A Comprehensive Analog Single-Event Transient Analysis Methodology

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***Abstract*—A new method for analyzing analog single-event transient (ASET) data has been developed. The approach allows for quantitative error calculations, given device failure thresholds. The method is described and employed in the analysis of an OP-27 op-amp.**

***Index Terms*—Analog, heavy ions, OP-27, operational-amplifier, single-event transient (SET).**

I. Introduction and Background

HEAVY ions penetrating sensitive structures in microelectronic circuits generate a charge which can produce a voltage shift at a circuit node. This voltage deviation or pulse is known as a single-event transient (SET) [1]–[42]. Over the years, there have been several attempts to categorize the SET response of analog devices [43]–[59].

In the traditional analysis methodology, the cross-section for any transient to occur versus the effective linear energy transfer (LET) is used. However, in many cases only a transient above a certain amplitude and longer than some critical duration are likely to cause system failure. In this case the traditional approach results in a large over-estimate of single-event system errors. The goal of this work is to develop a new technique to analyze analog SET data.

This document will show how this method was developed, and employ it in the analysis of analog single-event transient (ASET) data from the OP-27 op-amp.

These results are combined with CREME96 to calculate analog circuit SET upset rates for the space environment.

II. Test Circuit

The OP-27 was tested in three widely used configurations: voltage follower, noninverting amp, and inverting amp. Transients were not observed for the voltage follower configurations. It is important to note that operational amplifiers with different designs do not behave in the same fashion with respect to ASET, for example the LM124 does indeed show SETs in the voltage follower configuration, whereas the OP-27 does not. A possible explanation for the absence of ASETs on the OP-27 in the voltage follower configuration is that with a gain of 1 the transients that are generated were insufficient to trigger the oscilloscope, which was set just above the noise level. The test circuits for these configurations are shown in Fig. 1. To facilitate these configurations, the device under test (DUT) board was designed with six high frequency relays. The relays allowed the DUT to be configured into all three test circuits without changing the test board. The data collection process is described in Savage, *et al.* [43]. Since the OP-27 was free to respond over the full range of supply voltages, both positive and negative output voltage pulses were measured.

The test setup was computer-controlled, which greatly reduced the chance of operator error. The input voltage, V_{in}, was set at biases of -1.00 V, -0.40 V, -0.06 V, $+0.40$ V, and $+1.00$ V. V_{cc} was held at a nominal value of ± 5 V.

The output of the DUT was measured with a high impedance field effect transistor (FET) probe, which was connected to a 1 GHz digital oscilloscope.

III. Experimental Results

The cross-section is calculated by dividing the number of events by the fluence of ions incident on the DUT. The number of events is recorded by the oscilloscope. Plotting the cross-section against the ion stopping power or LET produces a typical cross-section curve [54]. Fig. 2 shows the cross-section curve for the OP-27 as a noninverting amplifier with a gain of 10 for V_{in} equal to -0.06 V, $+0.40$ V, and $+1.00$ V. Fig. 3 shows the cross-section curve for the OP-27 as an inverting amplifier with a gain of 10 for V_{in} equal to -0.06 V, -0.40 V, and -1.00 V. The data was taken at the Texas A&M University cyclotron, using Ne (100, 150, 200, and 250 MeV), Cu (409, 543, 677, and 808 MeV), Xe (792 and 1573 MeV), Ho (901, 1300, 1601, and 1987 MeV), and Au (986, 1477, 1940, and 2349 MeV).

By comparing Figs. 2 and 3, it is evident that the response of the device as a noninverting amplifier with V_{in} of 0.40 V is very similar to the response of an inverting amplifier with a V_{in} of -0.40 V. The same is true for both amplifiers with V_{in} of -1.00 V and $+1.00$ V, respectively.

While Figs. 2 and 3 are the traditional approach to visualizing single-event data, they do not address signal parameters, such as pulse height. These signal parameters are of interest to system designers and circuit modelers. The authors of this paper have developed a methodology that incorporates the signal parameters into an error rate model.

