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Emergency Locator Transmitter System Performance During Three Full-Scale General Aviation Crash Tests

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Abstract

Full-scale crash tests were conducted on three Cessna 172 aircraft at NASA Langley Research Center’s Landing and Impact Research facility during the summer of 2015. The purpose of the three tests was to evaluate the performance of commercially available Emergency Locator Transmitter (ELT) systems and support development of enhanced installation guidance. ELTs are used to provide location information to Search and Rescue (SAR) organizations in the event of an aviation distress situation, such as a crash.

The crash tests simulated three differing severe but survivable crash conditions, in which it is expected that the onboard occupants have a reasonable chance of surviving the accident and would require assistance from SAR personnel. The first simulated an emergency landing onto a rigid surface, while the second and third simulated controlled flight into terrain. Multiple ELT systems were installed on each airplane according to federal regulations. The majority of the ELT systems performed nominally. In the systems which did not activate, post-test disassembly and inspection offered guidance for non-activation cause in some cases, while in others, no specific cause could be found. In a subset of installations purposely disregarding best practice guidelines, failure of the ELT-to-antenna cabling connections were found.

Recommendations for enhanced installation guidance of ELT systems will be made to the Radio Technical Commission for Aeronautics (RTCA) Special Committee 229 for consideration for adoption in a future release of ELT minimum operational performance specifications. These recommendations will be based on the data gathered during this test series as well as a larger series of crash simulations using computer models that will be calibrated based on these data.

Introduction

The NASA Search and Rescue (SAR) Mission Office, located at Goddard Space Flight Center (GSFC), initiated a study in 2013 with the goals of collecting data for the use in updating performance standards for the next generation of Emergency Locator Transmitters (ELT) [1]. After a series of component and subsystem-level environmental tests in 2014, a series of three survivable, full-scale aircraft crash tests were performed at the Landing and Impact Research Facility (LandIR), located at NASA's Langley Research Center (LaRC) in the summer of 2015.

The test aircraft were outfitted with a variety of commercially available ELT systems, Anthropomorphic Test Devices (ATDs, a.k.a. "crash test dummies"), and an onboard Data Acquisition System (DAS). Additionally, each airframe included two non-functional, or "dummy", ELT installations for the purpose of recording dynamic loading conditions experienced by the antenna cables. ATD response data were used to establish the severity of pilot/co-pilot injury and is the subject of another technical report [2]. The ELT installation plans were varied throughout the series in order to assess how performance may be affected by system installation. Airframe response data supported calibration of a set of computer models that were used to assess ELT system installation performance under a wider variety of crash scenarios than had been previously tested [3].

The ELT systems tested were representative of typical installations found onboard General Aviation (GA) aircraft and included nine different models from six different manufacturers. Of the fourteen total ELTs included in the series, three had been exposed to vibration testing in accordance with Radio Technical Commission for Aeronautics (RTCA) environmental test standards in order to assess the effect of pre-crash conditioning. None of the units were re-used after crash testing and all were disassembled and inspected for internal damage.

Each ELT was registered with National Oceanic and Atmospheric Administration (NOAA) and permission was sought and granted for performing live tests of each installed system. This allowed for positive confirmation of full functionality before, during and after the crash tests as data collected by the Search and Rescue Satellite Aided Tracking (SARSAT) system was made available for review.

Analysis of the test and computer simulation data will guide ELT system installation recommendations that will produce performance gains in real-world aviation accidents, leading to safer, less costly, and more effective SAR operations. These recommendations will be made to the Federal Aviation Administration (FAA) via RTCA Special Committee 229 (SC-229), which was established in December 2013. Initial release of the Second Generation 406 MHz ELT performance specification, RTCA DO-204B, is currently scheduled for no earlier than 2017.

Background

Typical aircraft operations include an Automatic-Fixed (AF) type ELT. In an AF installation, the beacon is mounted to the primary structure of the airframe, most often in the aft section, and connected to an externally-mounted antenna by a coaxial cable and associated connectors. Later models also include a remote control switch with aural and visual status indicators in the cockpit. For the purposes of this document, the term "ELT" refers to the AF-type of system.

The vast majority of ELTs are passive-sensing systems relying on internal battery power and utilizing a mechanical g-switch to activate the system when a crash event is detected. The performance characteristic of the crash sensor is established by RTCA-approved regulations and essentially requires the system to activate due to a change in velocity greater than 5 feet/second opposite the direction of flight, but not less than 2 times the force of gravity or 10 milliseconds of force application [4].

Once activated, the ELT broadcasts a distress signal at 406 MHz, the internationally protected frequency for SAR. Transmissions received by SARSAT satellite assets are relayed to Local User Terminals (LUTs) on Earth, which in turn supply the processed data to Mission Control Centers (MCCs). The appropriate Rescue Coordinate Center (RCC) or foreign SAR Point of Contact (SPOC) is then alerted and SAR operations commence.

The Emergency Locator Transmitter Survivability and Reliability (ELTSAR) Study was formulated to investigate the performance and failure modes of current generation ELT systems. It is important to note the term “current” because much of the available literature and aviation crash reports include older generation ELT designs that have since been improved. Furthermore, the majority of in-service systems, particularly in GA – the largest contributing segment to all aviation accidents [5], continue to be of the older variety [6].

The issue of scarcity of detailed performance data related to the latest generation of ELTs makes statistical analysis by means of crash report or literature review a tremendous challenge. Nonetheless, it is apparent that performance gains have been realized since the 25% successful operation rate reported over the period 1983-1987 [7]. A more contemporary study, such as the one published by the Australian Transportation Safety Bureau in 2013, cited successful ELT operations in 40-60% of “high g-force accidents” reported to them over the period 1993-2012 and scarcity of data is also highlighted [8].

Through a thorough review of the available literature and a focused set of crash report records provided by the National Transportation Safety Board (NTSB), a series of environmental tests were designed and performed, each with the goal of examining one or more recurring failure modes in current generation ELTs. The findings related to component or sub-system testing will be included in the technical report that will summarize the entire study, including the crash tests that are the subject of this document, as well as the initial literature review [1].

Test Facility

All aircraft were tested at the Landing and Impact Research (LandIR) facility, shown in Figure 1, at NASA LaRC. The LandIR facility was built in 1965 for use by the Apollo astronauts to practice lunar landings. Since the mid-1970s, it has been used as a full-scale aircraft crash and spacecraft landing test facility. Crash testing has been conducted in the past for evaluation of safety features [9], some of which have included ELTs [10].

LandIR is a unique facility used to impart combined forward and vertical velocities onto test articles at complex impact attitudes, which create more realistic crash conditions and scenarios than those tests conducted by pure vertical drops. The facility uses a pendulum-like swing system to lift and swing the test articles into the ground and pitch rate can be varied or eliminated.

At the predetermined drop height (up to 240 feet), a pyrotechnic system severs the pullback cabling from the test article, causing it to swing in a pendulum-like flight path toward a location on the ground. Immediately before ground contact, onboard pyrotechnics sever the swing cable attachments, causing the test article to be in a free flight-like condition prior to impact.

The LandIR facility is capable of lifting and swinging test articles up to 32 tons in weight. Combinations of swing cable length, drop height, angle of attack, impact surface and location can all be varied, creating a wide range of impact conditions.

Figure 1 - Landing and Impact Research Facility (LandIR)

Crash Test Series

During the summer of 2015, three Cessna 172 GA aircraft were crash tested at the LandIR facility for the evaluation of ELT system-level performance and generation of airframe response data to be used for analysis model calibration purposes [11]. This particular aircraft model was chosen because research showed no correlation between airplane make or model and ELT performance, and GA is the highest contributing segment to aviation accidents. Figure 2 shows the airplanes acquired for testing.

Test article 1 Test article 2 Test article 3

Figure 2 - Cessna 172 test articles

The three test scenarios represented three different types of crash landing conditions. The first scenario simulated a pilot attempting to conduct an emergency landing on a prepared surface such as a runway or road, and proceeding to flare-to-stall the airplane above the ground, causing a large vertical sink rate. The second and third tests represented controlled flight into terrain scenarios. The second test oriented the airplane in a nose-down configuration, simulating a pilot unknowingly flying directly into the terrain, while the third test represented a condition where the pilot unsuccessfully attempts to pull the airplane up to avoid terrain impact, resulting in a tail-strike condition. All scenarios were designed to produce severe but human-survivable crash environments.

Multiple ELTs were mounted onboard each airplane in a variety of schemes that were representative of common installation plans. These plans were developed with input from certified aviation technicians and observation of numerous system installations onboard in-service aircraft. All system installations satisfied FAA requirements for local mounting surface strength, rigidity and airframe modification. Beacon locations, antenna locations, and antenna cabling treatment were varied amongst the test set as well. For the purposes of reporting, the term ELT or ELT system will be used to refer to the entire system (beacon, mounting tray, cabling and antenna) as a whole, while the term ELT beacon, or simply beacon will refer to the main box-like unit containing the crash sensor. Where applicable, the antennas and antenna cabling will be identified separately. Beacons are attached to the airplane using their mounting tray, which is typically a molded plastic or metallic plate, and a clasping mechanism which are included when purchasing the beacon. The mounting tray then interfaces to the aircraft attachment plate, which is a custom designed and machined metallic plate fastened to the aircraft structure, and is typically unique for each installation.

Of particular interest was to determine how the beacon location may affect crash-sensing and crashworthiness of the system given that current standards recommend installing the beacon in the aft-most section of the airframe as practicable. This guidance is based on crashworthiness, and may be at odds with crash-sensing since the energy dissipated in deforming forward and mid-airframe stations during a crash sequence may decrease the loads experienced by a beacon in the aft section to levels below crash-sensor activation threshold requirements. In fact, previous studies stated these same concerns, resulting in recommendations to mount the crash-sensor forward of traditional beacon locations [12]-[13].

Another area of interest was the relative location of the antenna with respect to the beacon and the treatment given to the antenna cabling system. Current performance standards include several “best practice” recommendations that include not crossing airframe production breaks with the cable run, providing “some slack” in the cables and using tethers to attach the cable to the airframe. While all of these recommendations appear to be sound, the installation schemes tested during the crash series included some that did not follow all best practices. The “dummy” ELT installations were utilized to further help quantify the loading environment experienced by cabling systems as a function of whether or not airframe production breaks were crossed and whether or not slack was provided in the cabling run. In all cases, tethers were used to protect cables from being snagged or pulled before or during the tests.

Test Article Preparation

All three airplanes were prepped in a similar manner to facilitate crash testing. An onboard 64 channel DAS was installed to collect airframe, ELT, and ATD accelerations and loads. ELT accelerometers measuring horizontal (fore/aft), vertical and lateral accelerations were bonded via epoxy directly onto the ELT beacon outer casing. Accelerometers were also fastened to the ELT beacon aircraft attachment plates both in the horizontal and vertical directions. By measuring accelerations on both the ELT beacon and aircraft attachment plate, differences in responses, if any, could be directly measured and compared, and an evaluation of the performance of the beacon mounting could be performed. Accelerometers mounted in a horizontal direction generally were aligned with the sensing axis of a single axis sensing ELT beacon, and vertical accelerometers were oriented perpendicular to the sensing axis. In most cases, this convention ran parallel to the airplane data collection convention, with horizontal accelerations in the aircraft coordinate system aligned with the thrust/drag directions, with forward being positive. Vertical accelerations were aligned with the lift/weight directions, with positive being upward. All data were sampled at 10 kHz, and the DAS was controlled via Cat 5e umbilical cabling, running between each test article and the control room.

Monochromatic ruggedized onboard high speed cameras, filming at 500 Hz, were focused on ATD responses and ELT beacon-to-mounting tray and aircraft mounting plate interaction. All high speed cameras and DAS data were synchronized using a common IRIG-B time code signal. Additional high definition cameras were installed around the interior and exterior of each test article to capture any significant item or event of interest. Camera location was determined by the ELT installation specifications and experimentation layout for each particular airplane, and was unique for each test.

Table 1 shows the ELT installation matrix. The ELTs used in testing were a 50/50 combination of purchased and manufacturer donated units. All ELTs were new and unmodified when installed in the airplanes, with the exception of a subset which underwent “robust” vibration testing in accordance with RTCA standards [14] prior to installation. These units are designated with ‘vib’ after their ‘Make’ identifier. In cases where antennas were not supplied by the ELT manufacturer, additional antennas and coaxial cables were procured and/or fabricated in-house.

All ELTs underwent functionality testing after receipt at LaRC and again subsequent to installation onboard the aircraft. Tests consisted of performing the internal self-test described in each manufacturer's operations manual, a manual hand shake test, and manual activation.

A successful self-test was indicated by the return of no error codes as reported by the beacon. A successful manual hand shake test was confirmed by placing the beacon in the "ARMED" mode and shaking the beacon rapidly by hand and observing automatic activation of the beacon and transmission of the 406 MHz distress signal to a beacon tester connected to the antenna coaxial cable output. During manual activation testing, the beacon was switched to the "ON" mode and transmission of the 406 MHz distress signal over the air via the ELT external antenna was confirmed with a local beacon monitor. Satellite transmission data were provided by NOAA and NASA SAR to confirm that the distress signals carried the appropriate information at sufficient power to be received in space. Each system passed all tests upon receipt and final installation onboard the aircraft.

Two "dummy ELT" systems were installed on each airplane. These dummy systems were specifically used to measure tension in the antenna cable during each crash test. The system contained a 3 lb. steel mass simulating the ELT beacon. The mass contained a Bayonet Neill-Concelman (BNC) terminal connection attached to an inline load cell, capable of reading tension and compression loads to 1,000 lb. The antenna cable attached to the BNC terminal and was routed in the same manner as a live ELT antenna cable, and like a normal beacon, each dummy cable was attached to an external antenna. A dummy unit was used to measure the loads because it was not possible to incorporate an in-line load cell with a live beacon without causing signal disruption. Each dummy beacon mass also contained a horizontal and vertical sensing accelerometer, in order to compare dummy mass to actual ELT beacon accelerations installed on each aircraft. The two dummy ELTs for each test are labeled "Dummy 1" and "Dummy 2" in Table 1.

