Testing a Flight Control System for Neutron-Induced Disturbances

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Atmospheric neutrons can cause single-event upsets in the microelectronic devices used in aircraft systems. Reducing the effects of those upsets is most important to the aircraft industry. We tested the robustness of a flight control computer containing our new rapid-recovery architecture by irradiating it in a beam of intense neutrons at the Irradiation of Chips and Electronics (ICE) House in Los Alamos. For a realistic test, the flight control computer was connected in a closed loop to a flight simulator. According to the results, our new architecture enabled the computer to recover from neutron-induced electronic upsets with no loss of flight control.

Individual cosmic rays were first suspected of causing temporary upsets in the electronics of orbiting satellites in 1975 (Binder et al.). By 1979, electronic upsets caused by cosmic rays in the atmosphere, as well as in space, had been studied in detail (Ziegler and Lanford). In 1992, Taber and Normand found that neutrons generated by cosmic rays in the atmosphere can cause "single-event upsets" (SEUs) in avionic systems during flight. A Naval Air Systems Command (NAVAIR) Avionics Working Group completed a survey of SEU phenomena and research in 2000 (Chambers). It is now clear that the effects of SEUs may become more severe as the feature sizes and operating voltages of modern microelectronic devices decrease.

The avionic systems used in commercial aviation are built with off-the-shelf microelectronic devices, which are not specifically designed for the neutron radiation environments in which aircraft fly. Shielding the avionics from atmospheric neutrons in order to overcome radiation effects is not feasible because of the extra weight that would have to be added. Using radiation-hard circuits in those systems would be prohibitively expensive for the commercial aircraft industry.

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Although the extent of SEUs in avionic systems has not been quantified, it is important to mitigate their potential effects. Our research shows that changing the computer architecture achieves efficiently and cost effectively the required system performance in the presence of atmospheric neutrons.

In the late 1990s, we studied the effects of electromagnetic events, such as lightning and nearby radar, on a flight control computer connected in a closed loop to software simulating the flight of a Boeing 737. For the flight control computer, we developed a new architecture aimed at mitigating the effects of upsets caused by those electromagnetic events (Belcastro 1998a and 1998b, Hess 1997 and 1999, Eure 2001). The new architecture allows a putative flight-control computer to recover its functionality rapidly and is described in the box “A Rollback Rapid-Recovery Computer Architecture” to the right.

In 2002, when the effects of neutron radiation on avionic systems were much discussed in the aviation community, NASA Langley Research Center, the Federal Aviation Administration, Los Alamos Neutron Science Center (LANSCE), Honeywell International, Inc., and Old Dominion University formed a research partnership whose goal has been to study the effects of atmospheric neutrons on flight systems that implement functions whose failure would be catastrophic to the aircraft. We decided to test our new computer architecture developed for studying the effects of electromagnetic events by irradiating the flight control computer with neutrons.

A Rollback Rapid-Recovery Computer Architecture

We tested a new computer architecture to detect and mitigate the effects of “soft” and “hard” faults in a hybrid flight-control computer (Belcastro 1997, Belcastro 1998a). A soft fault occurs when some event (neutron, lightning, and others) unintentionally changes the output of a digital circuit within a computer from “zero” to “one” or vice versa. After the fault, the circuit still functions properly, but the fault introduces an error into the system resulting in anomalous performance. The proper performance of the system will be restored when the change is cleared by placing (for example, by rebooting) the circuit into its proper state. A hard fault occurs when a circuit continues to generate errors because of damage by some event, and proper performance cannot be restored until the circuit is repaired.

At every clock cycle, the fault-detection hardware compares the flight-critical commands computed by the two microprocessors bit by bit (Figure A). If the two commands do not match, they are discarded, and the critical data for a previously computed command are retrieved from protected memory and used instead for computing the new command. Thus, essentially, the flight control computer recovers from the fault by rolling back to a previous command.

Our tests with the LANSCE neutron beam show that a flight control computer with this architecture will recover from SEUs induced by neutrons at the cruise altitudes of commercial airlines.