IV. Pulse-Height Versus Pulse-Width

Signals captured by the digital oscilloscope were saved in real time to a laptop computer. This allowed the full width at

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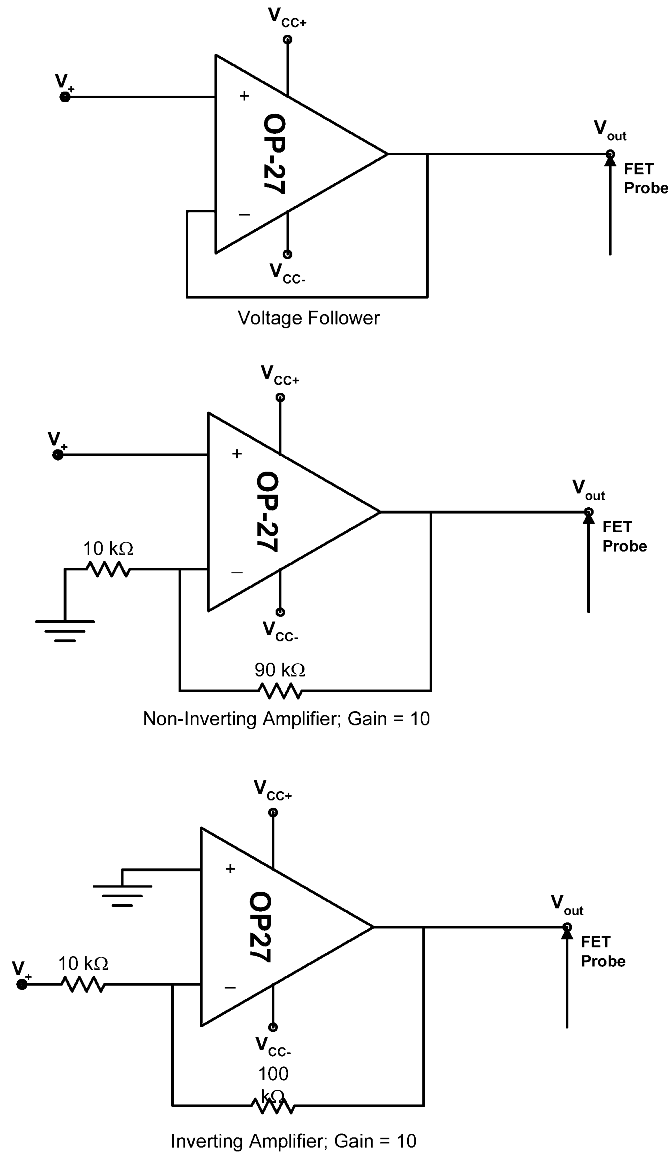

Fig. 1. Circuit configurations of the OP-27.

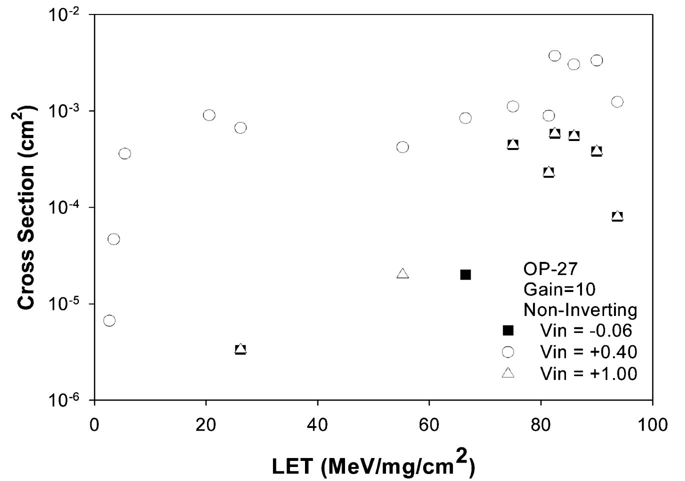

Fig. 2. Cross-section curve for the OP-27 as a noninverting amplifier.