A combination of purchased and NASA fabricated antenna cables were used in testing. Many of the antenna cables were included with the purchased ELTs when practical. Additional cabling was fabricated by NASA in-house certified aircraft technicians for either extended cable runs or to provide comparisons to purchased ELT cabling. Antenna cable systems are identified by the fabrication pedigree and coaxial cable type. Note that for ELTs 4 and 7 of Test 3, the cables were provided with purchased ELT units, but were unmarked.

Table 1 also contains columns defining in generality where each ELT beacon and antenna was located on each airplane. These general designations are provided for completeness and quick comparisons. The individual test sections will show precise installed locations for all ELT beacons and antennas.

Table 1 – ELT installation matrix

Test 1									
ELT	Beacon Make (Mfr.)	Beacon Model	Beacon Orientation on Airframe	Beacon Airframe Station	Antenna Location	Antenna Type	Antenna Cable System Pedigree	Antenna Cable Type	Antenna Cable Length
1	1	1	Left Side	Aft of 90	Cabin	Whip	NASA	RG400	36”
2	1	2	Right Side	Aft of 140	Aft Tail	Whip	NASA	RG400	45”
3	2 (vib)	3	Floor	Aft of 65	Cabin	Whip	MIL-DTL-17	RG142	36”
4	2	3	Floor	Aft of 65	Fwd Tail	Whip	NASA	RG400	108”
5	Dummy 1	N/A	Left Side	65	Fwd Tail	Whip	MIL-DTL-17	RG142	36”
6	Dummy 2	N/A	Right Side	65	Aft Tail	Whip	NASA	RG400	118”
Test 2									
ELT	Beacon Make (Mfr.)	Beacon Model	Beacon Orientation on Airframe	Beacon Airframe Station	Antenna Location	Antenna Type	Antenna Cable System Pedigree	Antenna Cable Type	Antenna Cable Length
1	3 (vib)	4	Ceiling, 45°	Aft of 65	Cabin	Rod	NASA	RG400	24”
2	1 (vib)	5	Ceiling	Aft of 108	Aft Tail	Rod	NASA	RG400	24”
3	4	6	Left Side	Aft of 108	Fwd Tail	Whip	MIL-DTL-17	RG142	72”
4	2	3	Right Side	Aft of 108	Cabin	Whip	NASA	RG400	108”
5	3	4	Floor	Aft of 65	Cabin	Whip	MIL-DTL-17	RG142	36”
6	Dummy 1	N/A	Floor	90	Fwd Tail	Whip	MIL-DTL-17	RG142	36”
7	Dummy 2	N/A	Side	90	Aft Tail	Whip	NASA	RG400	72”
Test 3									
ELT	Beacon Make (Mfr.)	Beacon Model	Beacon Orientation on Airframe	Beacon Airframe Station	Antenna Location	Antenna Type	Antenna Cable System Pedigree	Antenna Cable Type	Antenna Cable Length
1	4	7	Floor	Aft of 65	Cabin	Whip	MIL-DTL-17	RG142	72”
2	5	8	Left Side	Aft of 108	Fwd Tail	Whip	NASA	RG400	48”
3	3	4	Right Side	Aft of 65	Fwd Tail	Whip	NASA	RG400	72”
4	5	8	Right Side	Aft of 108	Aft Tail	Whip	*Unmarked	*Unmarked	72”
5	6	9	Floor	Aft of 65	Cabin	Whip	NASA	RG400	48”
6	Dummy 1	N/A	Floor	65	Aft Tail	Whip	NASA	RG400	96”
7	Dummy 2	N/A	Right Side	65	Fwd Tail	Whip	*Unmarked	*Unmarked	72”

All ELT beacon aircraft attachment hardware custom designed and fabricated at LaRC met current RTCA standards [4]. For ELT beacons which were to be floor mounted, 0.09-in. thick aluminum 6061 plates were used as doubler plates and riveted directly into the cabin subfloor support channels. For ELT beacons which were to be sidewall mounted, 0.09-in. thick aluminum 6061 plates were machined to fasten to two longitudinal stringers. Holes were drilled into the plates at locations specified by the specific ELT mounting bracket. Figure 3 shows an example floor mounted doubler plate while Figure 4 shows an example sidewall aircraft attachment plate.

Figure 3 – Example floor mounted aircraft attachment doubler plate

Figure 4 - Example sidewall aircraft attachment plate

In two instances, a ceiling mounted beacon configuration was used to replicate a helicopter installation. Per manufacturer guidance, 1-axis sensing ELT beacons are mounted to the cabin ceiling in a 45 degree nose-down orientation. This configuration addresses differences in both crash and normal vibration environments between rotorcraft and fixed wing aircraft.

All ELT remote switch connections were wired into their respective switches and mounted in series onto a plate on the airplane instrument panel. Cabling was routed beneath the cabin floor and fastened to frame sections for beacons in the tail. A high definition camera was focused solely on the remote switch panel to observe and record status light indications during checkout and test procedures.

ELT performance during and after the crash tests was confirmed by a variety of methods:

- Visual Inspection – The status of the beacon and remote switch visual and aural indicators, component connections and mounting structures were noted during pre- and post-test inspection of each aircraft.
- Radio – A hand-held radio was tuned to 121.5 MHz to confirm broadcast of local homing signals. Note, this method does not provide identification of the beacons(s) responsible for the broadcast.
- Video – Onboard cameras were oriented to observe status indicator lights on the remote switches and beacons, whenever possible, in order to confirm automatic activation of the ELTs.
- Beacon Monitor – A local beacon monitor was stationed in the LandIR control room to acquire and document 406 MHz distress signal transmissions, including the unique 15 Hex ID assigned to each beacon transmission that was received and processed.
- SARSAT – Satellite transmission data were provided by NOAA and NASA SAR subsequent to each test. The data sets included, among other things, the beacon 15 Hex ID associated with each transmission, transmission receipt time, and the particular satellite asset that received the transmission.

Airplane rigging required for test, along with details regarding airframe acceleration locations, acceleration response, impact conditions, and general test details can be found in [11]. However, summaries are provided for each test within its individual section. The final weight and balance for each airplane is listed in Table 2. Each aircraft was in its “Normal” category as defined by each aircraft’s Pilot Operating Handbook. The horizontal Center of Gravity (CG) is measured from the firewall, the lateral CG is measured from the aircraft centerline, and the vertical CG is measured from the ground. The column labeled “Moment / 1000” is calculated by multiplying the weight and horizontal CG. The entire data set is presented in Table 2.

Table 2 - Aircraft test article weight and CG properties

Test	Weight (lb.)	Horizontal CG (in.)	Lateral CG (in.)	Vertical CG (in.)	Moment / 1000 (in.-lb.)	Category
1	2,000	44.5	0.0	46.3	89	Normal
2	2,114	39.5	0.0	48.1	101	Normal
3	2,072	42.5	0.0	50.8	89	Normal

Since ELT crash-sensors are designed in accordance with a minimum change in velocity, or "delta-v", specification, each test section contains the delta-v computed from the measured accelerations at beacon locations. The delta-v section also includes the timeframe in which the computation was performed. A set of acceleration traces from each test can be found in [11].

A diagram showing station locations is shown in Figure 5. For general nomenclature, station 0 represents the firewall, stations 16 through 108 represent the cabin of the airplane, stations 108 through 140 represent the forward tail, stations 140 through 172 represent the mid-tail, and aft of 172 is the aft tail.

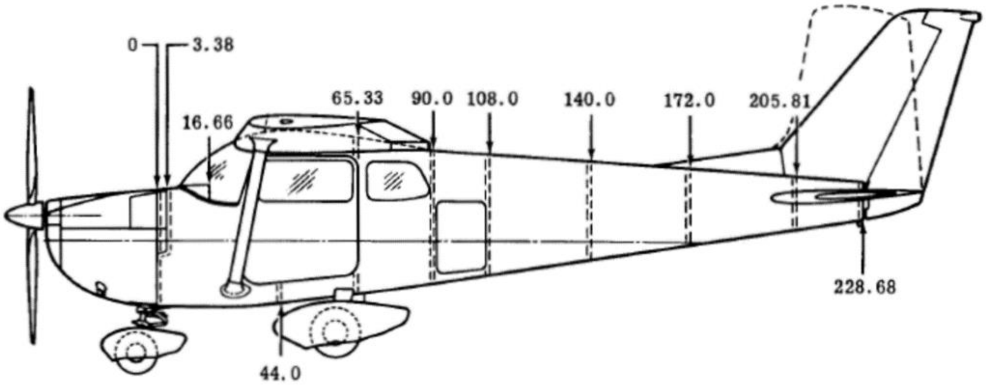

Figure 5 - Station locations for a Cessna 172

Test 1 Results

The original ELT for the Test 1 airplane was still present when the airplane was delivered to LaRC. The beacon was floor mounted beneath the rear bench seat on the pilot side of the cabin and the antenna cable was routed through an access hole in the cabin subfloor and into the external antenna located in the tail, directly behind station 108. The beacon was mounted onto an aluminum doubler plate, which was riveted into the subfloor support channels. Figure 6 shows the original ELT installation after removal of the aircraft interior components.

Figure 6 - Test 1 original airplane ELT beacon installation as viewed from the pilot door (left) and pilot seat looking aft (right)

The original ELT was removed, and four ELTs were installed in the airplane for Test 1. ELT beacon 1 was mounted on the pilot's side wall in the aft cabin. ELT beacon 2 was mounted on the co-pilot side wall in the mid-tail. ELT beacons 3 and 4 were mounted in symmetric arrangement on the cabin floor in a location which would be under the rear seat. ELT beacon 3 replicated the original beacon location. Figure 7 shows a graphical representation of the beacons, in yellow, at their mounting locations, with some components from the airplane removed for clarity.

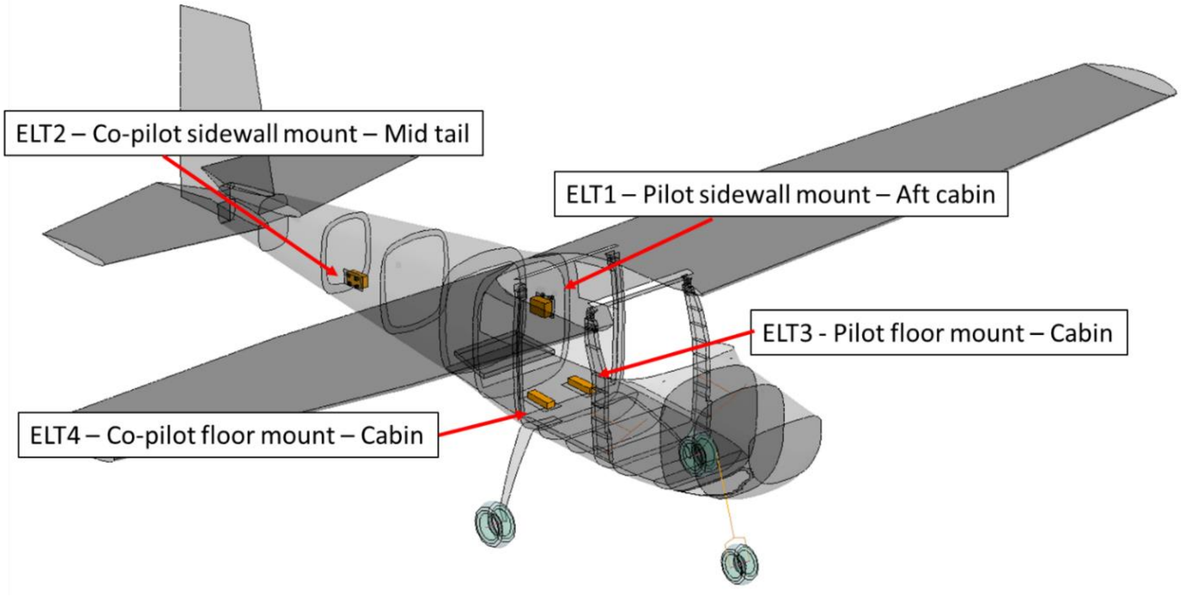

Figure 7 - Test 1 beacon configuration

The two dummy ELT beacons were mounted just forward of the station 90 frame section, beneath the rear window on both the pilot and co-pilot side with the BNC/load cell connection facing forward, as shown in Figure 8.

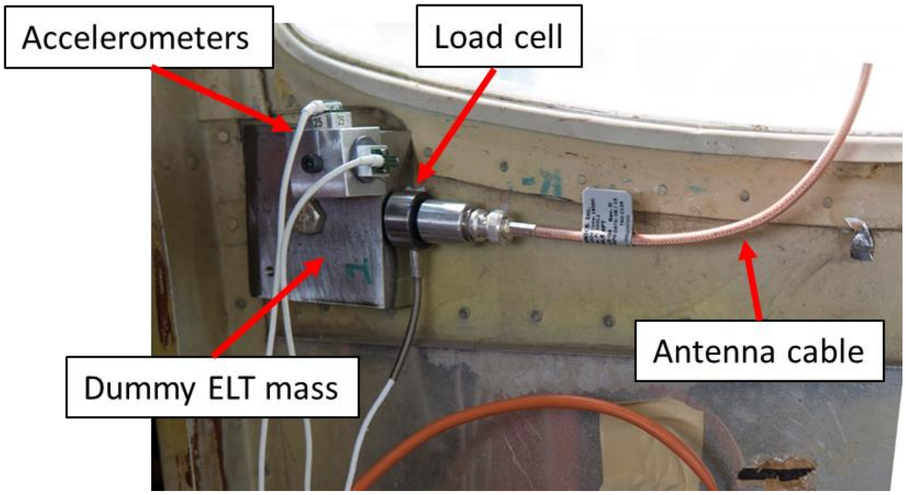

Figure 8 - Dummy ELT beacon installation for Test 1 (pilot side shown)

Antenna locations for Test 1 are shown in Figure 9. ELT installations 1, 2 and 3 followed current RTCA best practice guidelines by not crossing airframe production breaks when locating the antenna relative to the beacon and mounting them as close to the respective beacons as practicable. The cabling was secured to the frames of the aircraft via tie wraps. ELT installation 4, along with the two dummy ELTs, intentionally did not follow best practice guidelines to provide comparisons. ELT installation 4 used a 108-in. long cable, which had to be run from the floor of the cabin, up around the co-pilot rear door frame, along the ceiling and then into the antenna, which was located around the station 108 frame. Similarly, cabling for dummy beacon 2, which was located near beacon 3 on the co-pilot side, ran along the co-pilot side of the airframe, and then the ceiling until it attached to dummy antenna 2, located near the station 140 frame section.

