first indication of control response, coupled with the lack of throttle reduction during the response. These factors allowed the airplane to develop a flight condition which was not recoverable given the airplane’s initial altitude.

5 FURTHER ACTIONS

Given the significance of the nineteen second elapsed time between roll onset and first indication of recovery actions, Tamarack proposes that further investigation into human factors considerations may be helpful in understanding the cause for the delay, and therefore understanding the factors which escalated the initial roll event into the ultimately unrecoverable flight condition evident in the data. Tamarack does not have access to detailed medical, training, or crew rest data for the pilot, and therefore declines to draw conclusions about what factors may have contributed in this case. Bearing this in mind, Tamarack notes that human factors such as fatigue and unfamiliarity with cockpit equipment have been found to be contributing factors in several other fatal accidents caused roll upsets after takeoff, involving a variety of airplane models, underlying system failures, and flight conditions.

Tamarack also proposes that a broader review of the upset recognition and recovery guidance and training standards for this type of aircraft and similar may offer an opportunity to provide more detailed information about unusual attitude and upset recovery to pilots. There may be an opportunity to improve awareness of unusual attitude recovery procedures, particularly for nose-low attitudes. There may also be an opportunity to reinforce recommended scanning practices for operation in IMC, as well as best practices for Crew Resource Management (CRM) and Single Pilot Resource Management (SRM). It is inconclusive whether such additional information may have played a mitigating factor in this case, but Tamarack proposes that additional focus on these topics may help improve the general level of safety in future operations.