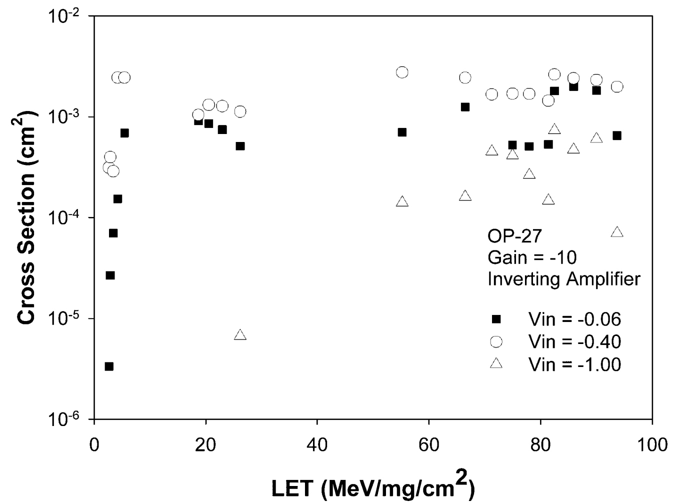

Fig. 3. Cross-section curve for the OP-27 as an inverting amplifier.

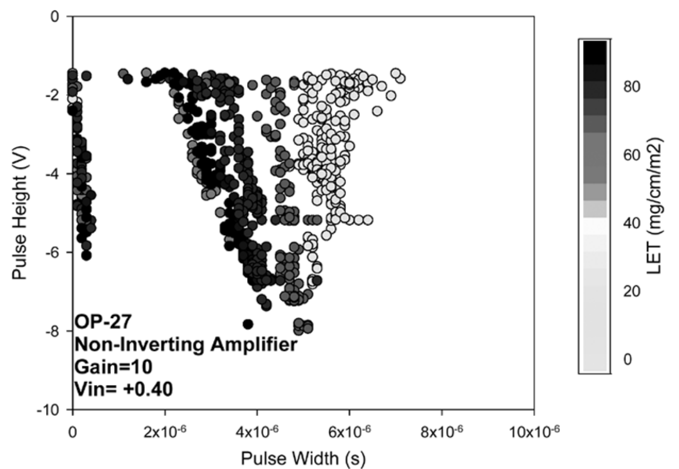

Fig. 4. Pulse-height versus pulse-width curve for the OP-27 as a noninverting amplifier with $V_{\rm in} = +0.4$ V.

half maximum (pulse-widths) and the transient signal amplitudes (pulse-heights) of the individual pulses to be measured.

Figs. 4–8 show pulse-height and pulse-width plotted as a function of LET for the OP-27 in inverting and noninverting configurations. Transients were not observed for the voltage follower, and hence data are not shown for that configuration.

There are two results that are immediately apparent. First, there is an obvious effect on device response due to LET. Second, the response of the device as an inverting amplifier with a $V_{\rm in}$ of -0.40 V is very similar to the response as a noninverting amplifier with a $V_{\rm in}$ of $+0.40$ V. However, when a $V_{\rm in}$ of -0.06 V is applied to both an inverting amplifier and a noninverting amplifier this graphical observation does not hold true, as shown in Figs. 7 and 8 respectively. This is to be expected, as the input transistors of the OP-27 are symmetric with respect to the power rails. Therefore a negative input in an inverting mode would appear nearly identical to a positive input in a noninverting mode.

For this methodology, the raw data presented in Figs. 4 and 5 were binned, from which the frequency of pulse-heights was obtained. Next, the frequency of pulse-heights was integrated so that any specific pulse-height will be the exact number of