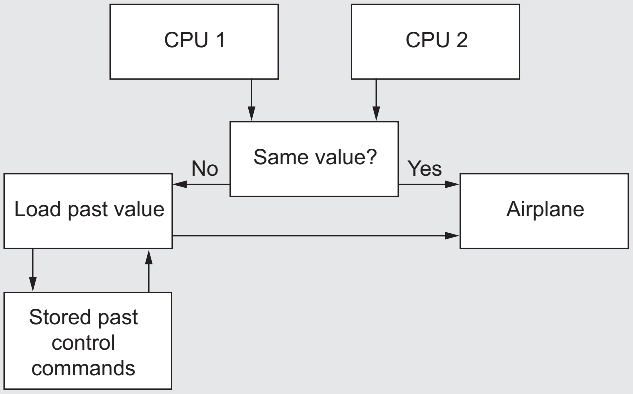

Figure A. Diagram of Rollback Computer Architecture

The neutron beam at LANSCE’s Irradiation of Chips and Electronics (ICE) House made these studies possible. The neutrons in the beam have an energy spectrum similar to that of atmospheric neutrons but a million times the intensity. This high intensity allows researchers to study neutron-induced SEU effects a million times faster than if the tests were done with natural neutrons in the atmosphere. Dozens of companies, including Honeywell International, Inc., have used the ICE House since 1992 to study the SEU-induced failure rates of individual microelectronic devices exposed to neutrons (refer to page 96 in the article “The ICE House”). However, ours is the first partnership to have tested the ability of a closed-loop flight control system to recover rapidly from the effects of neutron-induced SEUs. In our experiments at the ICE House, the computer operated successfully while being irradiated.

Testing the Recoverable Flight Control Computer with Neutrons

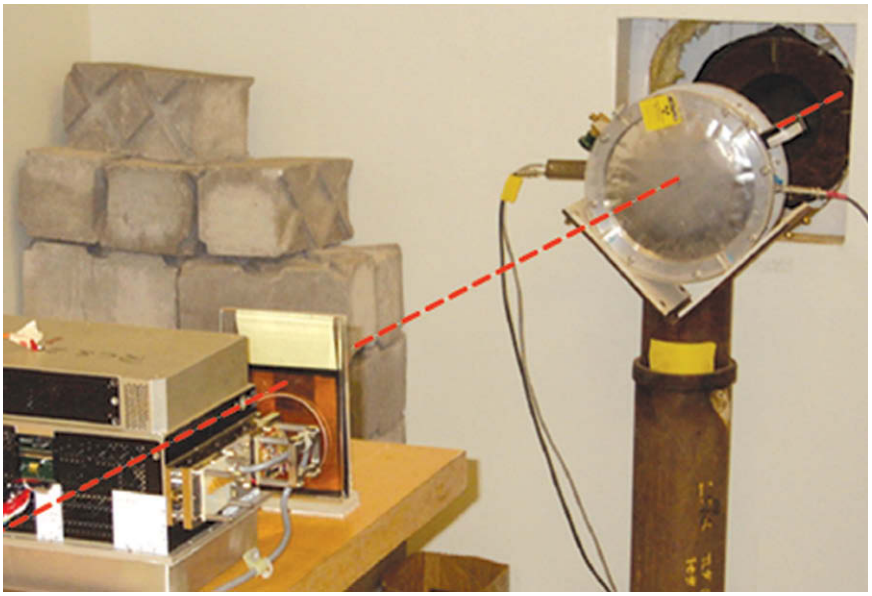

Figure 1. ICE House Tests
The rapid-recovery hybrid flight-control computer is aligned in the neutron beam at the ICE House at LANSCE.

Test Procedures. We conducted the ICE House experiments between February 20 and February 24, 2004. Figure 1 shows the closed-loop flight control computer positioned in the LANSCE neutron beam at the ICE House. During neutron exposure, the computer controlled the simulated aircraft's ailerons and elevators. Figure 2 identifies these surfaces that control motion. The ailerons control the aircraft's roll and yaw (banking of its wings); the elevators control the aircraft's pitch. The simulated flights were level at 34,000 feet with an option to apply random wind gusts. During the experiments, we recorded the flight conditions provided by the simulation, as well as the commands issued by the flight control computer.

