

# TRENDS OF IEMI INDUCED UPSET ON DIFFERENT MICROCONTROLLER DEVICES

Daniel Guillette, et al.

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Technical Memorandum

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# Trends of IEMI Induced Upset on Different Microcontroller Devices

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**Abstract** — Using a state-of-the-art automated testing system called SALVO, pulsed RF signals – referred to as Intentional ElectroMagnetic Interference (IEMI) – were direct-injected onto the clock line pin of 4 separate Microcontrollers (MCU) using careful timing. The MCUs were programmed in Assembly language to execute a simple binary counting operation, which counted from 0 to 7. The MCU’s output lines were monitored to verify the count value and determine whether the IEMI caused upset. Waveform characteristics such as frequency, power, pulse width, and injection time, were varied to explore the trends of upset for each device. Probability of Upset (PoU) was computed by holding one variable constant, while varying the others, then taking the number of upsets observed over the total number of samples collected. It was determined that an above 80% PoU was achieved in frequencies between 25MHz and 800MHz when the power was greater than 8W. Pulse widths greater than 100ns showed best performance; However, pulse widths exceeding 400ns did not provide a significant increase in PoU suggesting a diminishing return threshold above this value. Finally, injection of the IEMI during clock rise and fall edge times – regardless of the instruction being executed – showed the highest PoU. However, MCU4 did not conform to this trend - likely because it executes instructions in parallel – and highest PoU during clock high times.

**Keywords**—IEMI, Effects, Microcontroller, Microwaves, MCU, Upset, Trends, RF

## I. INTRODUCTION

In the discipline of electromagnetic effects a challenging technical problem is to understand and model upset for a digital system. The University of New Mexico (UNM) & the Air Force Research Laboratory (AFRL) have chosen to study microcontrollers for their relative simplicity, ease of programming, and as a basic model for more complex system operation.

Using a custom made automated testing system called SALVO, pulsed RF signals were direct-injected into the external clock-line pin of 4 microcontroller (MCU) devices using careful timing. The MCUs were programmed in Assembly language to execute a simple binary count from 0-7, and their output was monitored, via oscilloscope, to establish if the count changed – suggesting that upset had occurred. Frequency, pulse width, injection power, and injection time – relative to the clock – were varied to evaluate – and compare - any overarching trends in upset for the 4 MCU devices. Previous efforts have singly explored, upset as a function of frequency, injection time, injection power, or pulse width. [1][2] However, to date, no effort has

been made to compare upset trends of multiple microcontrollers using traditional trends analysis methods.

## II. BACKGROUND

### A. Experiment Set-up

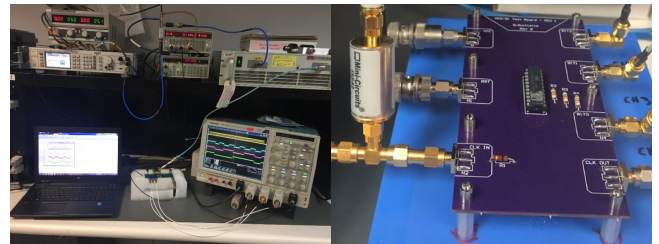


Figure 1: SALVO Test Apparatus (Left), MCU Test-board (right)

Four microcontrollers were methodically selected to quantify the differences in upset trend between: a) the same device but a second chip from the same lot, b) a different chip but the same architecture, and c) a chip with a different architecture. MCU1&2 are an MCS-51 architecture device with model number AT89LP2052-20PU. MCU3 is an MCS-51 architecture device with a different package, pinout, and model number of AT89LP213-20PU. Finally, MCU4 is a PIC based architecture chip with model number PIC18F26K42.

Each MCU was programmed to count from 0 to 7, in Assembly language using the same code for MCU1-3 and instructions fundamentally similarly for MCU4 - PIC has a different instruction set meaning the same code could not be used. The MCUs were then individually integrated into simple breakout boards which provided the essentials required for operation and data collection – See Fig. 1. The breakout boards were then attached – one at a time - to the SALVO test apparatus which contained: IEMI generating components, an oscilloscope (to record the count result of the MCUs), and a data acquisition computer. A block diagram of the test apparatus can be seen in Fig. 2.

SALVO acts as the overarching experiment conductor by controlling the operation of each connected instrument via a simple user input file and capturing the waveforms sent to the oscilloscope during each trigger of the system. Each input file defines, the IEMI waveform characteristics, the IEMI injection time, number of clock cycles, and the MCU reset command signal.