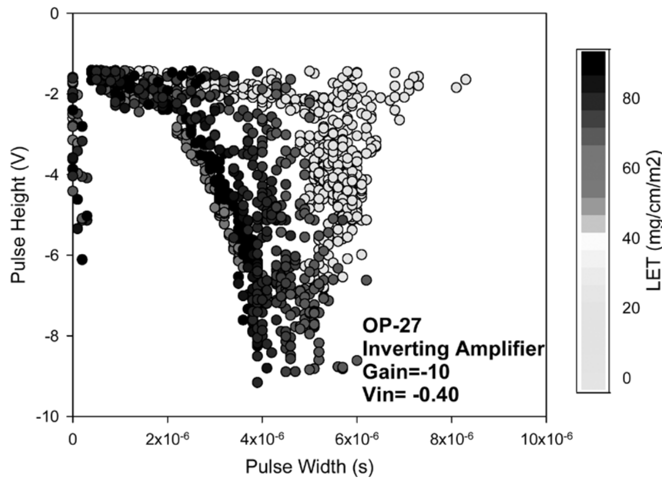

Fig. 5. Pulse-height versus pulse-width curve for the OP-27 as an inverting amplifier with $V_{\rm in} = -0.40$ V.

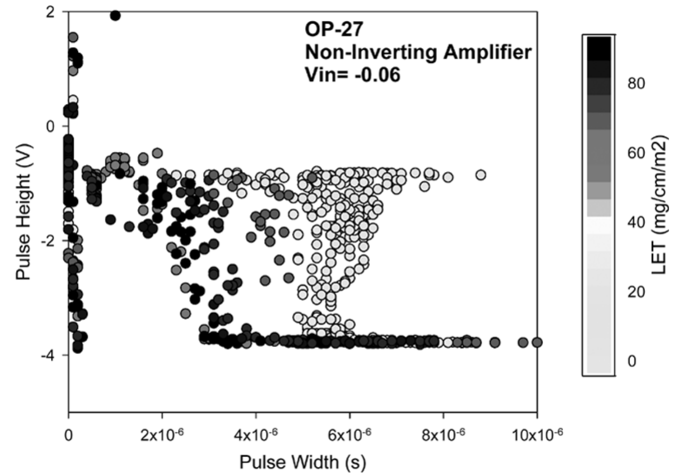

Fig. 8. Pulse-height versus pulse-width curve for the OP-27 as a noninverting amplifier with $V_{\rm in} = -0.06$ V.

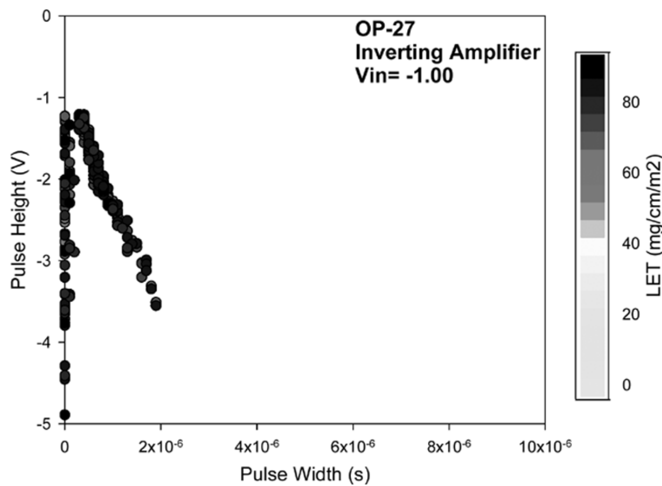

Fig. 6. Pulse-height versus pulse-width curve for the OP-27 as a inverting amplifier with $V_{\rm in} = -1.00$ V.

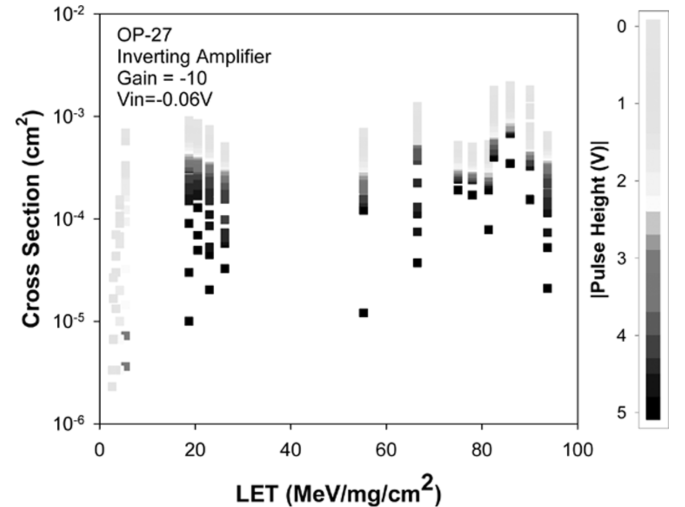

Fig. 9. Distribution of pulse-heights for the OP-27 as an inverting amplifier.