The computer contains microelectronics from the 1990s, whose feature sizes are 1 micrometer or less, an important detail because the smaller the size of the electronics, the higher the SEU rates. As mentioned before, we also used this computer in our studies of electromagnetic events. This computer is a modified version of the computer used in a Boeing 777 Airplane Information Management System (AIMS), and we will therefore refer to it in the rest of this article as the "hybrid" flight-control computer. To use the AIMS computer as a flight control computer, we first stripped it of all AIMS avionic tasks (including flight management, displays, monitoring the airplane's condition, thrust management, digital flight data, and the engine data interface) and then reprogrammed it to conduct flight control commands. The computer has a dual-lock-step architecture, which involves two microprocessors that compute commands simultaneously. If the two computed commands do not match, they are discarded, and data are retrieved by "rollback" to previously executed commands. Rollback requires additional memory for storage of the previously executed commands. Finally, as we did in our electromagnetic experiments, we connected the computer in a closed loop with software simulating the flight of a Boeing 737 aircraft. (For safety reasons, several flight computers doing the same calculations in tandem are normally used on an actual aircraft.)

For the tests at the ICE House, we replaced the circuit card assembly of the computer's power supply with four external current-limited power supplies. The purpose of these power supplies was to avoid damage to components that might latch up during the experiment. During a neutron-induced single-event latchup, a device gets stuck in a high-current state that could damage it. If the current exceeds the threshold of a current-limiting power supply, the power supply shuts down before the device can be damaged.

We performed 100 tests in which the hybrid flight-control computer was exposed to the neutron beam and approximately 100 baseline tests in which it was not. Each test lasted 60 minutes unless it was aborted for some reason. Our goals were to measure how many soft faults occurred during a test in which the computer was or was not exposed to the beam and to observe whether the architecture allowed the computer to recover rapidly from any soft faults that occurred during a test. Measuring how frequently a soft fault occurred when a specific portion of the computer was exposed to the neutron beam—whose flux we also measured—allowed us to predict how frequently a fault will occur when that portion of the computer is exposed to the flux of atmospheric neutrons at airline cruise altitudes.

We were able to expose specific groups of the computer's digital circuits during the experiments because the neutron beam's cross section was much smaller than the area of any side of the hybrid flight-control computer. In fact, 11 individual groups, or "positions," were exposed in the tests. Table I provides exposure instructions

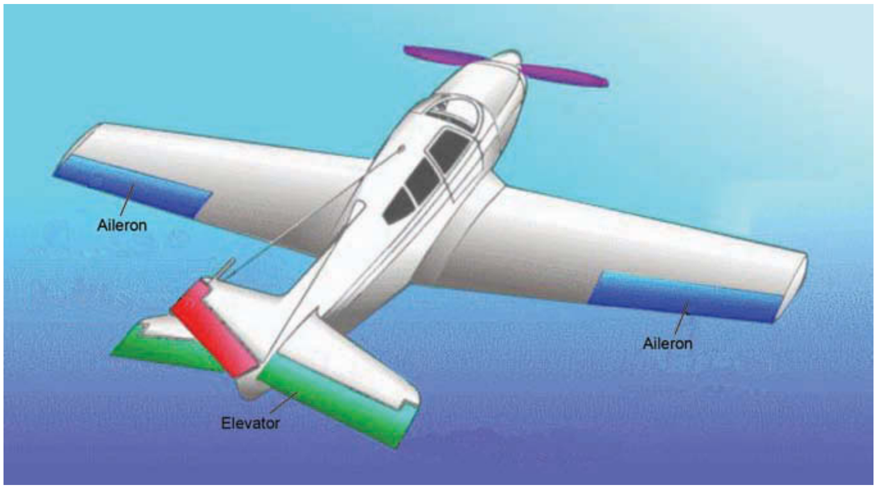

Figure 2. Placement of Ailerons and Elevators
Shown here are the simulated aircraft's ailerons and elevators controlled by the flight control computer during the neutron exposure tests.