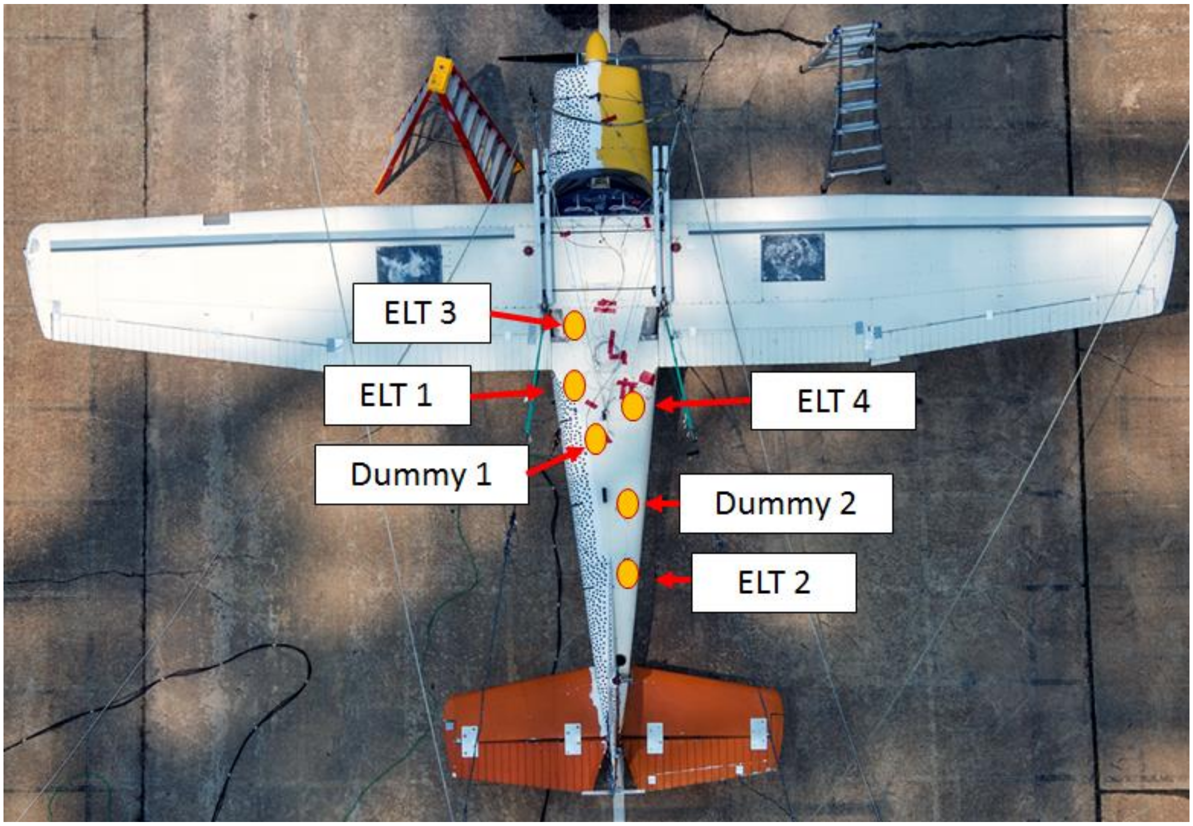

Figure 9 - Antenna locations for Test 1

Multiple activation checkouts were performed on the units prior to test day, both by performing the self-test function on the ELT beacons and by turning the ELTs to “ON” mode and reviewing satellite transmission feedback from NOAA and NASA SAR. The final checkout was conducted on test day with a self-test being performed on each ELT approximately 1 hour before the crash test occurred. The final self-test indicated that the ELTs were all functioning normally immediately prior to the crash test.

Test 1 occurred on July 1, 2015. The airplane impacted the concrete surface at a flight path velocity of 64.4 ft./sec. at an Angle of Attack (AoA) of 1.5 degrees nose high. The main landing gear compressed enough to allow the tail to strike the surface approximately 0.125 sec. after initial impact. The airplane rebounded with a large amount of residual horizontal velocity, which was then stopped by the catch net. The time between the initial impact and the first catch net contact was 0.475 sec., however the net capture occurred at approximately 0.800 sec. after initial impact. At a point during the net capture, the airplane tail impacted the ground a second time, causing a small portion of the lower tail to break free from the airplane. The airplane came to rest approximately 5.85 sec. after initial ground impact. Figure 10 shows the impact sequence.

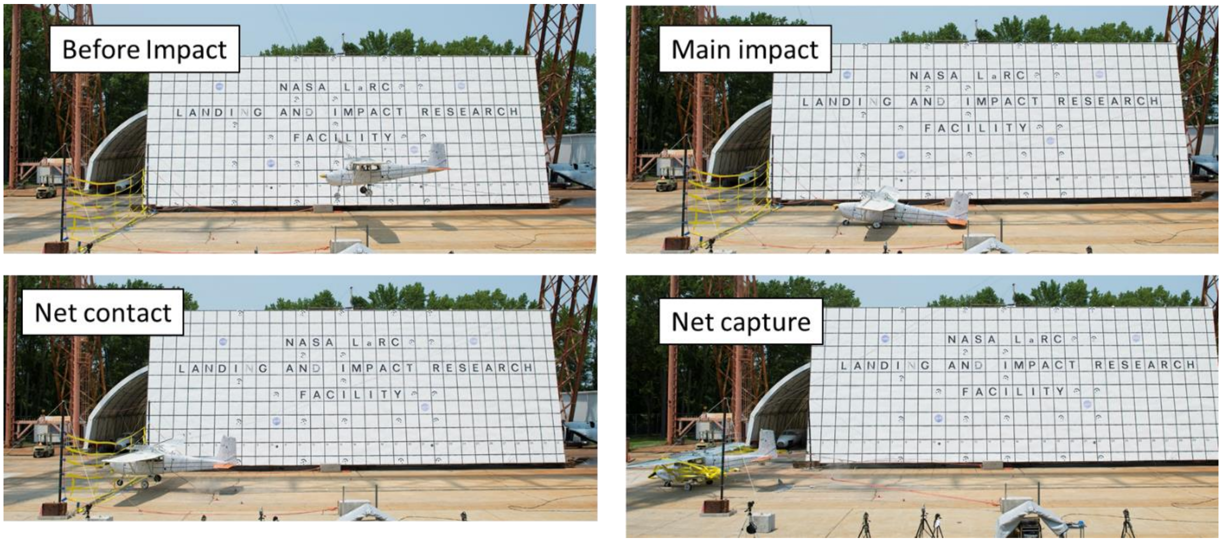

Figure 10 - Test 1 impact sequence

Other than minor damage in the nose gear mounting location and rear tail piece which broke free, the airplane appeared to be largely undamaged after the impact. Visual inspections confirmed that all ELT beacons remained seated in their mounting trays, with no structural failures detected on the mounting tray, aircraft attachment plates or beacons due to the ground impact or net capture events. Acceleration data captured from accelerometers mounted directly to the beacons are plotted in Figure 11. Accelerations for all beacons and aircraft attachment plates presented in this report are filtered at a SAE Channel Filter Class (CFC) 60 low-pass filter [15].

Test 1 is unique from the other tests because there are two very distinct impact events seen both in the image series and in the data. The first event is the ground contact, which consists of primarily a vertical deceleration of the airplane causing primarily landing gear deformation. The second, starting at approximately 0.475 sec. after the ground contact and lasting through approximately 1.6 sec. is the net capture, which is primarily a horizontal deceleration event. Note that single-axis-sensing beacons were mounted with the sensing direction aligned with the horizontal net capture event, which is in the direction of flight. ELT beacon accelerations in both the horizontal and vertical directions are shown in Figure 11.

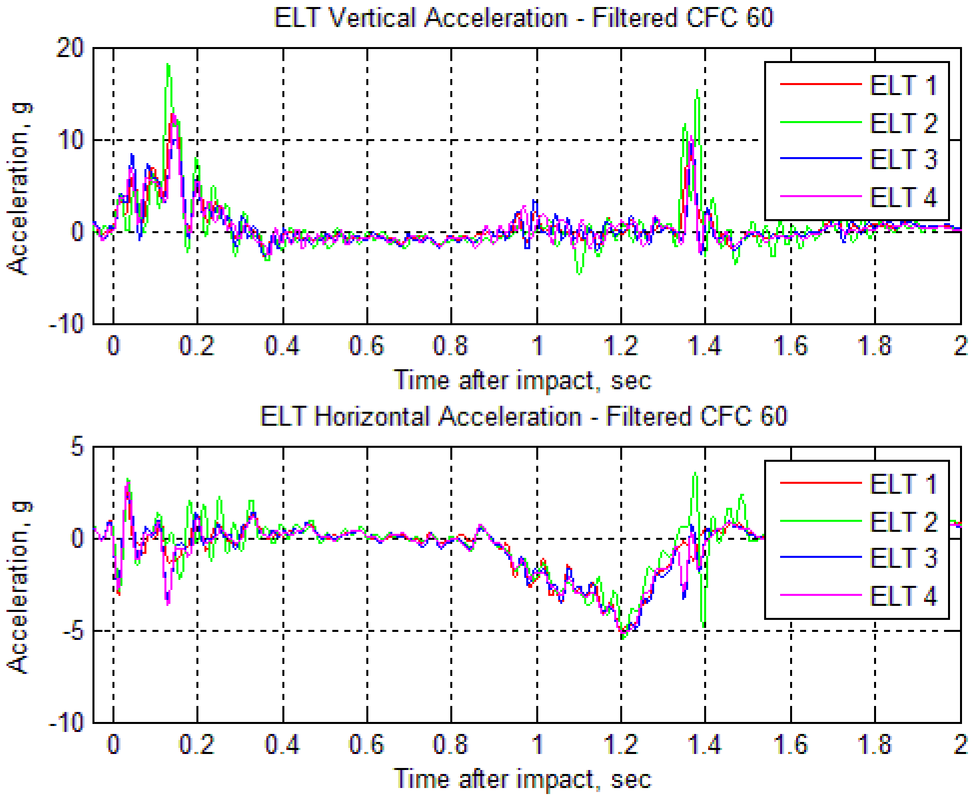

Figure 11 – ELT beacon accelerations from Test 1

Vertical accelerations during the ground impact event reached peak values of 12.7, 18.1 10.1 and 12.7 g for ELT beacons 1, 2, 3 and 4, respectively. The maximum values occur 0.125 sec. after impact, and are due to the tail strike condition. ELT beacon 2 is closest to the tail and has the highest maximum peak accelerations. All peaks resemble a trapezoidal pulse shape with a sharp spike at the end. The duration of the pulse was 0.300 sec. with rise and fall times of 0.050 sec., and a sustained time of 0.200 sec. Another spike in acceleration occurs at 1.36 sec. after impact. This spike is due to a second tail strike which occurred during the net catch. The duration of this impact was approximately 0.030 sec. with maximums close to 10 g for ELT beacons 1, 3 and 4, and 15 g for ELT beacon 2.

Horizontal accelerations, which are shown in the lower plot in Figure 11 are mainly concentrated between 0.800 and 1.600 sec. There are short spikes which occur during the ground contact portion of the impact event, and oscillate between -3 and 3 g initially. The main portion of horizontal acceleration is evidenced from the net capture. The ground impact event is complete by 0.475 sec. after impact, after which the airplane makes contact with the net. Little acceleration is seen between 0.475 and 0.800 sec. after impact, mainly due to the net breaking away from the supports and beginning to wrap around the airplane. The actual capture begins 0.800 sec. after impact where the net tension begins to pull the drag weights in order to decelerate the airplane. The deceleration reaches maximums of 5.1, 5.5, 5.1 and 5.2 g for ELT beacons 1, 2, 3, and 4, respectively. The pulse is triangular in shape.

Change in velocity, which is simply the integrated acceleration signal from the plots show in Figure 11 is presented in Table 3. Data are computed in the vertical direction at ground contact between times 0.000 and 0.400 sec., and computed in the horizontal direction during net contact and catch, between times 0.800 and 1.600 sec. For reference, peak accelerations described above are also included. It should be noted that these delta-v results are substantially higher than what is required for automatic activation of the ELT [4].

Table 3 - Delta velocity and peak accelerations for Test 1

ELT	Vertical Peak Acceleration (g)	Vertical Delta-v (ft./sec.)	Horioznta1 Peak Acceleration (g)	Horizontal Delta-v (ft./sec.)
1	12.7	36.84	5.1	37.40
2	18.1	38.96	5.5	35.26
3	10.1	35.11	5.1	39.76
4	12.7	35.09	5.2	39.42

Data acquired from each of the beacons aircraft attachment plates were next examined to determine whether large differences in acceleration both in the horizontal and vertical directions were present. Comparisons between the plates and the ELT beacons showed almost identical acceleration response, with only very minor differences either due to minor variability in the sensors, location and/or filtering. The vertical acceleration plots are shown in Figure 12 while horizontal accelerations are shown in Figure 13. All ELTs used in Test 1 complied with the latest applicable Technical Standard Order (TSO) from the FAA [16].