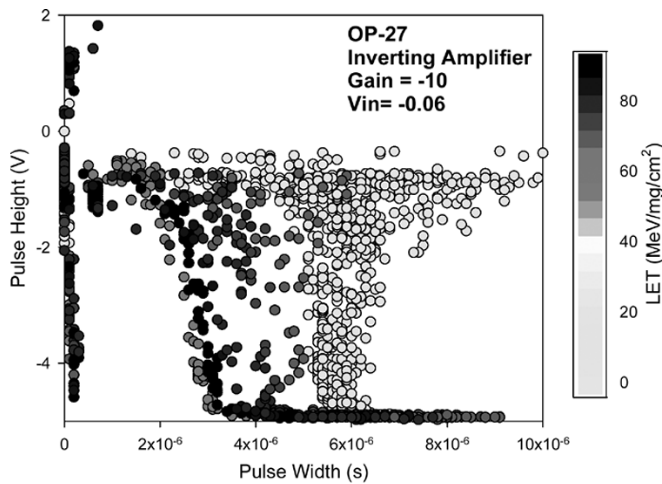

Fig. 7. Pulse-height versus pulse-width curve for the OP-27 as a inverting amplifier with $V_{\rm in} = -0.06$ V.

pulses with that height or greater. The cross-sections of pulse-height were then calculated by folding the normalized integrated frequency of pulses with the DUT cross-sections. These data are now presented in Fig. 9 as the cross-section of pulse-heights versus LET. This methodology is shown in Fig. 10 for clarity.

V. ASET Amplitude Contour Plots

The distribution of pulse-heights for the OP-27 as an inverting amplifier, shown in Fig. 9, is limited to the range of ions used during the experiment, and is subject to statistical fluctuations. To extend the analysis of the data, each pulse-height was best fit to an equivalent lognormal curve, as is shown in Fig. 11. Each fitted curve represents a contour of constant pulse-height. When these contours of constant pulse-height are combined, a contour plot is produced which represents the probability of experiencing a transient signal with a given amplitude at a given LET. This plot puts transient data in a logical format that can be understood by system engineers. The pulse-heights shown represent minimum transient amplitude, where 4 V are transients of at least 4 volts and greater, and 0 V are transients of any amplitude.

Figs. 12 and 13 show the ASET response of the OP-27 at a $V_{\rm in}$ of -0.06 V as a noninverting and inverting amplifier. The data clearly show that the device response is different for the two