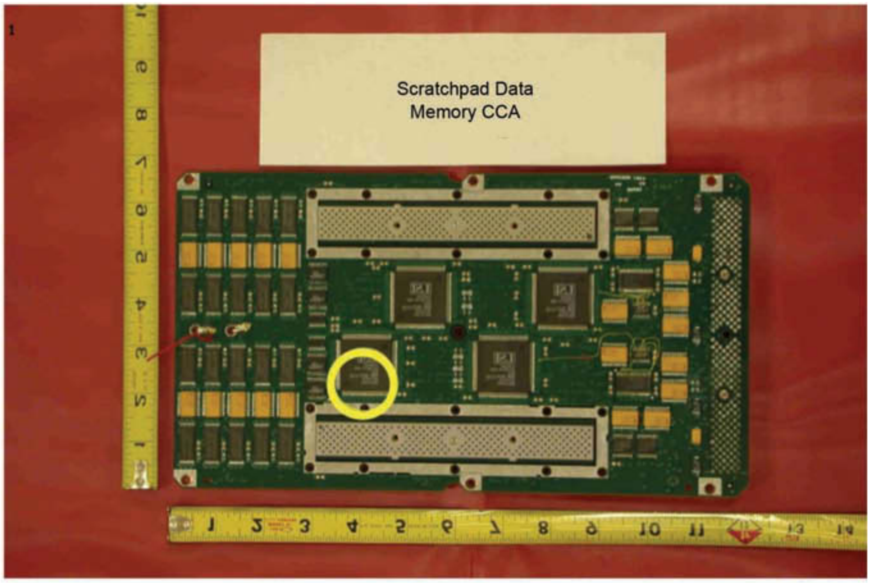

Figure 3. Neutron Beam Exposure for Position 3
For this position, the neutron beam, suggested by the yellow circle, exposed a large portion of the scratchpad data memory in the circuit card assembly (CCA).

for each of the positions of the flight control computer in the neutron beam. Figure 3 is a photograph of the circuit card exposed at position 3.

Our Los Alamos collaborators used Fuji Film image plates to measure the diameter of the neutron beam and a neutron counter to measure the total number of neutrons per square centimeter striking a given position during the exposure time, or the time-integrated neutron flux. The data obtained from the image plates also allowed us to identify the circuits exposed at each position.

An image plate displays the two-dimensional distribution of the time-integrated neutron flux. When scanned by a laser beam, the image plate emits an amount of light proportional to the total number of neutrons absorbed at the scan point, an effect called photo-stimulated luminescence. Figures 4a and 4b are false-color images of the data obtained with the image plates. In these images, red indicates high values of time-integrated neutron flux, and purple indicates low values (following the rainbow's color order). This pair of images was obtained by placing an image plate just in front of the spot where the beam entered the flight-control computer and just behind the spot where the beam exited the computer.

Los Alamos collaborators also provided the image plate data in two other forms. Figure 4c shows the image plate data displayed as a black-and-white x-ray image, which allowed us to see exactly which components were illuminated by the neutron beam for a given position. Figure 4d shows horizontal and vertical line scans of the image-plate data, which allowed us to measure precisely the width of the neutron beam in two perpendicular directions.

Knowing the time-integrated neutron flux before the beam entered the flight-control computer for each position allowed us to calculate the probability that an SEU will occur for that position over a given period for the flux of cosmic-ray neutrons at a given flight altitude. We calculated these probabilities from the cross sections measured during the tests, as described below.

Test Results. The measured fluxes of the incident neutron beam were all about a million times the flux of atmospheric cosmic-ray neutrons at an altitude of 34,000 feet. The conditions at the ICE House are therefore ideal for performing accelerated tests of the susceptibility of avionic systems to neutron radiation. As shown in Table I, the total exposure for each position was several hours because we conducted many tests for each position.