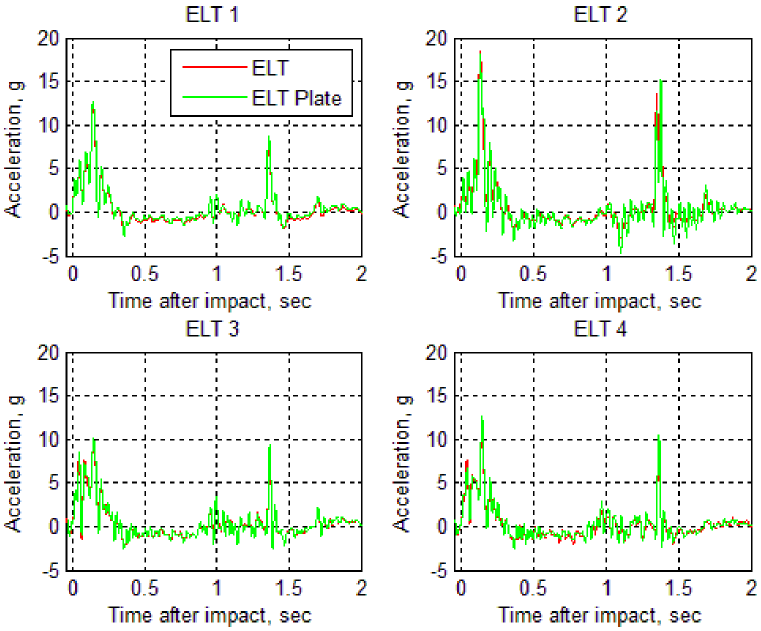

Figure 12 - Test 1 beacon to aircraft attachment plate vertical acceleration comparisons

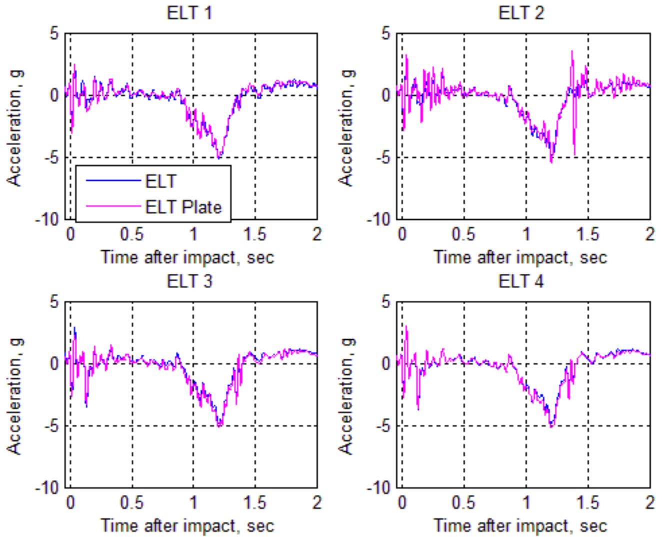

Figure 13 - Test 1 beacon to aircraft attachment plate horizontal acceleration comparisons

The resultant accelerations both in the horizontal and vertical directions demonstrate that the various mechanisms used for securing the beacons to their trays in Test 1 were all sufficiently rigid. Furthermore, when examining acceleration data gathered from the tests, the entire ELT, mounting tray and aircraft attachment plate assembly can be thought of as a single rigid body experiencing a single acceleration profile. Consequently, comparative results from the ELT beacon-to-aircraft attachment plate will not be reported further in this report, unless anomalous behavior is evident.

Cable loads were minimal in the dummy antenna cables due to the large amount of slack present in both of the dummy cable lengths. Since cables were slack, maximum loads developed were less than 2 lb. for both cables. No antenna cabling showed signs of damage or pullout from the attachment points. Figure 14 shows the results.

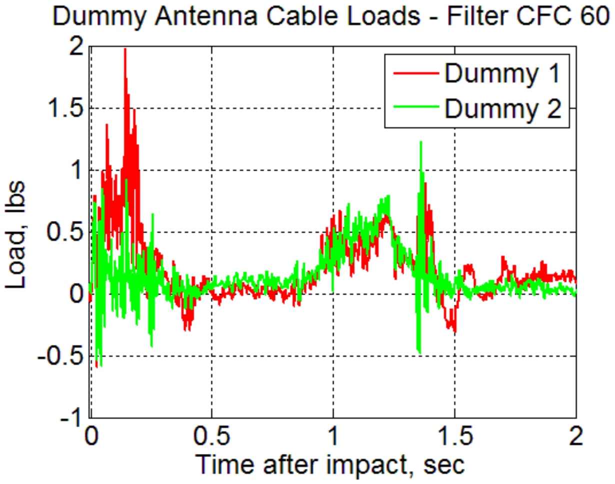

Figure 14 - Test 1 dummy antenna cable loads

Accelerations in the dummy masses closely follow the accelerations seen in the instrumented beacons. Acceleration traces exhibited much more noise in their signals, primarily due to being mounted directly onto the aircraft skin which exhibited much more oscillation than other components. Figure 15 shows the dummy ELT results.

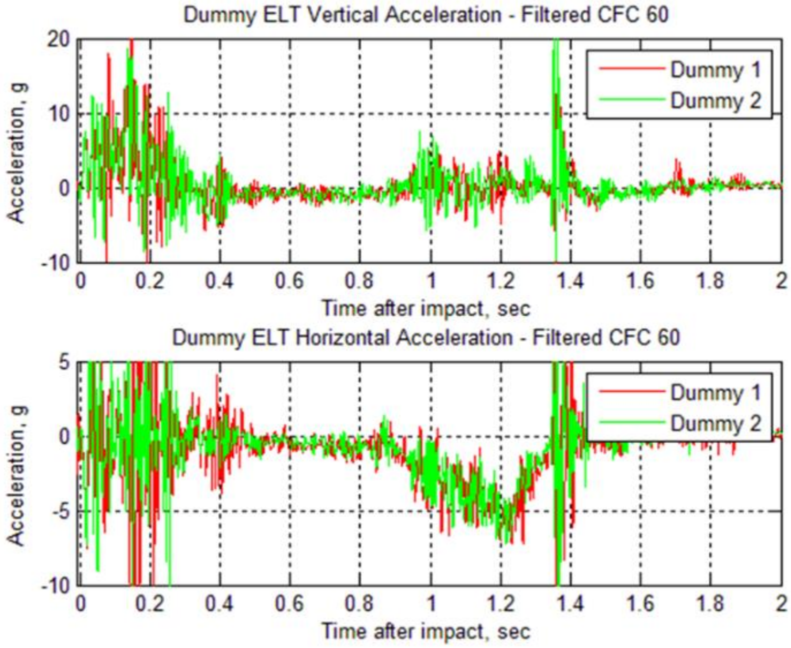

Figure 15 - Test 1 dummy ELT beacon accelerations

All four of the ELTs activated automatically and transmitted during the test. Since Test 1 was comprised of two major separate impact events, ELT beacon activation timing is critical to determining whether ground impact or net capture led to the distress signal transmissions. A sequence of events was reconstructed by examining when the visual status indicator lights on the beacons and remote switches illuminated. The analysis included the utilization of timing data, frame rate information and the common DAS/camera time-code from each of the cameras to reconstruct a complete timeline. The timeline showing the first indicated illumination is overlaid onto the aircraft engine acceleration data in Figure 16.

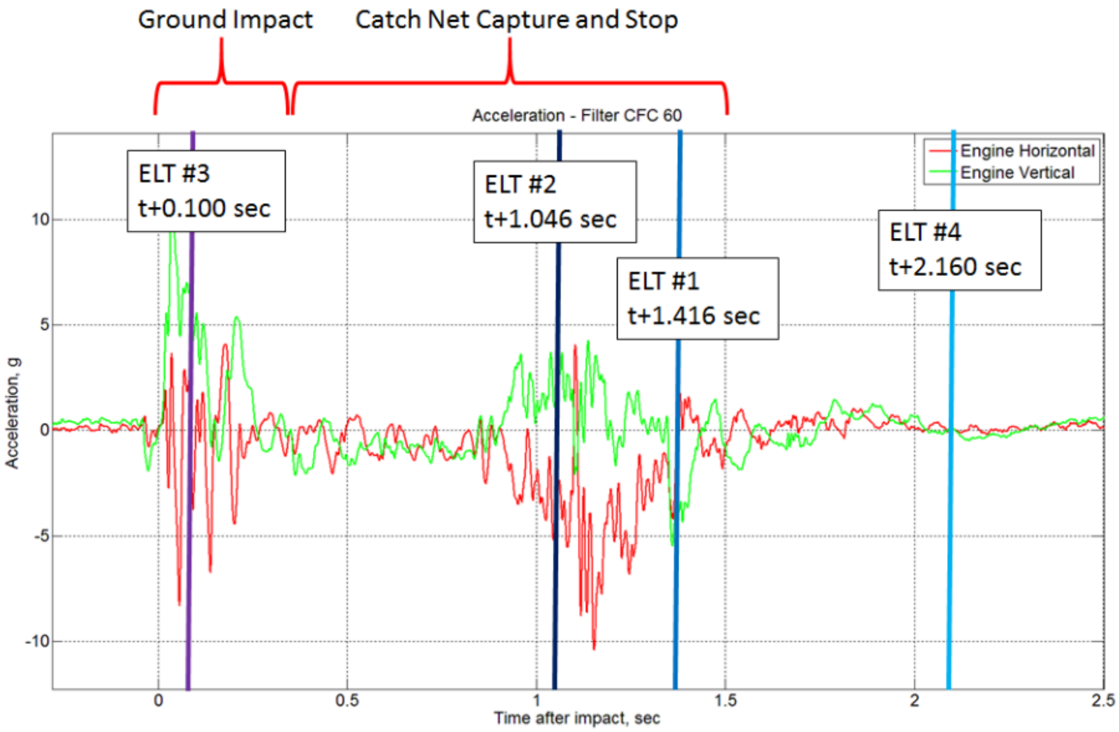

Figure 16 - Test 1 LED illumination timing

ELT beacon 3 was the only beacon that clearly sensed the initial ground impact event, consisting of the high vertical (cross-axis with respect to the sensitive direction of the crash sensor) acceleration. The light illumination occurred at 0.100 sec. after impact, which is in the middle of the ground contact acceleration pulse. ELT beacon 3 was a single axis sensing beacon which had undergone vibration tests, which are described in more detail below, prior to being used for the crash test. The other three ELT beacons showed LED illumination occurring more than 1 sec. after impact, either during or after the net capture.

However, what is unknown is the time delay between when the three ELT beacons sense the crash event and when the LED lights illuminate. A subset of data does exist from previous drop testing conducted on the same make and model (but different physical unit) for ELT 1 [1] and can provide a partial answer for that particular beacon. In a subset from 5 of 48 drop tests where both the impact and LED could be seen, the average length of time between first contact of the drop mass and LED illumination was 0.474 sec. and ranged between 0.464 and 0.484 sec. Using the average number as the time delay, the actual ELT beacon activation time shifts to 0.942 sec. after impact, which was near the beginning of the airplane deceleration due to the net capture. It is clear that ELT beacon 1 activated because of the net contact, and not due to the ground contact. Data, unfortunately, do not exist for ELT beacons 2 and 4, so no further interpretations could be made.

ELTs 3 and 4 were identical models, purchased in the spring of 2015. ELT 3 had undergone robust random vibration testing in accordance with the RTCA standard prior to being installed onboard the aircraft. After Test 1 was conducted, all ELTs were removed from the airplane and disassembled to inspect for damage or wear. The crash-sensors from ELT beacons 3 and 4, comprising of mechanical g-switches in this case, were then removed and part of the cylinder wall was carefully cut away to reveal the internal ball and spring mechanism.

As Figure 17 shows, wear from the vibration tests did create a marked location inside the cylinder (highlighted), and noticeable discoloration on the compressive side (left) of the marked line. This location is where the ball diameter would rest when not under compressive (or impulsive loading). It was not determined whether the spring stiffness changed due to the vibration testing; however, the automatic activation performance of ELT 3 was noted to have changed throughout that test series with a higher cross-axis sensitivity and altered in-line sensitivity. Further details regarding the entire vibration test series will be provided in the comprehensive report published after the conclusion of the study [1]. Other than the noticeable line and discoloration, there were no additional noticeable differences between the g-switches for ELT beacons 3 and 4.

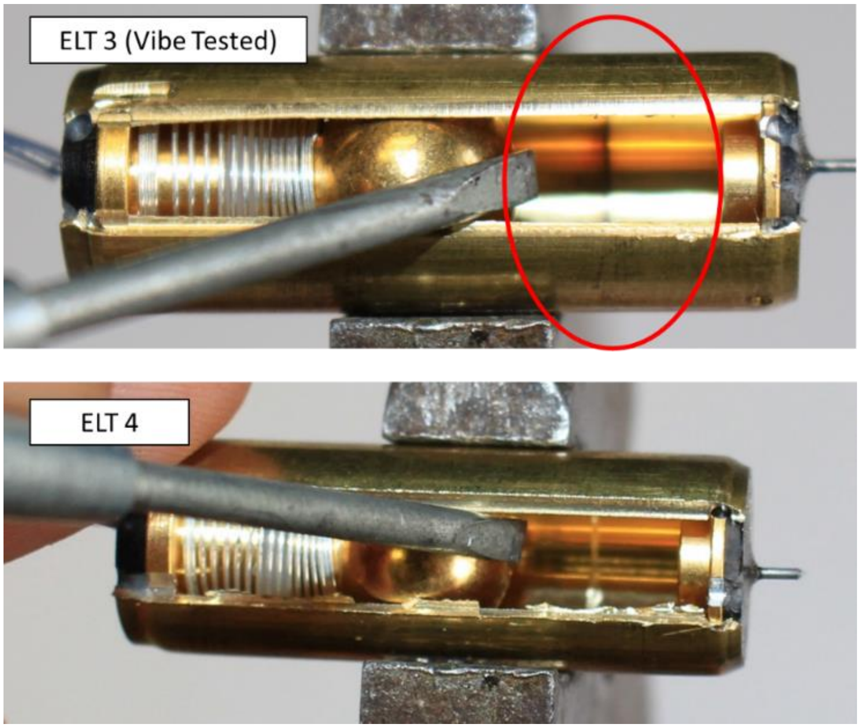

Figure 17 – G-switch comparisons between ELT beacons 3 and 4 for Test 1

Test 2 Results

The configuration of the Test 2 ELT beacons is shown in the graphic in Figure 18. Test 2 included a ceiling mounted beacon, oriented in a 45 degree nose-down configuration, simulating a helicopter installation for ELT beacon 1. ELT beacon 2 was also ceiling mounted; however, because it included a 6-axis crash-sensor, it was oriented in a level configuration per manufacturer's instructions. ELT beacon 3 was mounted to the side wall of the forward tail section on the pilot side. ELT beacon 4 was also side wall mounted; however, it was located in the mid-tail section on the co-pilot side. ELT beacon 5 was floor mounted in the main cabin on the pilot side. Dummy beacon 1 was installed on the cabin floor next to ELT beacon 5. Dummy beacon 2 was installed similarly to Test 1, on the co-pilot side, underneath the rear window.