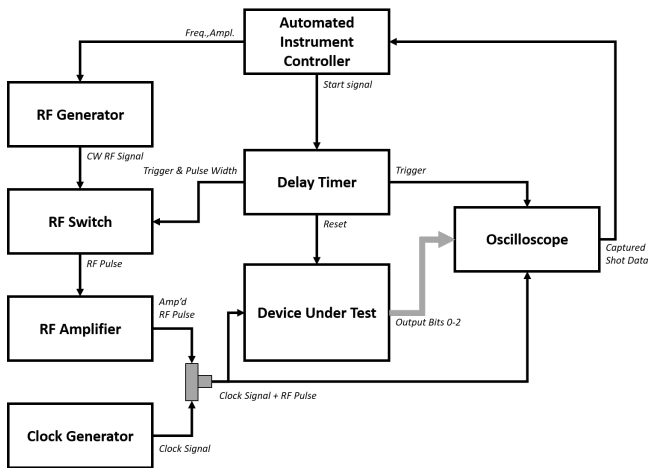


Figure 2: SALVO Test Apparatus Block Diagram with MCU DUT

### B. Examples of Upset

During the MCU's counting task, an RF pulse is direct injected into the MCU ext. clock in pin. The outputs of the MCU are monitored using an oscilloscope which records the counting state in real-time. Samples of nominal operation were captured before collecting upset data, for the purpose of determining whether upset took place. In post processing the nominal sample is compared to the new sample containing IEMI. If the two samples match, the new sample is marked as "Normal" denoting upset is not present, while samples that do not match are marked as "Upset".

Normal operation of the MCU1-3 can be observed in Fig. 3. MCU4's operation is similar but takes place on a slightly different timing. Consequently, the examples of upset and normal operation are sufficient for communicating all 4 devices.

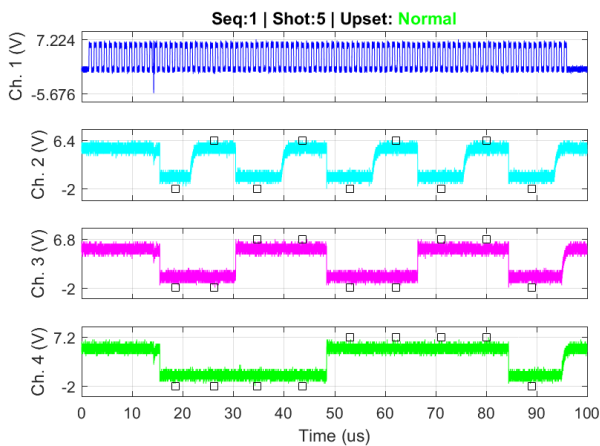


Figure 3: Normal MCU1-3 operation as observed and recorded by oscilloscope

In Fig. 3, the RF pulse can be seen on Ch.1 at about 16us mixed with the clock signal. The black square markers seen on channels 2-4 represent known output state values for each microcontroller output bit. These markers are helpful for understanding whether upset has occurred as their state can be compared to determine whether the new sample matches or not. Fig. 4&5, show examples of abnormal operation, classified as upset, through the mismatch in where the markers line up, or not.

Fig. 4 shows a common example of an IEMI induced latch upset, where immediately following the IEMI the MCU's output lines are all set to zero as if they were latched into place. Nominal operation does not return until the MCU is reset. Fig 5 shows an example of an IEMI induced shift upset, where the MCU continues to perform its counting operations but does so at a time shifted later than the expected nominal operation time.

Given, that a microcontroller may be implemented in a time synchronous manner, any output that does not exactly match the nominal, expected operation is designated as an upset.

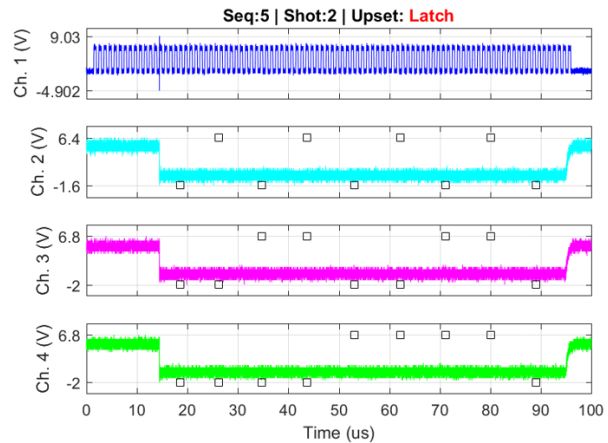


Figure 4: Latch style upset MCU1-3 operation as observed and recorded by oscilloscope.