Table I also summarizes the

Table I. Exposure Instructions for Computer Positions in the Neutron Beam and Observed Events

Position	Exposure Instructions	Time (h)	Beam Diam. (in.)	Recoveries	Reboots	Lost I/O	Lost Sync.
1	Maximize beam exposure to the RAM[a] on the scratchpad data memory in the CCA[b].	8.9303	2	2	0	0	0
2	Maximize beam exposure to flash memory on the instruction memory CCA but miss the processor CCA.	7.8761	2	0	0	0	0
3	Target the processor and miss all other chips on the processor CCA.	1.9736	2	1	1	0	0
4	Target the LSI[c] chip next to the processor and miss the processor on the proccessor CCA.	5.5674	2	0	0	1	0
5	Maximize beam exposure to one CPU[d] on the processor CCA but miss the instruction memory CCA.	2.8312	3	27	1	5	1
6	Same as 5 but target the alternate processor on the processor CCA.	5.1884	2	72	2	3	1
7	Center beam on the first processor.	2.0486	3	12	0	0	0
8	Expose a single CPU on the processor CCA, as much flash memory as possible on the instruction memory CCA, and as many RAMs as possible on the scratchpad data memory in the CCA.	5.8951	3	18	1	2	0
9	Same as 8 but with a 3-inch beam diameter.	2.2188	1	7	0	1	0
10	Same as 8 but with a wider beam to hit the protected rollback area.	5.9294	1	16	1	1	0
11	Same as 5 but with a 3-inch beam diameter.	5.5610	1	145	9	10	6

[a] Random access memory
[b] Circuit card assembly
[c] Large-scale integration
[d] Central processing unit

events observed at each position: the number of recoveries during the total exposure, the number of times the flight control computer rebooted, the number of times communication was lost between the flight control computer and the 737 simulator, and the number of times synchronization between the flight control computer and the simulation was lost. When the computer recovered or rebooted, the simulated flight ended successfully; when communication or synchronization was lost, the flight ended unsuccessfully. The events listed in Table I occurred only when the flight control computer was exposed to the neutron beam. Therefore, all these events were caused in some way by neutron-induced SEUs.

The unsuccessful flights shown in the table and mentioned above are not relevant to this study because they were caused by the built-in “strike counters,” which were part of the AIMS computer and which had not been deactivated before the ICE House tests. The purpose of the strike counters in the AIMS computer was to count the number of times a computer tried to recover within a preset time determined for actual flight

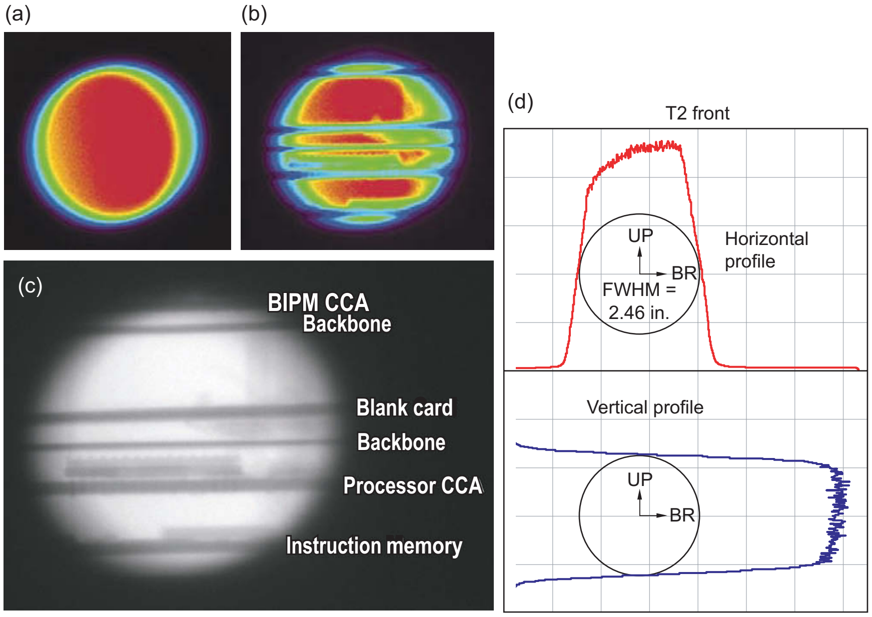

Figure 4. Measuring the Time-Integrated Neutron Flux during ICE House Tests

The false-color images are of the two-dimensional spatial distributions, obtained from image-plate data, of the time-integrated neutron flux (a) entering and (b) exiting the flight-control computer. Red indicates a high value of time-integrated neutron flux; purple, a low value. (c) This “x-ray” display of the image-plate data was obtained from a position just behind the spot where the beam exited the computer. One can see exactly what circuits were exposed to the neutron beam during the test. (d) These line scans of the image-plate data are from a position just in front of where the beam entered the computer. Line scans allowed precise measurements of the beam widths in two perpendicular directions.

conditions and then to shut the computer down by rebooting or stopping it if that number had been exceeded. Because the neutron intensity for the ICE House tests was about a million times that at aircraft cruise altitudes, the rates at which the strike counters rebooted or stopped the computer because of SEUs also increased by about a million times. These artificially high rates do not therefore reflect the actual performance of the rapid-recovery architecture and must be disregarded.