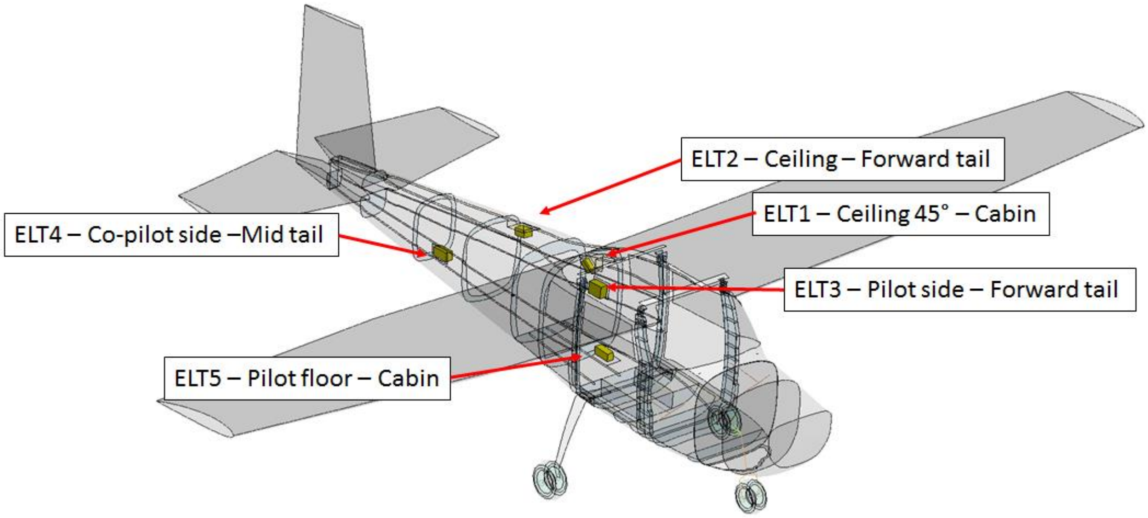

Figure 18 - Test 2 ELT beacon configuration

A combination of rod and whip antennas were used for Test 2. For the two helicopter ELT installations (ELTs 1 and 2), rod antennas were used per typical practice, and the remainder used whip antennas. Figure 19 shows the antenna locations, in black, on the rear cabin and forward tail, with approximate beacon interior locations also identified in red. The blue connecting line is an illustration to show the cable run between the beacon and antenna. ELTs 1, 2 and 3 all used best practice guidelines in trying to keep the antenna as close to the beacon as possible and without crossing airframe production breaks. Since beacons 1 and 2 were both ceiling mounted, the cable was a short 24-in. in length. The longest cable was used on the installation of ELT 4. This cable spanned four production breaks, connecting the ELT near station 140 to the antenna near station 65.

Unlike Test 1, the dummy ELT 1 antenna was very short. Dummy ELT 2, however, ran from the side window location at station 90 to the rearmost antenna near station 205. The antenna at station 205 was the rearmost mounted antenna amongst all three tests. As with Test 1, all cabling was secured via tie wraps to frame sections.

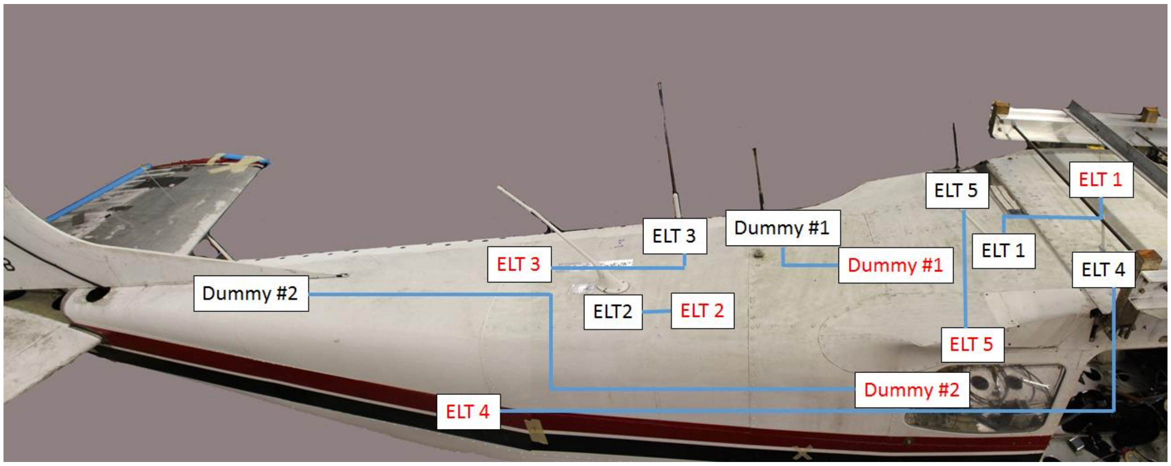

Figure 19 - Antenna locations for Test 2 with cable runs annotated

Test 2 occurred on July 29, 2015. The airplane CG impacted the soil at a flight path velocity of 74.4 ft./sec., consisting of a 68.6 ft./sec. horizontal and 28.7 ft./sec. vertical velocity components, resulting in an impact velocity vector angled at 21.6 degrees. The AoA was 12.2 degrees nose down with a pitch rate of +16.1 deg./sec. The airplane nose gear impacted the soil first, and then immediately began plowing into the soil. After 0.111 sec., the left wing separated away from the fuselage, and 0.169 sec. after impact, buckling initiated in the tail near the station 108 frame section. The airplane started to flip over 0.240 sec. after the initial impact. At some point during the flip, the nose gear broke away from the nose section of the airplane. At 1.976 sec. after the impact, the airplane orientation was upside-down. The airplane rocked back and forth for a few seconds before finally coming to rest 6.790 sec. after impact. Figure 20 shows the impact sequence.

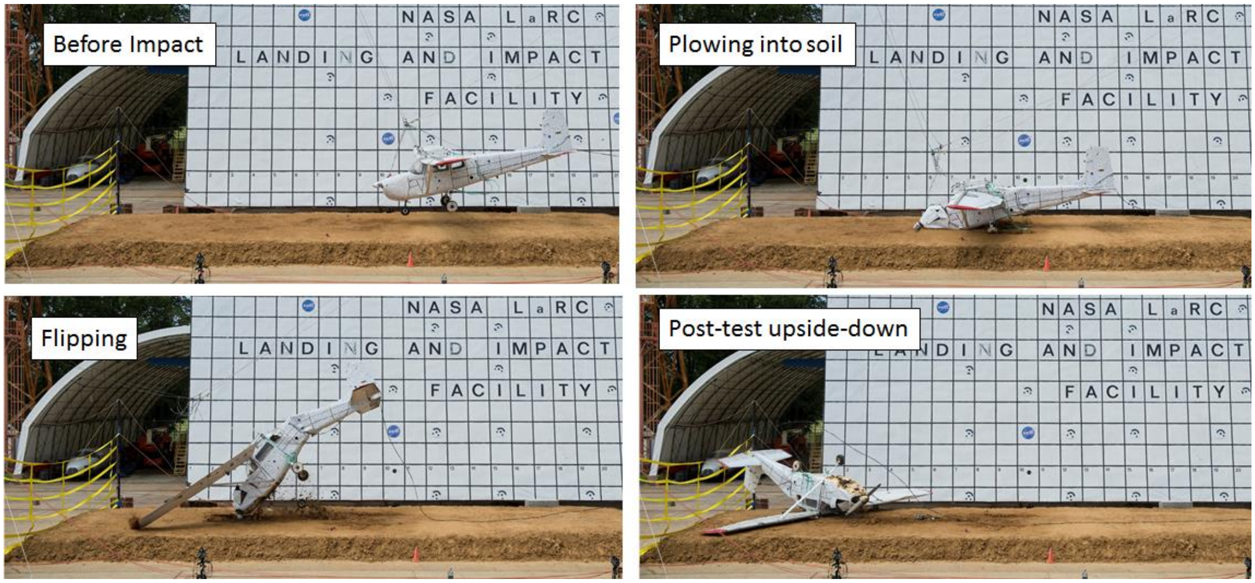

Figure 20 – Test 2 impact sequence

As shown in Figure 21, ELT beacons 1 and 5 show the highest horizontal accelerations during the impact, with peaks of 26.1 and 23.2 g, occurring at 0.145 sec. and 0.107 sec. after impact. It should be noted that both ELT beacons 1 and 5 were mounted in the cabin of the airplane, on the ceiling for ELT beacon 1 and on the floor for ELT beacon 5. ELT beacon 1 was the only ELT used in all tests which did not follow instrumentation orientation consistent with the airframe coordinate system. Instead, the two accelerometers mounted on ELT beacon 1 were mounted in the ELT beacon sensing direction and perpendicular to the ELT beacon sensing direction, respectively. For purposes of reporting, the ELT beacon accelerations are not transformed into the airplane coordinate system because it is important to show the accelerations experienced by the ELT in the beacon sensing direction. Therefore, the results from ELT beacon 1 shown in Figure 21 do not follow the acceleration traces acquired from the other ELT beacons.

ELT beacons 2, 3, and 4 show similar results, both in magnitude and in shape of horizontal accelerations from the impact. The accelerations are presumably similar due to the close proximity of mounting locations of the beacons in the tail. These accelerations approximate a trapezoidal shaped pulse, with a sustained acceleration duration of 0.63 sec. at average values of 10.3, 12.0 and 10.7 g, for ELT beacons 2, 3 and 4, respectively.

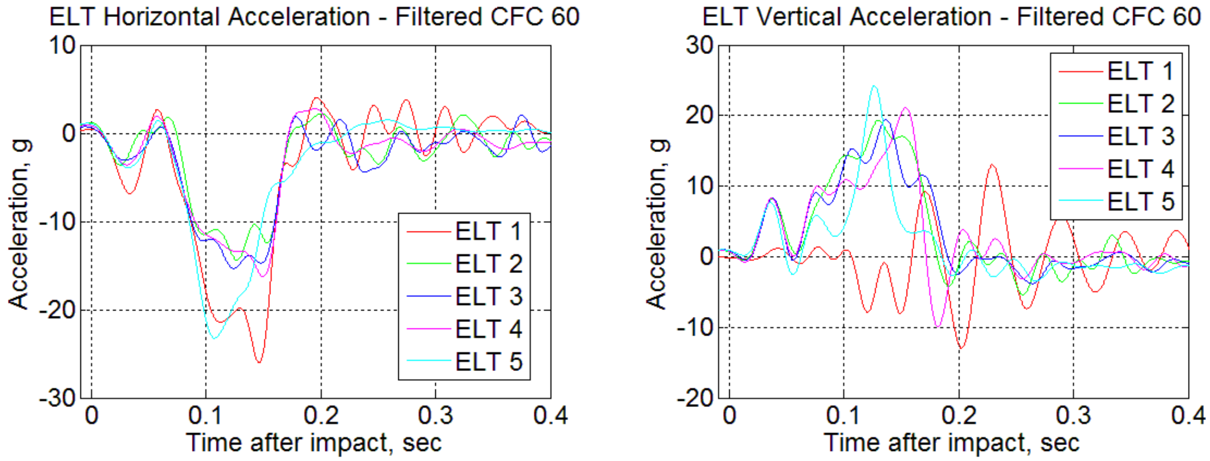

Figure 21 – ELT beacon accelerations from Test 2

Vertical accelerations, as shown in Figure 21, from the test closely matched between ELT beacons 2 through 5. The vertical accelerometer orientation on ELT beacon 1 was oriented at a 45 degree angle. Combined with a 12.2 degree nose down impact angle, the vertical accelerometer mounted on ELT beacon 1 was actually measuring accelerations at a 57.2 degree angle from the vertical, relative to the ground. It is because of this angle offset that the vertical accelerometer was measuring the complementary angle of acceleration relative to the flight path angle of 21.6 degrees, and thus, not registering high accelerations.

The vertical accelerations from ELT beacons 2 through 5 approximated a triangular shape with a duration of approximately 0.133 sec. Peak accelerations ranged between 19.3 g, which occurred on ELT beacon 2 to 24.2 g, which occurred on ELT beacon 5.

Change in velocity, which is simply the integrated acceleration signal from the plots shown in Figure 21 is presented in Table 4. Data are computed between 0.000 and 0.300 sec. For reference, peak accelerations described above are also included. Velocities resolved from ELT beacon 1 are in the beacon coordinate system.

Table 4 - Delta velocity and peak accelerations for Test 2

ELT	Vertical Peak Acceleration (g)	Vertical Delta-v (ft./sec.)	HorioznPeak Acceleration (g)	Horizontal Delta-v (ft./sec.)
1	13.0	10.1	26.1	58.6
2	19.3	54.3	14.4	36.1
3	19.4	52.0	15.3	44.1
4	21.1	48.2	16.3	39.7
5	24.2	35.6	23.2	51.0

Four out of the five ELTs activated and transmitted during the crash test with ELT 4 being the beacon that did not activate. During post-test inspections, the remote switch LED indicating activation was noted as not illuminated or blinking. Since the beacon was in the tail of the airplane and inaccessible from visual inspection or aural cues, the remote switch light was the only indication as to whether it had activated when undergoing immediate post-test inspections. Neither the local beacon monitor nor SARSAT system reported a transmission from this beacon.

Since the ELT beacon failed to automatically activate, the test procedure called for a self-test to be performed at the aircraft, immediately following the crash test, before any configuration changes occurred or equipment was disturbed. The self-test was successfully conducted via the remote switch, indicating that the connection between the ELT beacon and remote switch was intact and functional. The self-test produced an error code indicating “High VSWR or High Current,” according to the owner’s manual.