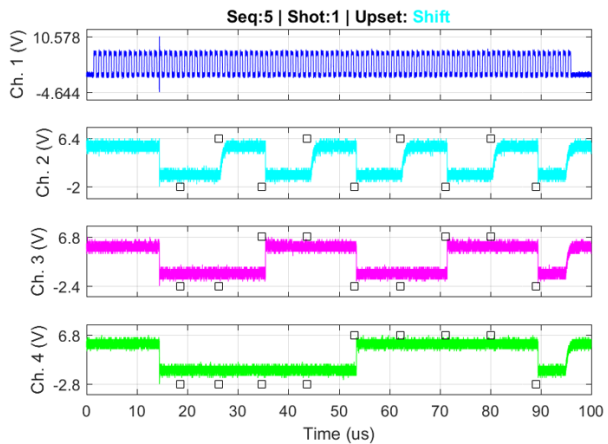


Figure 5: Shift style upset MCU1-3 operation as observed and recorded by oscilloscope.

Probability of Upset (PoU) is defined and computed by dividing the number of upsets observed by the number of samples taken. For example, if there were 10 upsets over 100 samples, the PoU would be 0.10 or 10%. Fig 3, 4, & 5 would each be considered a sample of data.

### C. Experiment Description

This experiment focused on capturing the trends of 4 primary variables – 1) frequency, 2) injection power, 3) pulse width, & 4) injection time – with an unofficial 5<sup>th</sup> variable being the MCU Device Under Test (DUT.)

A list of variables and their tested ranges can be found in Table 1.

TABLE I. TESTING PARAMETERS

Variable	Discrete samples	Number of sequences
Frequency (MHz)	20, 50, 100, 200, 400, 800	6
Pulse Width (ns, FWHM)	25, 50, 100, 200, 400, 800	6
Amplitude (dB, 20W CW)	-24 to -3 in 3dB steps	7
Injection Time (us)	6 to 8us w. curated spacing	80

The frequency values were selected to ensure the entire frequency spectrum of the RF amplifier was tested while minimizing the number of discrete steps.

The pulse width values were selected by successively doubling the pulse width 5 times. The minimum value of pulse width was determined experimentally by the capability of the RF switch. The RF switch has a rise time of ~15ns while its' fall time is ~5ns. Therefore, the absolute minimum amount of time the switch could be toggled on-and-off would be 20ns. However, this 20ns time-period would not guarantee that the peak amplitude of the CW RF signal would be fully observed depending on the frequency and where the CW signal was in its' phase when the RF switch was toggled on. Therefore, it was decided that leaving the switch on for an additional 5ns between rise and fall would ensure that CW wave's peak was observed.

The amplitude values were selected to correspond to a change in 3db steps – with respect to the characterized 20W RF amplifier used. An amplitude of -27dB was chosen because during experimentation it was found to produce no upset and therefore would be a good starting point to capture nominal operating conditions against all additional variables. An amplitude of -3dB was found to commonly produce an upset response and was the specified as the amplifier's suggested maximum input amplitude.

Since the MCUs' operation takes place in a loop ending after the 22<sup>nd</sup> clock cycle, it was concluded that it would be redundant to collect data past the 22us time span. Moreover, previous work showed no difference in upset trend when comparing different instructions. Therefore, data was only collected over two cycles from 6 to 8us.

### III. RESULTS

The following graphs depict the total number of upsets observed when a single parameter – frequency, pulse width, input power, or injection time – is fixed at a specific value.

In the graphs that break out the trends by frequency, the black line with the circle markers is the aggregate trend – specifically the aggregate is the summed total of each frequency trend over the total number of samples. It is important to understand the distinction between the two trend types because the comparison plots between MCU devices, are of the aggregate trends.

#### A. Trend of Frequency and Upset

Fig 6 suggests all four MCU devices have a similar upset response since all are most susceptible to upset between 25 and 100 MHz. However, this trend is partially misleading

because the power injected is not the same for all frequencies. This is caused by a combination of instrumentation, and RF coupling – specifically the RF amplifier has a higher gain at certain frequencies causing more power to be output, and every device will couple RF with a different efficiency based on geometry. The amplifier's output can be seen in Fig 7 for reference. It is important to note that frequencies such as 400 and 800MHz have a lower average power across the range of input power values used. The input power is set on the RF signal generator as a dB value relative to a 1mW output, where all frequencies have the same amplitude relative to that set dB value. However, the power curves seen in Fig 7, are largely similar up to -11dB input power, but deviate beyond that value. Therefore, the trend seen in Fig 6, needs to be looked at in tandem with the power output graph, Fig 7, and the power upset trend (as a function of frequency) seen in Fig 8. Table II presents the values seen in Fig. 7.