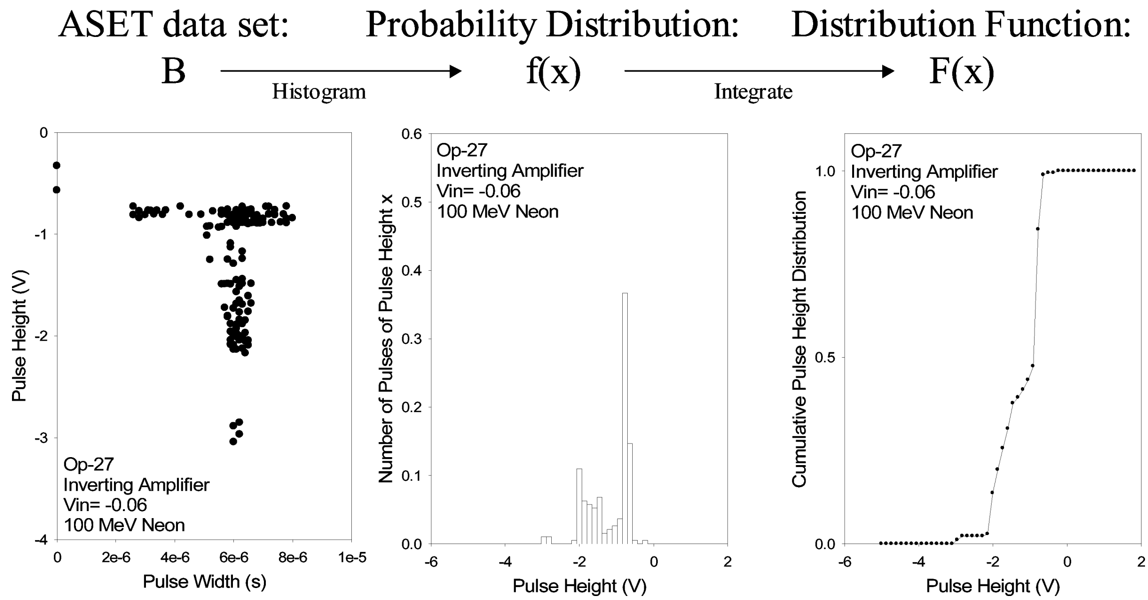

Fig. 10. Methodology to convert ASET data into distribution functions.

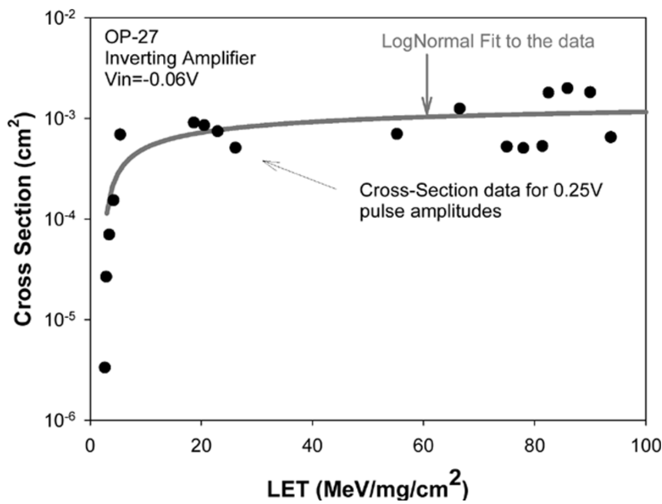

Fig. 11. Example of lognormal data fitting of pulse-heights for the OP-27 as an inverting amplifier.

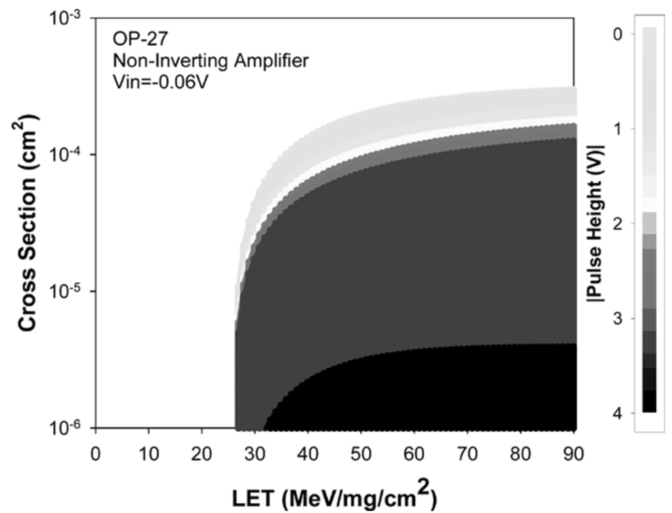

Fig. 12. Contour plot for the OP-27 as a noninverting amplifier at −0.06 V.

configurations. As previously stated, the input transistors of the OP-27 are symmetric with respect to the power rails. Because of this, when the same bias is applied to two different configurations the internal configurations for each bias condition is different.

Figs. 14 and 15 show the ASET response of the OP-27 as a noninverting amp with $V_{\rm in} = +0.40$ V and inverting amplifier with $V_{\rm in} = -0.40$ V. The data clearly display that the device response is identical for these configurations. The internal configurations for each bias condition are similar when biases of opposite polarity are applied to two different configurations because the input transistors of the OP-27 are symmetric with respect to the power rails.

