Autonomous Flight Safety System – Phase III

The autonomous flight safety system is an independent and autonomous flight termination subsystem intended for expendable launch vehicles. It uses tracking and attitude data from an onboard GPS and inertial measurement unit sensors and configurable rule-based algorithms to make flight termination decisions. The system is a joint Kennedy Space Center and Wallops Flight Facility project.

The autonomous flight safety system testing and development philosophy is a graduated approach, emphasizing bench tests and flight tests of incremental system changes using available resources and clearly defined objectives. Data from each test is carefully analyzed and used to identify the current system's performance and any problems that need to be resolved before changes are made.

The ultimate objectives of the autonomous flight safety system are to increase capabilities by allowing launches from locations that do not have existing range safety infrastructure, reduce costs by eliminating some downrange tracking and communications assets, and increase safety by reducing the reaction time for flight termination decisions.

First Test Flight—White Sands Missile Range 2006

The autonomous flight safety system first flew on the Terrier Improved-Orion, two-stage sounding rocket shown right at White Sands Missile Range on April 5, 2006. A single-chassis, dual-processor, dual-GPS system was used.

Purpose of Flight. The primary purpose of the flight was to demonstrate the key elements of the autonomous flight safety system concept of operations pertaining to pre-launch set-up (loading and verifying the application and configuration files), bench testing, vehicle integration, in-vehicle end-to-end testing, countdown system verification procedures, and flight operations. A secondary purpose was to gather lessons learned which could be codified into the Autonomous Flight Safety System System Level Requirements document currently under revision.

Test. The test incorporated redundant GPS sensors and used two independently programmed processors. One was loaded with a nominal trajectory and the other programmed with artificial rules under which the nominal flight would violate safety parameters and provoke termination commands. The autonomous flight safety system was not connected to actual explosives. The system functioned and reacted correctly during the entire flight from launch to parachute deployment.

Mission Rules. Two different sets of mission rules were developed for this test, one for each processor. The set for Processor 1 (designated as the *nominal* processor) was configured so that a nominal flight would not result in any flight termination actions. The set for Processor 2 (designated as the *errant* processor) included three additional rules so that multiple destruct activations would occur during a nominal flight. *The autonomous flight safety system was not connected to a flight termination system and it could not initiate any destruct actions.*

The prelaunch success criteria of loading and verifying the application and configuration files and verifying that the applications were running correctly using simulated sensor data were satisfied. The rocket behaved nominally and the software performed as expected. The nominal processor did not

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execute any unplanned destruct actions and the errant processor successfully initiated three destruct actions as planned.

The Ashtec G12 GPS receiver lost lock on liftoff and did not regain it until after the flight was over. The Javad GPS receiver maintained lock throughout the flight. Both processors were operational during the flight and provided navigation and status messages via the vehicle telemetry stream. Navigation and status messages were stored in the nominal processor's nonvolatile (flash) memory for the entire operation, but the errant processor's flash memory chip became partially dislodged during the flight and stopped recording at T+335 seconds. Otherwise, the hardware performed as expected.

Second Test Flight—Kwajalein Reagan Test Site 2007

An autonomous fight safety system developmental test article flew on the SpaceX Falcon 1 expendable launch vehicle from the Kwajalein/Reagan Test Site on March 21, 2007. The primary test item was a single autonomous fight safety system chassis containing redundant flight processors, a custom-built voting circuit known as the *command and switching interlock circuit*, a power supply module, and a GPS receiver. An externally mounted GPS receiver for navigation solution redundancy and a 10-Watt Low-Cost Tracking and Data Relay System (TDRS) Transceiver (LCT2) for a space-based range demonstration were also flown.

The Falcon I, shown right, is a two-stage, liquid oxygen and rocket-grade, kerosene-powered launch vehicle designed to achieve substantial improvements in reliability and cost and to deliver 480 kilograms (1058 pounds) to an orbit of 200 kilometers at 28.5° inclination. The first stage is almost entirely reusable and returns via parachute to a water landing. Lift-off weight for the standard Falcon I is approximately 27,000 kilograms (60,000 pounds), length is about 22 meters (70 feet) and diameter is 1.67 meters (5.5 feet).

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Minimum Success Criteria

The minimum success criteria for this test were met and included the following:

Power-up, configure, verify configuration and test both flight processors and the command and switching interlock circuit during countdown operations.
Acquire and maintain a navigation solution on the internal GPS throughout the terminal countdown.

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Maintain at least one GPS navigation solution throughout all portions of flight where the GPS antenna axis had a positive elevation angle. Correlate all GPS outages with unfavorable antenna attitudes using the vehicle attitude data.
Confirm proper application of Green Time destruct rule for portions of the trajectory with insufficient GPS coverage.
Maintain sufficient telemetry data coverage from launch to orbit insertion (100 kilometer perigee) to transmit valid navigation data from at least one GPS receiver and mission rule evaluation status from at least one processor. Telemetry outages are permissible; however, there must be coverage over 50 percent of the flight time with outages that do not exceed 10 seconds in duration.
Evaluate the full set of mission rules on at least one processor from launch to orbit insertion.