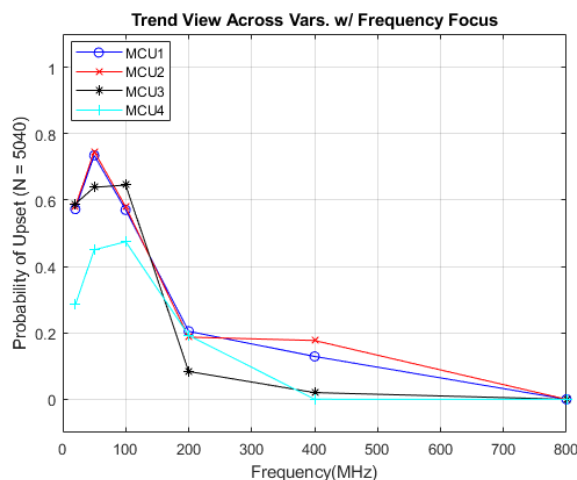


Figure 6: MCU1-4 Probability of Upset vs. Frequency Trend Comparison

TABLE II. AMPLIFIER OUTPUT BY FREQUENCY AND INPUT POWER

Input Power (dB)	20MHz	50 MHz	100 MHz	200 MHz	400 MHz
-33	0.05	0.05	0.05	0.05	0.07
-30	0.07	0.07	0.05	0.07	0.07
-27	0.13	0.09	0.09	0.09	0.13
-24	0.16	0.20	0.13	0.20	0.16
-21	0.65	0.34	0.34	0.34	0.34
-18	0.52	0.58	0.39	0.52	0.52
-15	1.07	1.07	0.81	0.81	0.98
-12	3.09	1.95	1.37	1.59	1.71
-9	5.71	3.76	2.63	3.09	2.94
-6	9.14	7.08	4.88	5.29	5.50
-3	11.45	13.35	9.14	8.86	9.69

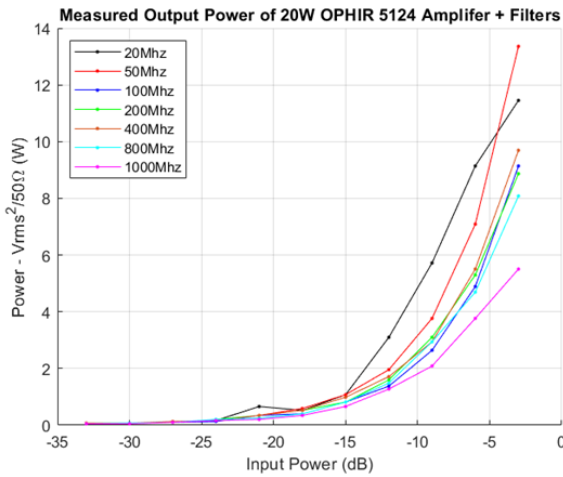


Figure 7: Input Power vs. Amplifier Output Power by Frequency

### B. Trend of Power and Upset

Fig 8 shows that the power upset trend is different based on the frequency of the IEMI, which is further confirmed by Fig 9, because the power into the device is nearly identical from -35dB to -15dB, and similar enough from -15dB to -3db. An important detail to observe is that the 200 and 400 MHz frequencies have equally high PoU at powers above -9dB but are effectively 0 PoU at powers below -9dB. This suggests that the frequency trends seen in Fig 6 are true, in an aggregate sense, but obscure the hidden power threshold for 200 and 400MHz.

Fig 9 shows the upset vs. power trends for the 4 MCUs. The trend suggests that an increase in power results in an increase in PoU. MCU1-3 all have nearly identical upset responses suggesting that the upset to power trend doesn't largely change within an architecture. What is surprising, is that MCU4 does not have a significantly different response either, but MCU4 is more resilient to upset compared to MCU1-3. At powers above -15dB MCU4's PoU hits a sort of asymptote around 0.35 while MCU1-2 continue to climb and MCU3 flattens out around ~0.50.