These figures allow system engineers to estimate cross-section, or probability, of SET output voltages spikes for any incident ion of known LET.

Both pulse-width and pulse-height can be evaluated using the same methodology by eliminating those pulses that *will not* cause system upset and only plot those pulses that will cause upset. Fig. 16 shows a contour plot for the OP-27 as a noninverting amplifier at +0.40 V for pulses wider than 5 μs.

A three-dimensional (3-D) figure can be generated by repeating this procedure several times for different pulse-widths. The cross-section would be on the x-axis, the LET would be on the y-axis, and the pulse-width would reside on the z-axis. Fig. 16 can be then seen as a slice from this 3-D figure.

The error rates can be calculated by using CREME96 [60]. The rapid fall-off in the cross-section above 80 MeV/mg/cm^2 is not a major concern as the flux of ions with LET above 28 MeV/mg/cm^2 (Ni) is negligible. If an application is sensitive to a pulse greater than 5 μs and to any amplitude, the calculated error rate is 8.99×10^{-9} upsets/day. In an application which is sensitive to a pulse greater than 5 μs, and to an amplitude greater than 6.4 V, the error rate is 2.48×10^{-10} upsets/day. Fig. 17 shows the results of a CREME96 heavy ion error rate for pulses greater than 5 μs.

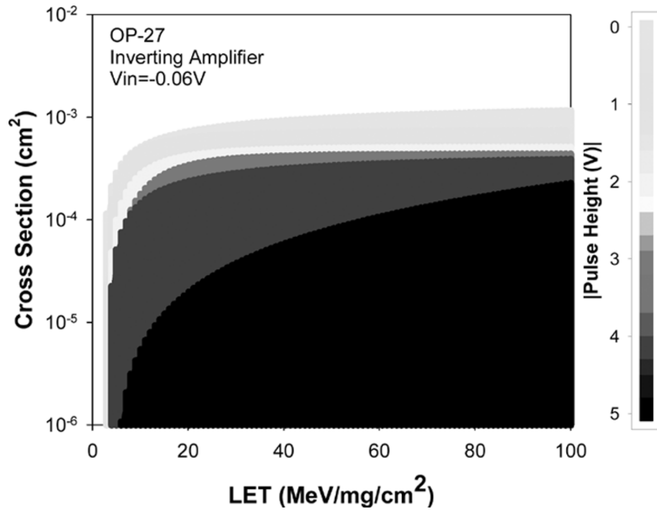

Fig. 13. Contour plot for the OP-27 as an inverting amplifier at −0.06 V.

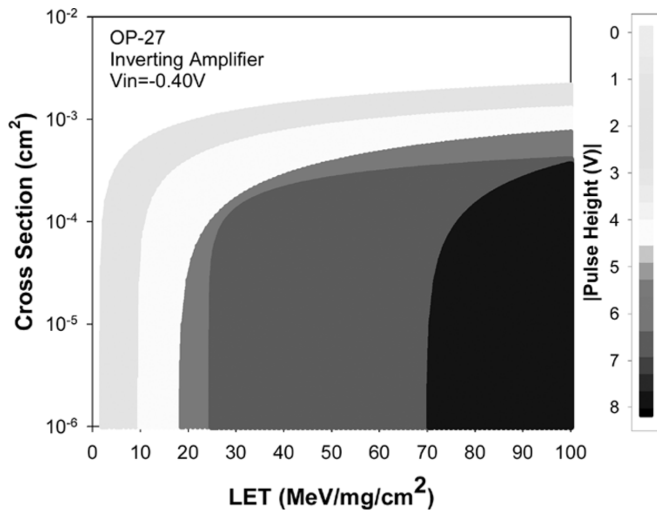

Fig. 14. Contour plot for the OP-27 as an inverting amplifier at −0.40 V.