While inspecting the ELT antenna connections on the airplane back in the preparation hangar, it was discovered that the antenna cable had partially pulled out of the end fitting on the end terminating at the antenna. Note that the cable run between the beacon and antenna for this particular ELT did not follow the best practice guideline suggestions. Figure 22 shows the connection post-test. Furthermore, when connected to a beacon tester during further post-test checkouts in the preparation hangar, the beacon successfully passed the self-test, manual shake test and manual activation test.

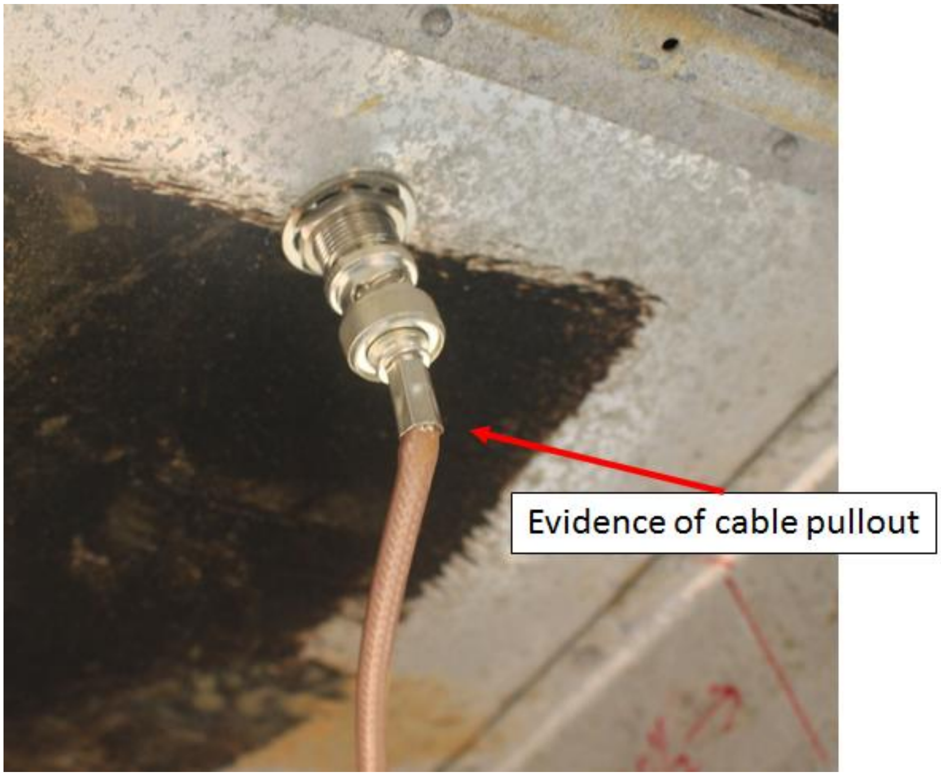

Figure 22 - Test 2 ELT 4 antenna connection

Antenna cable pullout from the end fitting may have been initiated by large deformation of the tail of the aircraft and relative motion of the antenna with respect to the beacon. There are two overall conclusions from ELT 4. First, the beacon did not activate, and second, had it activated, there is a chance the ELT would not have transmitted due to an antenna cabling connection pullout issue.

Note that even with the airplane upside-down after coming to rest following the impact, the beacons which activated were able to transmit a signal to the SARSAT system. ELT 1 and 5 antennas were mostly obscured from the soil near where the roof was in contact with the ground, while the antennas for ELTs 2 and 3, located on the tail were pointing downward at the soil. It is noteworthy that the activated beacons were able to successfully transmit the distress signal to the SARSAT system with the antennas in these orientations.

The cable loads developed in the dummy ELT cables are shown in Figure 23. As with Test 1, the loads measured in the dummy cables were very low, reaching peaks of 12.2 and 2.1 lb. for dummy 1 and 2, respectively. These loads occur in the first 0.200 sec. of the crash, which follows when the ELT beacons saw the acceleration pulses from the crash.

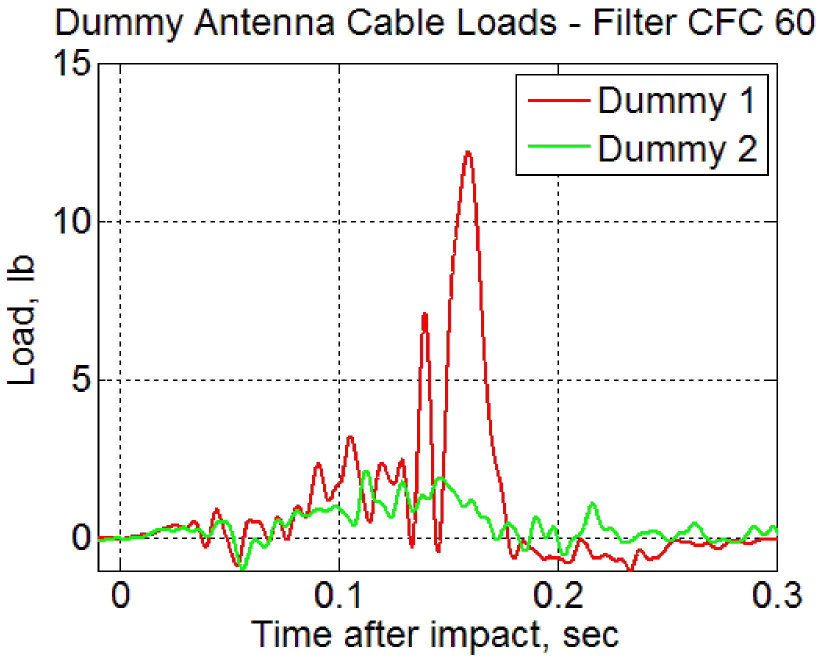

Figure 23 - Test 2 dummy antenna cable loads

All ELT beacons were disassembled post-test, after functional checkouts had been completed, with the focus being on ELT 4. The crash sensing unit, in this case a mechanical g-switch, from ELT beacon 4 was removed and the sidewall of the cylinder was carefully cut away. Figure 24 shows the disassembled g-switch.

Figure 24 – G-switch assembly for ELT beacon 4 on Test 2

Post-test visual inspections of both the disassembled ELT beacon and g-switch revealed no obvious mechanical defects which would cause the beacon to fail to activate. With the sidewall partially removed, the ball was moved to compress the spring without any noticeable obstruction. The performance issue on this ELT at this time is unexplained.

Test 3 Results

As with the Test 1 aircraft, the Test 3 aircraft arrived at LaRC with the original ELT installation present. As shown in Figure 25, the beacon was installed on the co-pilot side, in the forward tail section, directly behind the cabin-to-tail transition area. The aircraft attachment plate did not follow current installation standard [4], and was riveted directly onto the skin, and not attached to any primary structural elements. The beacon was secured in its mount via a tie wrap located at the forward end and a leather buckle in the middle. The antenna was located near the beacon, centered on the tail at the same approximate station location. Note the tie wrap has been removed from the aircraft attachment plate view.

Figure 25 - Test 3 original airplane ELT location (left) and aircraft attachment plate (right)

Five ELTs were installed for Test 3. ELT beacons 1 and 5 made were in a symmetric configuration, behind the pilot and co-pilot, under the location where the rear seats would have been located at station 65. ELT beacon 2 was mounted in the forward tail, on the pilot sidewall. ELT beacon 3 was wall mounted on the co-pilot sidewall, at a location just aft of station 65. ELT beacon 4 was installed in the approximate location as the original beacon, on the co-pilot side just aft of station 108. The original mounting plate was removed and a new mounting plate was used, which fastened to the airplane skin stiffeners in the tail. ELT beacons 2 and 4 were mounted such that they were in a symmetric arrangement along the airplane centerline. Dummy beacon 1 was located on the floor next to ELT beacon 1. Dummy beacon 2 was located on the co-pilot wall just below the rear window, next to ELT beacon 3. These ELT locations are highlighted in Figure 26.

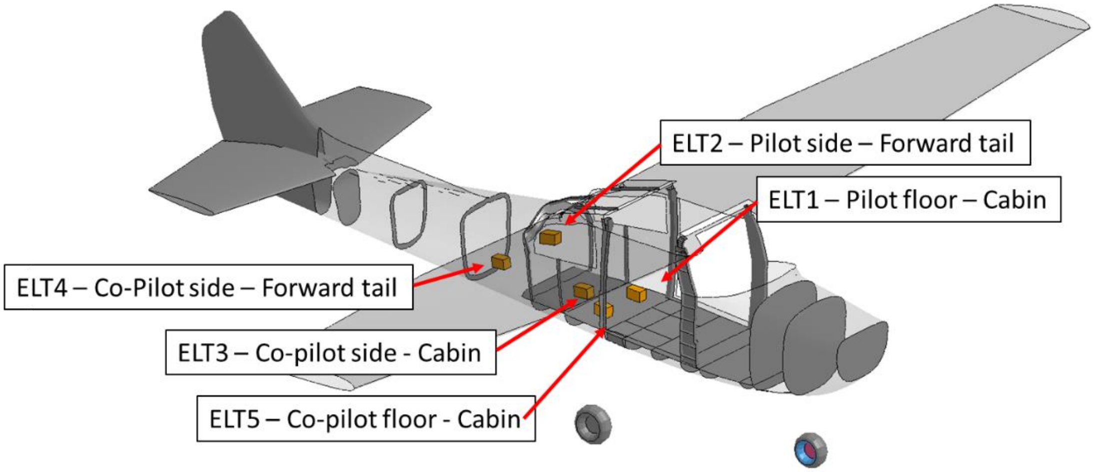

Figure 26 - Test 3 ELT beacon configuration

For ELTs 1, 2 and 5, the shortest cable run distance was implemented. The ELT 4 cable originated at the beacon location just aft of station 108, ran through frames at stations 140 and 172, and terminated at an antenna located aft of station 172. ELT 3 antenna cabling crossed frames located at stations 90 and 108. The longest runs were the two dummy ELTs. Dummy ELT 1 cabling ran under the floor of the cabin, crossed frames at stations 108, 140 and 172 and terminated at an antenna aft of station 172. The cable length was chosen such that the cable developed significant tension when attached to the beacon and antenna. Dummy ELT 2 included an antenna located forward of station 140. The cable, while having more slack than Dummy ELT 1, was purposely chosen to be almost the exact length as the run needed, causing very little slack to be present. Figure 27 shows an illustration of the ELT beacon (in red) and antenna locations (in black), with the cable runs noted.

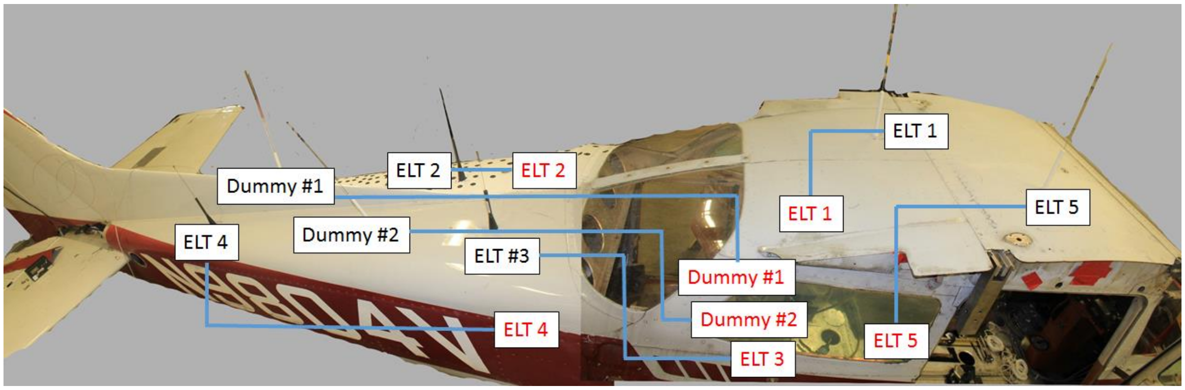

Figure 27 – Antenna locations for Test 3 with cable runs annotated

Test 3 occurred on August 26, 2015. The airplane CG impacted the soil at a flight path velocity of 66.1 ft./sec., consisting of a 56.9 ft./sec. horizontal and 23.6 ft./sec. vertical velocity components. The AoA was 8.0 degrees nose up with a pitch rate of +13.3 deg./sec.

There was a slight amount of roll (co-pilot high) and yaw (nose left) at impact. Due to these conditions, the pilot main gear impacted the soil initially. The tail contacted the soil 0.030 sec. after initial gear impact and the nose contacted the surface 0.116 sec. after impact. Similar to Test 2, the nose gear penetrated the soil surface and acted as a pivot point for the airplane to rotate around. The airplane started to exhibit noticeable rotation shortly after nose contact. At 0.138 sec. after impact, tail failure occurred, causing a large fracture at the tail-cabin junction to appear. The airplane landed upside-down 1.53 sec. after impact and rocked back and forth for an additional 3 seconds. The airplane came to rest approximately 5 sec. after initial impact. This sequence is depicted in Figure 28.