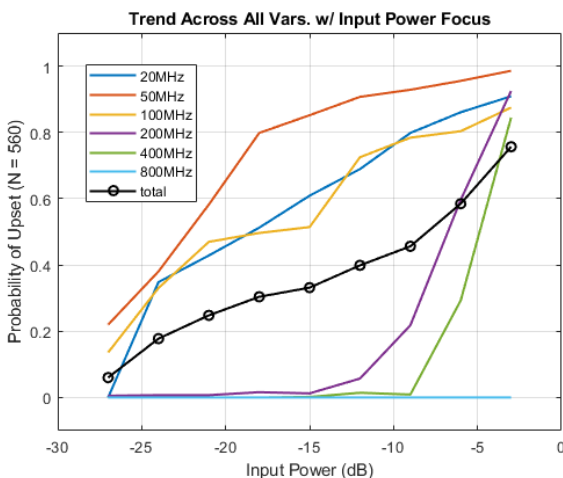


Figure 8: MCU1 Probability of Upset vs. Input Power by Frequency Trend

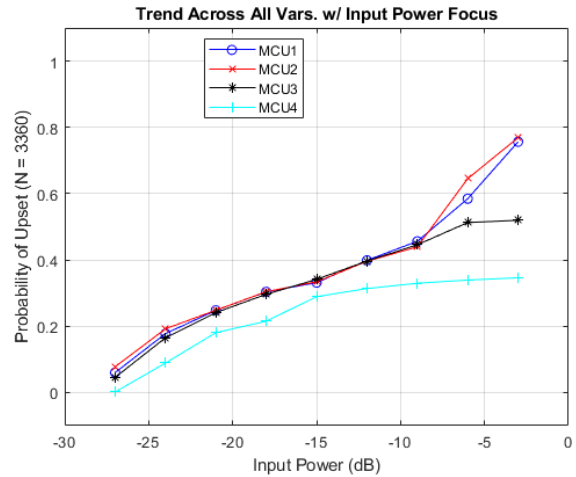


Figure 9: MCU1-4 Probability of Upset vs. Input Power Trend Comparison

### C. Trend of Pulse Width and Upset

Fig 10 shows the pulse width trends by frequency for MCU1. The trends all have a logarithmic curve that flattens out as the pulse width increases – except the 800MHz trend shows no response. This makes sense because the trends discussed, so far, have suggested that nothing is happening at 800MHz. The area under each of the curves also tracks the input power & frequency trends previously described in that frequencies between 20 and 100 MHz had highest PoU. Here it is seen that the 20 to 100 MHz have the most pronounced logarithmic curve while the others are more damped. The data also suggests a trend threshold at 100ns. At values above the threshold the Probability of Upset is “high”, and at values below PoU is “low.”

Fig 11 shows the aggregate pulse width vs upset trend response for MCU1-4. As suggested in the previous variables' trends, MCU1-3 have very close agreement while MCU4 is not far off.