Test Configuration. The test article was configured with a telemetry link from each of the two flight processors within the autonomous flight safety system chassis. The link from flight processor 0 (FP0) was routed through the Falcon 1 line-of-sight telemetry system. The link from flight processor 1 (FP1) was routed through the LCT2. Despite the previous successful completion of compatibility testing with launch vehicle systems, a concern was raised on launch day that LCT2 could potentially interfere with the vehicle GPS. With insufficient time available to permit additional conclusive testing, a decision was made by the Falcon 1 launch management team to fly with the LCT2 powered off. As a result, detailed mission rule response data was not available from FP1 for post-test analysis.

Test Results. The telemetry data integrity from FP0 was satisfactory throughout the entire flight, with no data dropouts prior to L+6 minutes. From L+6 minutes through the remainder of the propulsive phase of flight, there were 8 telemetry dropouts less than 0.3-seconds in duration. The GPS receiver housed within the autonomous flight safety system chassis maintained a navigation solution throughout the flight with no observed dropouts.

Both GPS receivers maintained navigation solutions throughout the flight with four observed momentary dropouts experienced after the onset of the vehicle anomaly. The autonomous flight safety system sensor redundancy management algorithms were able to properly cross-compare the two solutions and supply navigation data to the onboard range safety algorithm modules throughout the flight. The voting circuit properly responded to commands from the two flight processors throughout the flight.

The autonomous flight safety system properly detected lift-off and enabled the appropriate flight termination mission rules. A test exclusion zone was included in the mission rule set to simulate a flight termination event in the nominally planned vehicle trajectory. Both flight processors properly issued and released ARM and FIRE commands to the voting circuit when the vehicle instantaneous impact point intruded and exited the test exclusion zone. Both processors issued ARM and FIRE functions associated with the anomalous vehicle performance experienced during flight. Using the available telemetry data, it was confirmed that the FP0 termination command was issued due to a violation of a moving-gate rule established to catch erratic flight from “in-plane” vehicle failures.

Post-Flight Analysis. During post-flight analysis, a number of anomalies were observed and investigated. Shortly after launch, an anomaly in the navigation solution issued by the externally housed GPS receiver caused FP0 to improperly flag stage 1 burnout and stage 2 ignition events. Stage 2 ignition was flagged at T+18.0 seconds when it really occurred at T+176 seconds.

The GPS solution anomaly was traced to marginal satellites swapping in and out of track. This was a known vulnerability for this test article, and an attempt was made in the mission rule design to decouple all of the flight termination rules from in-

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flight detection of staging events to prevent spurious event detections from affecting the processing of mission rules. In the future, acceleration data from one or more inertial measurement units will be used for in-flight ignition and burnout event detection.

Both processors issued ARM and FIRE functions when it was expected that the moving-gate would have overtaken the instantaneous impact point because of anomalous flight conditions. FP1 issued ARM/FIRE commands approximately 163 seconds after FP0 issued its commands for the moving-gate rule. This lack of synchronization was caused by a set-up error in the configuration of the second stage moving-gate rule that resulted in the use of the elapsed time from second stage ignition as the time reference for the tabulated gate coordinates instead of time from launch in combination with the erroneous stage 2 ignition detection by FP0.

Comprehensive Minimum Success Criteria. In spite of these anomalies, all of the established minimum success criteria noted above were met. Moreover, two of the three comprehensive success criteria given below were met:

All Minimum Success Criteria are met.
Sufficient telemetry data exists to show that all hardware and software configuration items within the autonomous flight safety system RT4 chassis functioned properly through countdown, launch, and the entire propulsive phase of flight. This includes verification of proper functioning of the two flight processors, the command and switching interlock circuit, and the internal GPS.
A navigation solution was maintained on any GPS through enough of the propulsive phase of flight to avoid a Green-Time destruct violation.

Criterion 2 could not be met because the LCT2 was the only path for telemeter detailed status data from FP1.

Results of Rocket Tests

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED07-0090-05 Date: May 3, 2007 Photo by Lori Losey

The results of these rocket tests has led to improvements in the autonomous flight safety system design concept and the general functional requirements set for autonomous flight termination. Work continues on improving the autonomous flight safety system by making the chassis more rugged, formalizing the requirements and design, and adding a loosely coupled GPS/Inertial Navigation Solution to improve the reliability of the autonomous flight safety system sensor suite.

A prototype of this GPS/Inertial Navigation Solution was flown on an F104 at Kennedy Space Center on November 8, 2007. The equipment was integrated on the F104 and recovered undamaged, but the GPS receiver did not function properly for reasons still being investigated. Consequently, insufficient data was collected to determine how the GPS/ Inertial Navigation Solution system performed.

A second set of flights is planned for January 2008.