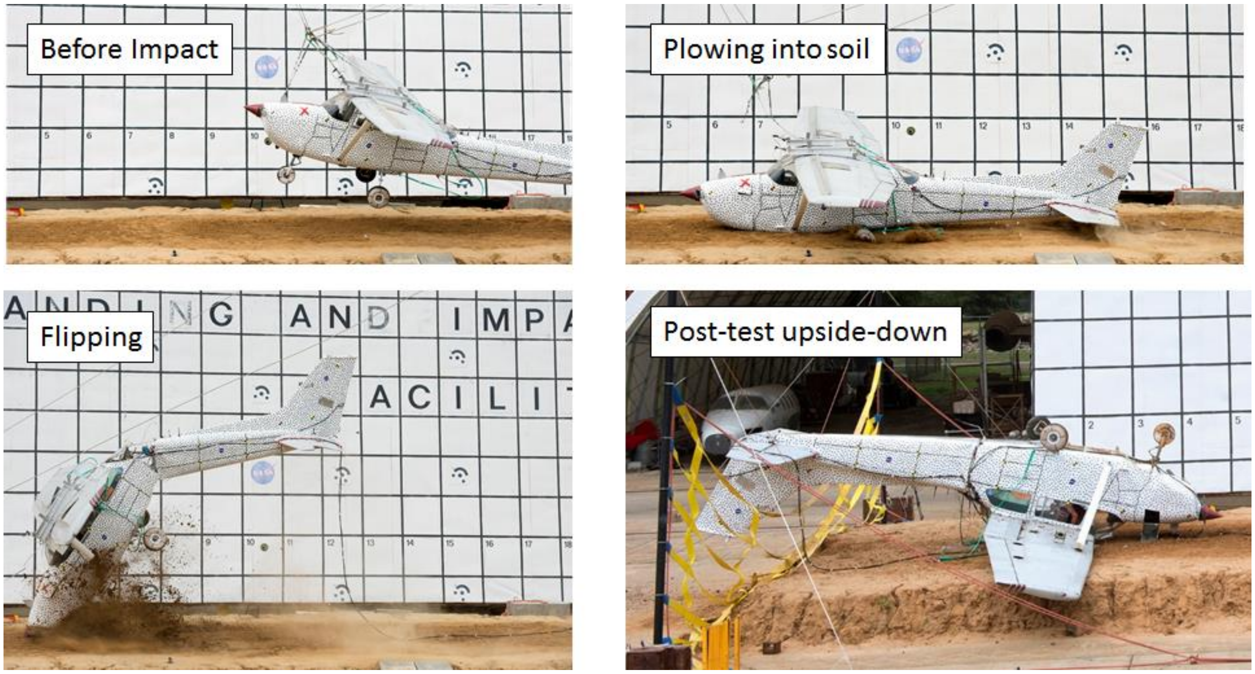

Figure 28 - Test 3 impact sequence

The airplane sustained major damage from the impact. Large amounts of deformation were seen in the engine area by the nose and firewall. The most noticeable failure that occurred was the tail separation from the cabin section. A fracture occurred at the tail-to-cabin transition area in the skin of the aircraft, causing the skin to fail on three sides. The only material holding the tail onto the rest of the airplane was a small section on the bottom of this area, and the tail hinged about this section. This fracture occurred very early in the crash event, during the time the airplane was plowing into the soil. During the flip over, the hinging caused the tail to become oriented at a 90 degree angle perpendicular to the fuselage creating a large opening at what would be the top of the tail/cabin connection.

As shown in Figure 29, horizontal accelerations were triangular in shape, with a pulse duration of 0.300 sec. The peak acceleration values occurred for ELT beacons 1, 2, 3, and 5 at approximately 0.168 sec. after impact, with the peak for ELT beacon 4 occurring a short time later at 0.200 sec. ELT beacon 4 showed more oscillations than the other ELT beacons, which affected its peak value. Visual inspections of the ELT beacon-to-mounting tray and aircraft attachment plate connections post-test revealed nothing unusual or loose regarding the instrumentation. The noise was attributed to physical differences in the sensors used. The peak accelerations occur at the point where the airplane nose is plowing through the soil bed. At 0.300 sec. after impact, the plowing has ended, and it is at this point where the airplane first begins to flip over.

As shown in Figure 29, the vertical accelerations resembled a trapezoidal shape of approximately 0.250 sec. in duration, with two defined peaks at the beginning and end of the plateau. The first peak occurs between 0.085 and 0.98 sec. after impact, depending on which ELT beacon is examined. The second peak occurs at an average time of 0.167 sec after impact. The first peak is due to the initial impact of the fuselage structure with the soil. The airplane rotation in which the nose finally impacts the soil causes the second peak a short time later. Maximum accelerations for the first peak range between 11.9 g for ELT beacon 1 and reach 19.4 g for ELT beacon 4. For the second peak, accelerations are more uniform but slightly higher, ranging between 19.2 g for ELT beacon 5 and 23.7 for ELT beacon 4.

Note that ELT beacons 2 and 4 are in symmetric arrangement in the forward tail, but experience large differences in the first peak of vertical accelerations. This finding is likely due to the slight amount of roll at impact. For the second peaks, which occur during the nose contact and plowing, the accelerations are more closely matched.

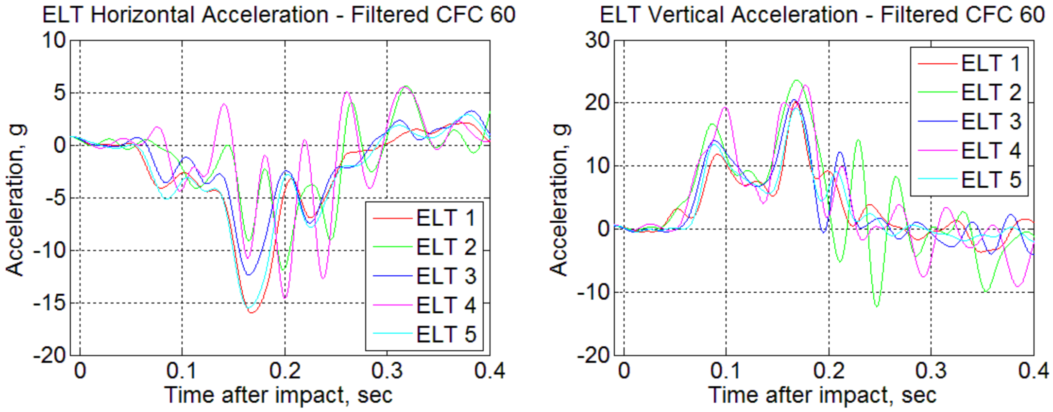

Figure 29 ELT beacon accelerations from Test 3

The change in velocity is presented in Table 5. Data are computed between 0.000 and 0.400 sec. For reference, peak accelerations described above are also included.

Table 5 - Delta velocity and peak accelerations for Test 3

ELT	Vertical Peak Acceleration (g)	Vertical Delta-v (ft./sec.)	Horiozntal Peak Acceleration (g)	Horizontal Delta-v (ft./sec.)
1	20.2	49.1	16.0	41.2
2	23.7	68.1	11.9	27.8
3	20.5	53.3	12.4	30.8
4	22.8	64.7	14.6	24.3
5	19.2	48.7	15.5	42.0

Four out of the five ELTs activated upon sensing the crash. ELT 2 was the beacon that did not activate automatically. Post-test inspections, conducted immediately after the impact, showed that the LED remote switch light was not blinking and the distress signal was not being received by any of the monitoring methods. ELT 2 was in the forward tail of the airplane, mounted symmetrically with ELT 4, which was the same make and model.

Antenna cabling connections showed signs of damage for three out of the six total connections. ELT 3 contained the only cable from the live ELTs that showed signs that the internal cable had partially detached from the end fitting. However, it did not prohibit the transmission of the distress signal to the satellites. The two dummy ELT connections showed much worse damage. Dummy connection 1 cabling was intact, but the end connection had displayed noticeable pullout from the end fitting. Dummy connection 2 cabling sustained even more damage. The end connection was still attached to the antenna; however, the cable had pulled out and physically separated. If this had been a live ELT connection, the beacon would not have been able to transmit the distress signal via the external antenna. The cable/antenna connection failures are shown in Figure 30.

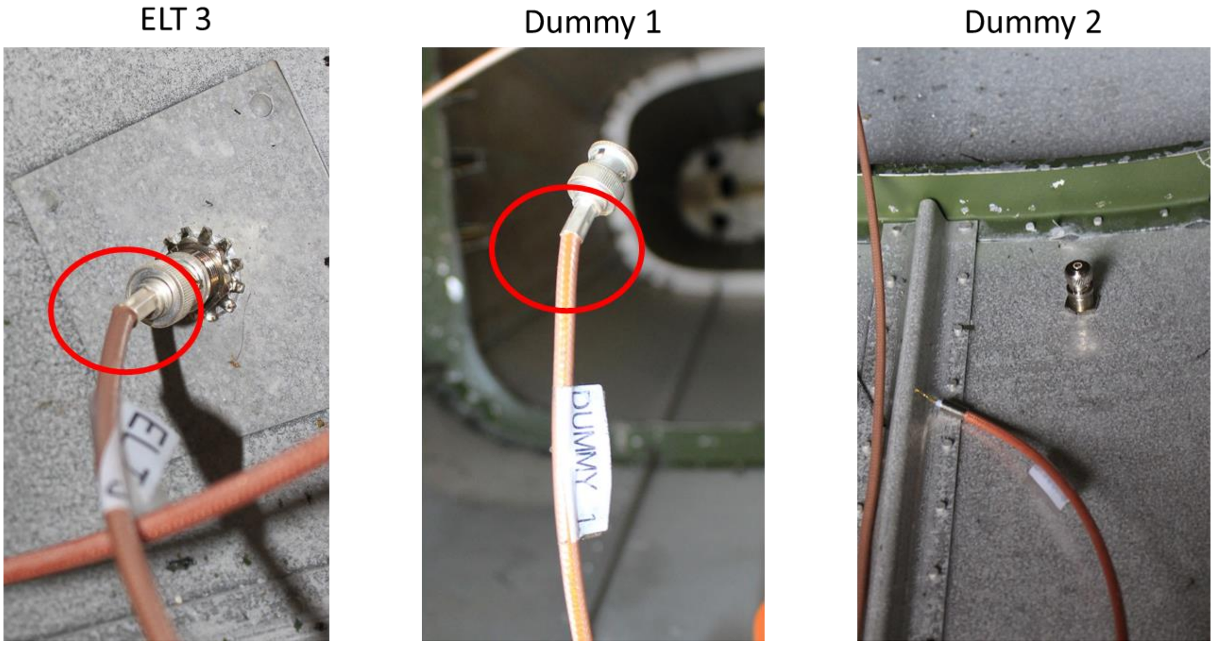

Figure 30 - Antenna cabling failures for Test 3

When examining the cabling layout diagram in Figure 27, the three connections that failed are the only ones that had crossed a production break between the cabin and tail of the airplane. The connections failed due to the large amount of deformation which occurred in the tail after the fracture initiated during the crash sequence. The long length of these connections was intentional, and specifically made in an attempt to magnify the failure response exhibited in Test 2. All other cable runs were made as short as practical, with one exception made for ELT 4. The cable spanned the entire tail length, originating from the beacon in the forward tail to the antenna in the rear tail. The loads measured from the dummy ELT cables are plotted, and shown in Figure 31.

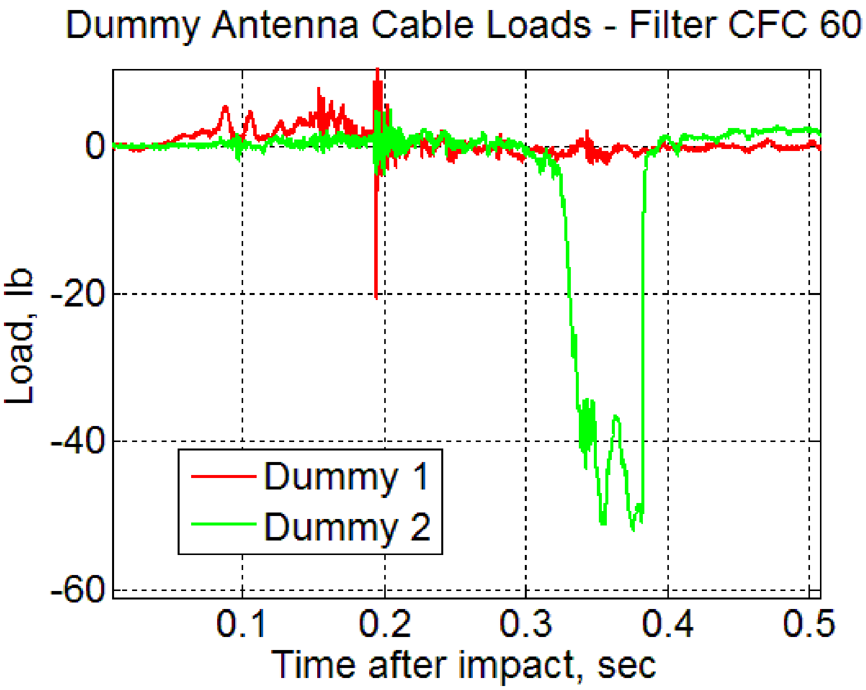

Figure 31 - Test 2 dummy antenna cable loads

At first glance, the negative loading in Dummy ELT 2 creates a cause for concern. The sign convention used for these tests indicates a tensile load to be a positive value and a compressive load to be a negative value. A pullout load would indicate a tensile loading condition, while a compressive load is somewhat nonsensical due to the lack of capability of the cable in sustaining a compressive load. However, posttest inspections determined that pulling on the cable from an angle of greater than 90 degrees applied relative to the load cell orientation caused a compressive load to be read in the load cell due to the bending moment.

This scenario is plausible because the antenna cable was attached into the BNC end which was attached to the load cell, which then attached to the dummy ELT weighted block. This configuration created a long moment arm extending from the load cell. Referring to Figure 8, both the load cell and BNC end were pointed forward, as they would be in a typical ELT beacon configuration. The antenna cabling attached to the dummy beacon, and then made a 180 degree change in direction turn after which it was subsequently routed under the assembly to an antenna in the tail of the airplane and pulled taught. During the crash when the airplane experienced the tail fracture, the subsequent hinging relative motion between the tail and cabin created tension on the cable, which pulled down on the dummy ELT 2 fixture. This downward motion created a bending moment at the load cell to dummy mass attachment location, and caused the load cell to register a negative reading. Dummy ELT 1 also experienced signs of cable pullout; however, during the timeframe of data collection, the pullout load was not able to be measured.

ELT beacons 2 and 4 were disassembled for further investigation. The beacon case, batteries, circuit boards, switches and wiring all appeared to be undamaged. The g-switches were extracted and a portion of the cylinder was carefully cut away to expose the internal ball and spring mechanism, as shown in Figure 32. The ELTs were identical models, acquired in a single procurement from a commercial vendor, mounted in a symmetric configuration in the forward tail, with sufficient measured acceleration and delta-v to initiate ELT activation.