An Example of a Successful Recovery. Figure 5 shows data from a test in which the rapid-recovery architecture successfully mitigated the effect of a neutron-induced SEU. For this test, we selected the flight simulation option of random wind gusts at 1 foot per second. Figure 5a shows the commands sent by the computer (in degrees) to the simulated aircraft’s elevators near the time of the SEU. Figure 5b shows the corresponding commands sent to the simulated aircraft’s ailerons.

The hybrid computer computed new flight-control commands every 50 milliseconds. The time it takes to issue a new command corresponds to a “frame.” Starting at frame 5991, the flight computer began to send the same commands (indicated by constant degrees) because the outputs of its two microprocessors did not agree, indicating the occurrence of a soft fault (for further details on the role of the two microprocessors, see the box “A Rollback Rapid-Recovery Computer Architecture” on page 105). By frame 5997, however, new computed commands were accepted and sent to the simulated aircraft’s ailerons and elevators, indicating that the computer had recovered from the SEU. The recovery introduced no noticeable perturbations in the flight dynamics while compensating for the neutron-induced error in the control command calculations.

SEU Cross Sections. Table II lists the SEU cross sections (σ), in square centimeters, calculated from our experimental measurements. The probable number of occurrences per unit time divided by the neutron flux [ϕ, in neutrons (n) /cm^2·s] for a particular type of event equals the cross section for that type of event—see Equation (1). Thus the number of events equals the cross section times the neutron flux, as shown in Equation (2).

$$\sigma = \text{Number of events per time}/\phi \quad . \ (1)$$

$$\text{Number of events per time} = \sigma\phi \quad . \ (2)$$

Table III lists the probable number of occurrences per flight hour for each type of event. These values were obtained with Equation (1), using the cross sections in Table II and the atmospheric cosmic-ray flux at 34,000 feet of about 1.7 n/cm^2·s.

For a commercial transport airplane, one flight year equals 3000 flight hours. Although the values in Table III indicate that SEUs are relatively rare, these rates individually apply to only a portion of one flight-control computer. However, for the air transport fleet, thousands of aircraft fly fully exposed to atmospheric neutrons at any given time. The effects of the SEUs could become significant when the fleet is considered as a whole.