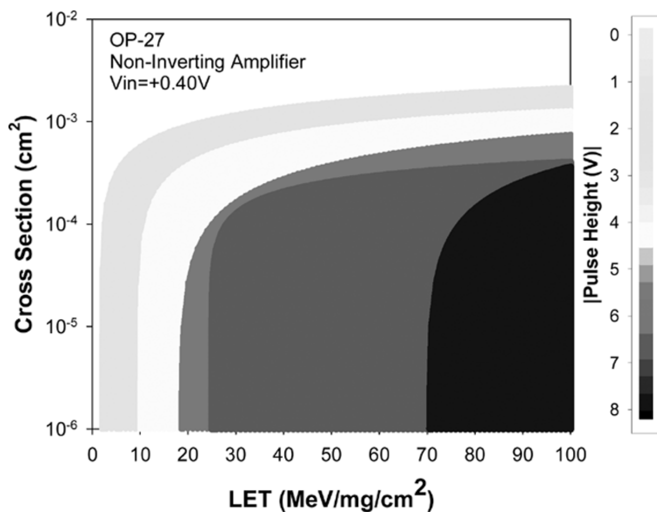

Fig. 15. Contour plot for the OP-27 as a noninverting amplifier at +0.40 V.

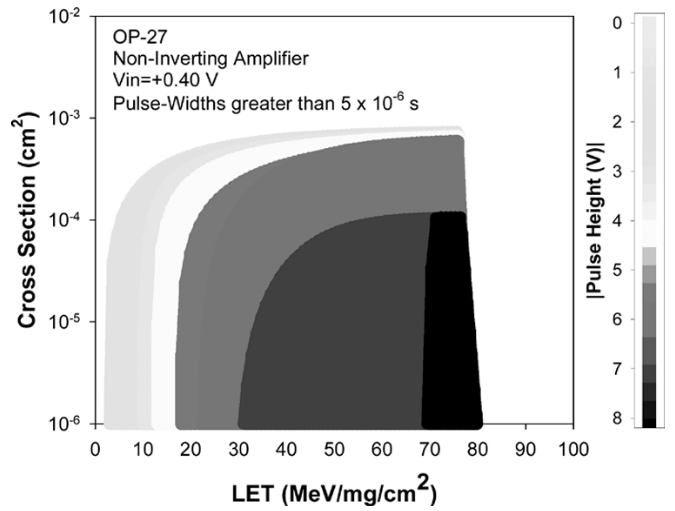

Fig. 16. Contour plot for the OP-27 as a noninverting amplifier at +0.40 V for pulses wider than 5 μs.

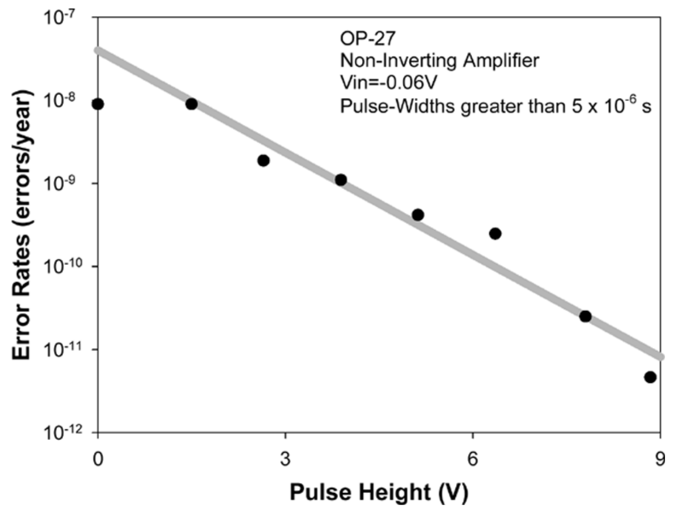

Fig. 17. CREME96 heavy ion error rate for the OP-27 as a noninverting amplifier at +0.40 V for pulses greater than 5 μs.

VI. Conclusion

In this paper, a new technique to analyze ASET data is demonstrated. The developmental path is shown and the method is applied to test data from the OP-27 op-amp. The method allowed for actual calculation of upset cross-sections, for both pulse-amplitude and pulse-width, for any incident ion.

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