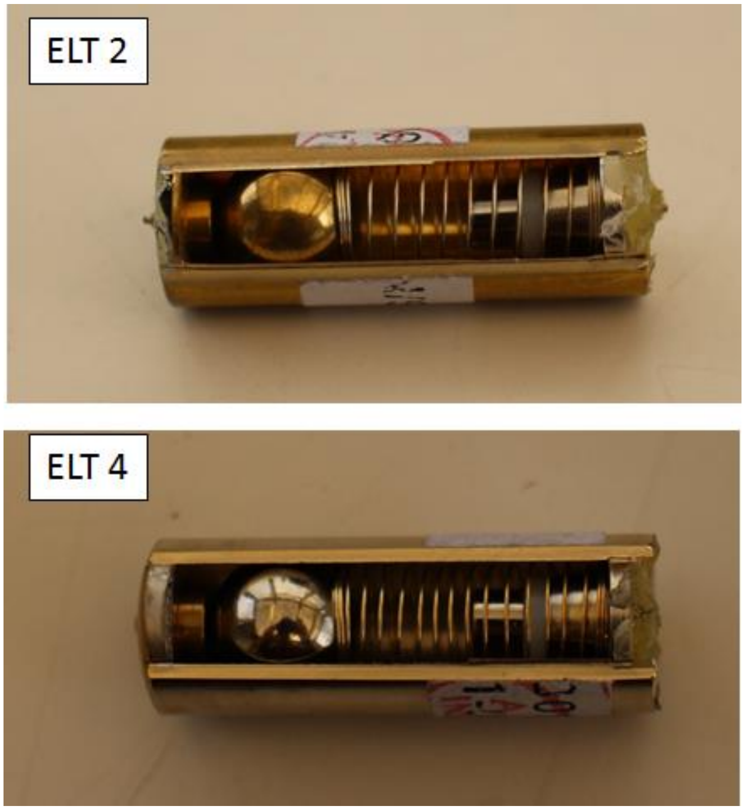

Figure 32 – G-switch assemblies for ELT beacons 2 and 4 on Test 3

First examination of the g-switch assemblies showed different materials used for the ball, spring and casing. The ball color varied between ELT beacons 2 and 4 and the spring contained a different number of wrapped coils. The physical weights of the units were within 0.2 gram of each other. The g-switches were then measured under a 1-g static load by placing them upright and examining the ball position and spring compression under gravity load only, as shown in Figure 33.

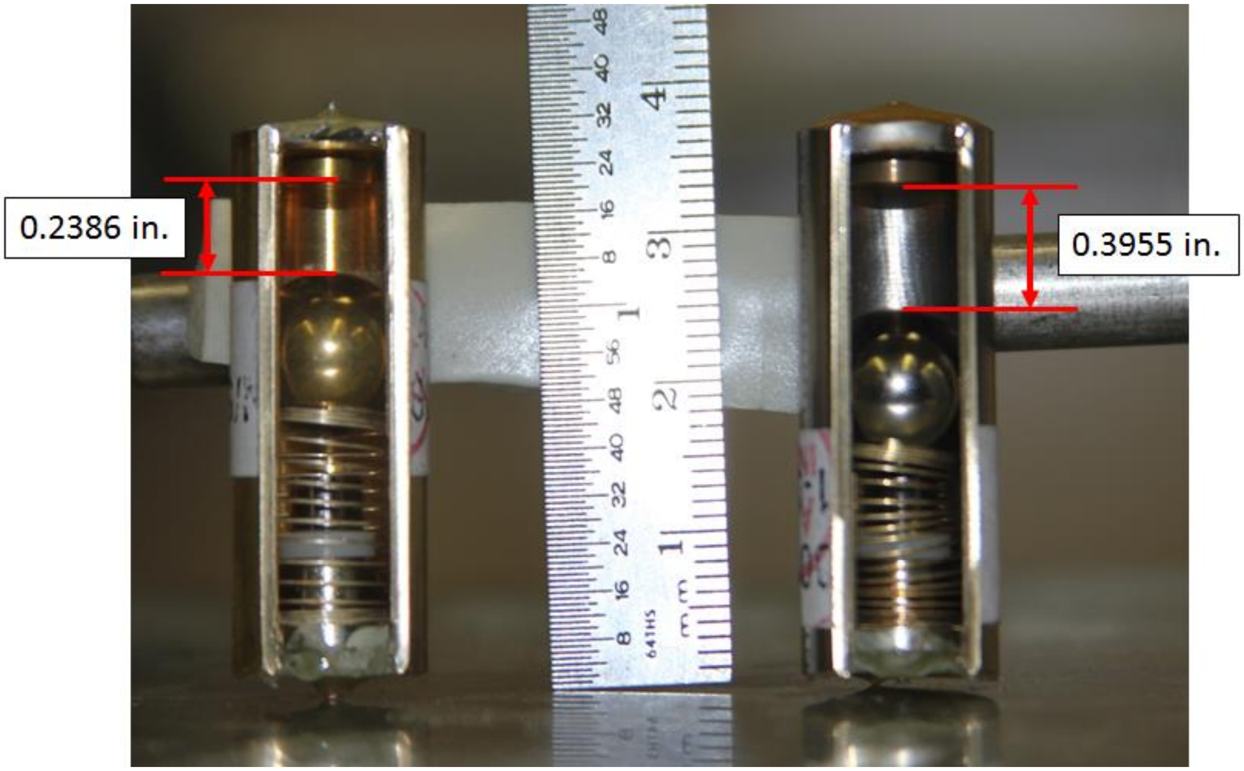

Figure 33 - G-switch assemblies for ELT beacons 2 and 4 on Test 3 under 1-g loading

It is clear from examining the ball position in Figure 33 that there are differences in the g-switch response under 1-g loading. The spring from ELT beacon 2 compressed 0.2386 in. while the spring from ELT beacon 4 compressed 0.3955 in. The spring on ELT beacon 4 compressed enough to allow the ball to make contact with the post in the middle. It is unknown whether the ELT 4 g-switch had arrived at LaRC in this condition or whether the crash caused the spring stiffness to change. The spring stiffness was unknown prior to g-switch disassembly. However, as with all units, once the ELTs had arrived at LaRC, they were put through functional checks to ensure proper operation. All ELTs, including Test 3 ELT 4, passed functional checkouts before being used in testing, and ELT 4 performed normally and activated upon sensing the impact from Test 3.

ELT beacon 5 was the only ELT from all three tests which did not use a mechanical g-switch sensor, but instead contained a solid-state sensor. This type of beacon required a constant connection to aircraft power both to operate the crash sensor under normal conditions and also to keep the internal ELT batteries charged in the case of the loss of aircraft power. The internal batteries allow the ELT the ability to operate under its own internal power should the aircraft power connection be lost for the minimum duration required by current ELT performance specifications. A ruggedized 28-volt battery was installed in the original airplane battery box to power the unit. ELT 5 performed nominally during the crash, both sensing the crash event, and sending a signal to the SARSAT system.

Discussion

All mounting systems performed as designed in each test. In all cases, the ELT beacon remained in its mounting tray, secured and not posing a threat to other onboard equipment. All restraints remained closed and all cabling remained attached. For aircraft attachment, the beacon attachment plates interfaced with primary aircraft structure. NASA followed all applicable requirements and incorporated guidance from aircraft technicians in order to replicate traditional in-service methods.

G-switch activation performance was inconsistent across the test series. Out of the 14 ELTs, 12 beacons activated automatically. However, evidence suggests that 3 out of the 4 ELTs in Test 1 may have activated due to post-crash vehicle arrest by the catch net. All non-activated ELTs were disassembled for post-test inspections in an attempt to identify a possible root-cause for non-activation. In the case of the non-activated ELT on Test 2, the internal ELT beacon structure, along with internal components of the g-switch assembly appeared to be fully intact, with no apparent signs of damage or wear. In the case of the non-activated ELT on Test 3, the unit was disassembled and compared to an identical, functional ELT mounted in a similar location in the airplane. Upon inspection and comparison of the g-switches, noticeable differences were observed, suggesting that a difference in performance would be expected.

ELT 5 in Test 3 was the only ELT beacon which used an active solid-state crash sensor. This sensor was non-mechanical in nature and required that it be connected to aircraft power for normal operations. This ELT performed nominally.

Critical data were obtained from examining the different types of antenna cable run conditions. Cables which intentionally did not use best practice guidelines were much more susceptable to damage, especially under large aircraft deformation. Four cases of cable pullouts were observed, and all occurred on long cable runs. Some type of cabling damage occurred on almost all instances where a long run was present, and where the antenna cable spanned the cabin/tail junction. It was also noted that the damage to the cabling was insensitive to cable brand or type. In general, crashworthiness of cabling system was improved when the antenna was installed in the same longitudinal station of the airframe as the beacon and when best practice guidelines were followed for including cable slack and usage of tethers.

Conclusions

Three airplane crash tests containing either four or five Emergency Locator Transmitter (ELT) systems were documented in this report. The tests, considered severe but survivable in terms of occupant survival, offered significantly different impact environments in which various makes and models of ELTs were required to operate, and provided valuable data to examine ELT performance. The first test simulated a hard or emergency landing onto a rigid surface with subsequent impact into a compliant barrier or obstruction. The second and third tests simulated controlled flight into terrain conditions, either nose up or nose down. In each of these tests, the ELTs were installed in a variety of locations and orientations representative of typical in-service configurations. All ELT activations and transmissions were monitored using a variety of methods, and failure of ELT cabling was examined using cable tension readings, and visual inspections.

Examination of the results showed inconsistent crash sensor performance and a variety of antenna cable failures that occurred when best practice installation guidance was not followed.

It is anticipated that the data generated in this study will assist in identifying methods for improving the installation and performance of ELT systems. Future recommendations to the RTCA will incorporate lessons learned from this test series with the goal of assisting the design and installation of higher performing ELT systems. In the past, TSOs have successfully initiated changes in ELT designs. It is conceivable that future guidance can be issued to update installation requirements based on the results presented.

Hopefully, a pilot never encounters a situation where their ELT must be used. If this unfortunate circumstance does occur, the functionality of the ELT system must be reliable, and the data collected from this study will assist in achieving this goal.

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References

1. Stimson, C.M., et al. “Emergency Locator Transmitter Survivability and Reliability Study.” NASA-TM-2016. In Publication.
2. Littell, J.D., and Annett M.S. “ATD Occupant Responses from Three Full-Scale General Avation Crash Tests.” NASA-TM-219175. March 2016.
3. Annett, M.S., Littell, J.D., Stimson, C.M., Jackson, K.E., and Mason, B.H. “Full-Scale Crash Tests and Analyses of Three High-Wing Single Engine Aircraft.” 2015 Aerospace Structural Impact Dynamics International Conference. November 17-19, 2015. Seville, Spain.
4. RTCA DO-204A. “Minimum Operational Performance Standards for 406 MHz ELT.” December 2007.
5. NTSB Press Release. “Acting Chairman Hart Announces Slight Drop in 2013 Transportation Fatalities in Most Categories.” www.ntsb.gov/news/press-releases/Pages/PR20150202.aspx, February 2015.
6. NTSB Safety Alert 030. “’Armed’ for Safety: Emergency Locator Transmitters.” December 2013.
7. Trudell, B.J. and Dreibelbis, R.R. “Current Emergency Locator Transmitter (ELT) Deficiencies and Potential Improvements Utilizing TSO-C91a ELTs.” NASA-CR-4330. October 1990.
8. ATSB Transport Safety Report. “A Review of the Effectiveness of Emergency Locator Transmitters in Aviation Accidents.” AR-2012-128. May 2013.

9. Jackson, K.E., Boitnott, R.L., Fasanella, E.L., Jones, L.E., and Lyle, K.H. “A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center.” NASA-TM-20040191337. January 2004.
10. Carden, H.D. “Evaluation of Emergency-Locator-Transmitter Performance in Real and Simulated Crash Tests.” NASA-TM-81960. April 1981.
11. Littell, J.D. “Crash Tests of Three Cessna 172 Aircraft at NASA Langley Research Center’s Landing and Impact Research Facility.” NASA-TM-218987. November 2015.
12. RTCA Paper No. 132-77/SC127-33. “Light Aircraft Longitudinal Crash Pulse Data.” 1977.
13. Hall, D.S. “Systems Analysis of the Installation, Mounting, and Activation of Emergency Locator Transmitters in General Aviation Aircraft.” NASA-CR-160036. CRI-7846-14. January 1980.
14. RTCA DO-160G. “Environmental Conditions and Test Procedures for Airborne Equipment - Section 8, Vibration.” December 2010.
15. Society of Automotive Engineers. “Surface Vehicle Recommended Practice: Instrumetation for Impact Test –Part 1 – Electronic Instrumentation.” SAE J211-1. July 2007.
16. Federal Aviation Administration. “TSO-C126b, 406 MHz Emergency Locator Tranmitter (ELT).” Technocal Standard Order C126b. November 26, 2012.

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14. ABSTRACT

Full-scale crash tests were conducted on three Cessna 172 aircraft at NASA Langley Research Center’s Landing and Impact Research Facility during the summer of 2015. The purpose of the three tests was to evaluate the performance of commercially available Emergency Locator Transmitter (ELT) systems and support development of enhanced installation guidance. ELTs are used to provide location information to Search and Rescue (SAR) organizations in the event of an aviation distress situation, such as a crash. The crash tests simulated three differing severe but survivable crash conditions, in which it is expected that the onboard occupants have a reasonable chance of surviving the accident and would require assistance from SAR personnal. The first simulated an emergency landing onto a rigid surface, while the second and third simulated controlled flight into terrain. Multiple ELT systems were installed on each airplane according to federal regulations. The majority of the ELT systems performed nominally. In the systems which did not activate, post-test disassembly and inspection offered guidance for non-activation cause in some cases, while in others, no specific cause could be found. In a subset of installations purposely disregarding best practice guidelines, failure of the ELT-to-antenna cabling connections were found. Recommendations for enhanced installation guidance of ELT systems will be made to the Radio Technical Commission for Aeronautics Special Committee 229 for consideration for adoption in a future release of ELT minimum operational performance specifications.

15. SUBJECT TERMS

Airplane testing; ELT; Emergency locator transmitter; Full scale crash testing; Impact testing

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