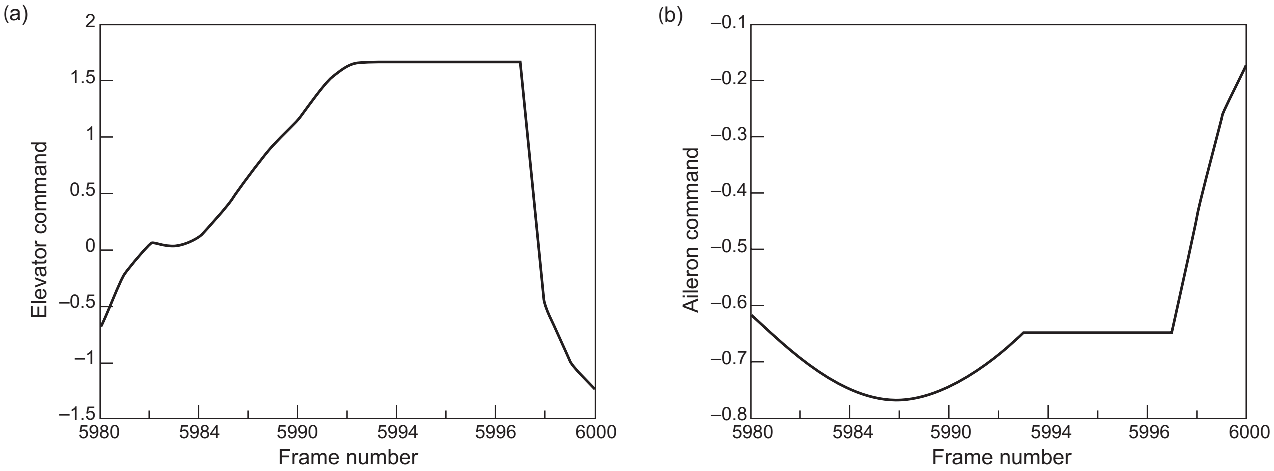

Figure 5. SEU Effects on Flight Control Commands to Elevators and Ailerons
The flight control computer sent commands to the simulation's elevators (a) and ailerons (b) before, during, and after a neutron-induced SEU. The commands are sent in degrees. New commands are computed every 50 ms, and that amount of time corresponds to a "frame." The flight command computer began sending the same commands at frame 5991, indicating the occurrence of an SEU at that time. By frame 5997, the flight computer started sending new commands again, indicating that the computer had fully recovered from the SEU.

Table II. SEU Cross Sections for Each Position

Position	$\sigma_{Recovery}$ (cm^2)	σ_{Reboot} (cm^2)	$\sigma_{I/O}$ (cm^2)	$\sigma_{Sync.}$ (cm^2)
1	4.28918×10^{-11}	0	0	0
2	0	0	0	0
3	8.80598×10^{-11}	8.80598×10^{-11}	0	0
4	0	0	3.45474×10^{-11}	0
5	1.68654×10^{-9}	6.24644×10^{-11}	3.12322×10^{-10}	6.24644×10^{-11}
6	2.35334×10^{-9}	6.53706×10^{-11}	9.80558×10^{-11}	3.26853×10^{-11}
7	9.55673×10^{-10}	0	0	0
8	5.50792×10^{-10}	3.05995×10^{-11}	6.11991×10^{-11}	0
9	6.36923×10^{-10}	0	9.09890×10^{-11}	0
10	5.57584×10^{-10}	3.48490×10^{-11}	3.48490×10^{-11}	0
11	4.71361×10^{-9}	2.92569×10^{-10}	3.25077×10^{-10}	1.95046×10^{-10}

Future Work

Future experiments will focus on the effects of rollback recovery on closed-loop stability and on exactly which chips and chip sets in the flight control computer are susceptible to neutron-induced SEUs. Identifying these components and subsystems could affect fault-tolerant design strategies if similar components are currently used, or will be used, in avionic systems.

In future work, we will expose an Integrated Modular Avionics (IMA) computer to the ICE House neutron beam. A microwave link will connect the IMA computer in Los Alamos to a flight simulation running at the System and Airframe Failure Emulation Testing and Integration (SAFETI) Laboratory at NASA Langley Research Center in Virginia. During the tests, the IMA computer will run flight management and display software, and the SAFETI Laboratory will run a simulation of the large transport aircraft for which the IMA computer performs flight management and display functions.

In addition to providing aircraft simulations, the SAFETI Laboratory has a full-scale mockup of an airplane flight deck, so we can close the airplane's control loop through a human pilot. Such an experiment would determine if a pilot can compensate for upset of the flight management/display system during a simulated flight. ■

Table III. Predicted SEUs per Flight Hour at 34,000 Feet

Position	Recovery	Reboot	Lost I/O	Lost Sync.
1	2.4×10^{-7}	0	0	0
2	0	0	0	0
3	5×10^{-7}	5×10^{-7}	0	0
4	0	0	2×10^{-7}	0
5	9.6×10^{-6}	3.5×10^{-7}	1.8×10^{-6}	3.5×10^{-7}
6	1.3×10^{-5}	3.7×10^{-7}	5.6×10^{-7}	1.9×10^{-7}
7	5.4×10^{-6}	0	0	0
8	3.1×10^{-6}	1.7×10^{-7}	3.5×10^{-7}	0
9	3.6×10^{-6}	0	5.2×10^{-7}	0
10	3.2×10^{-6}	2×10^{-7}	2×10^{-7}	0
11	2.7×10^{-5}	1.7×10^{-6}	1.8×10^{-6}	1.1×10^{-6}

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