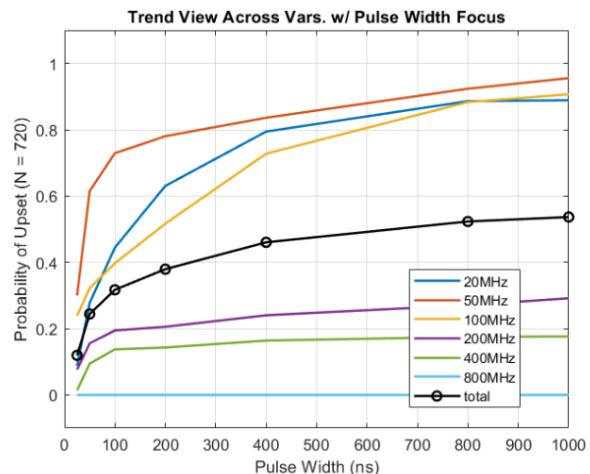


Figure 10: MCU1 Probability of Upset vs. Pulse Width by Frequency

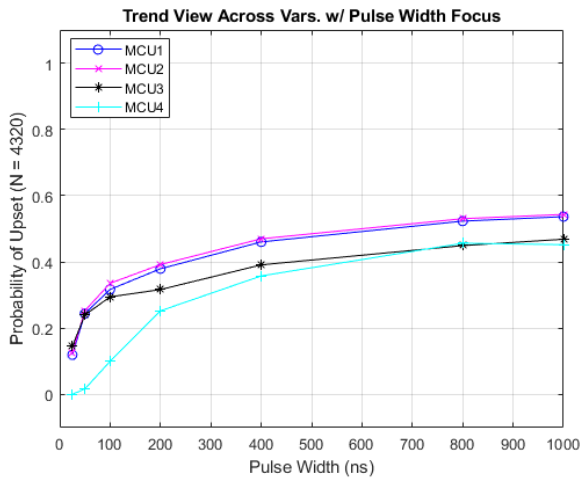


Figure 11: MCU1-4 Probability of Upset vs. Pulse Width Comparison

#### D. Trend of Injection Time and Upset

Fig 12 shows the trends of upset while changing the injection time for each frequency on MCU1. In general, the trend is consistent with previously observed efforts. [1] Moreover, the damping of the response can be observed based on the how well the RF couples to the circuit – for instance, at 50 and 100 MHz the trend is most pronounced because IEMI event couples well at those frequencies.

Fig 13 shows the aggregate injection time vs upset trend comparison between the 4 devices. In general, MCU1-3 agree and show upset being most likely during clock rise and fall edges. MCU4 does not conform to the MCU1-3 trend. Instead, upset happens more often during the clock high state for MCU4. This makes sense given that MCU4 is a different architecture and latches data differently. Specifically, MCU4 executes instructions in parallel, and gives each an extra cycle of waiting space to finish; compared to the MCS-51 architecture which performs instructions sequentially and as rapidly as possible.

#### E. Overall Trends

For frequency, upset is most likely (>80% Probability of Upset) at 25, 50, 100MHz, while upset is less likely (<20% PoU) at 200 & 400 MHz, and 0% for 800MHz. This set of thresholds suggest that higher frequencies do not correspond to higher PoU and that the devices share a sort of “resonance” for upset between 25 and 100 MHz. Therefore, the devices may couple energy best at those frequencies.

Regarding input power, more power roughly translates to a higher Probability of Upset. Changes in frequency greatly impact the consistency – and prominence - to which the trend appears. Furthermore, the data gathered suggests this applies to all of the testing parameters not just input power.

Pulse Widths with greater than 100ns show a diminishing return towards Probability of Upset and therefore could be considered the threshold. For example, doubling the pulse width from 400ns to 800ns does not produce the same increase in PoU as what is seen when doubling the pulse width from 50ns to 100ns. Additionally, the slope of the pulse width curve may be a function of

power (or coupling frequency), because, as the power level was reduced, the PoU slope was also less steep.

Lastly, Injection Time has the highest upset probability during clock rise and fall states – for MCS-51 devices, while MCU4 bucks this trend and is highest during clock high times. This set of trends suggests that the frequency plays a role in the trend’s prominence, but again this is believed to be a result of signal coupling.

#### IV. CONCLUSION AND SUMMARY

In the discipline of electromagnetic effects a challenging technical problem is to understand and model upset for a digital system. The University of New Mexico (UNM) & the Air Force Research Laboratory (AFRL) have chosen to study microcontrollers as a digestible surrogate for more complex system operation.

Using a custom made automated testing system called SALVO, pulsed RF signals were direct-injected into the clock-line pin of 4 microcontroller (MCU) devices using careful timing. Each MCU was programmed to count from 0 to 7, in Assembly using similar instructions.

The experiment focused on capturing, and comparing, the upset trends of 4 primary variables – Frequency, Power, Pulse Width, & Injection Time – with an unofficial 5<sup>th</sup> variable being the MCU Device Under Test (DUT.)

The primary trend observed were that all four devices were surprisingly similar and MCU1-3 were all nearly identical. Frequency was shown to play a role in nearly all the other trends by acting as a sort of damping or amplifying function based on the frequency that best coupled with the device.

Regarding input power, more power roughly translates to higher upset probability. It was determined that an above 80% PoU was achieved in frequencies between 25MHz and 800MHz when the power was greater than 8W.

Pulse Widths with greater than 100ns appear show a diminishing return towards upset chance and therefore could be considered a threshold – meaning that pulse widths beyond this point do not show significant improvement in PoU for a large change in value.

Lastly, injection time has the highest upset probability during clock rise and fall states – for MCS 51 devices, while MCU4 bucks this trend and is highest during clock high times.

Given the repeated aggregate trend similarly of each device, interested parties could determine the average and standard deviation bounds of the data and build a generic upset trend – by variable - for microcontrollers. Ultimately, this may be valuable because it would reduce the need for effects data to be exhaustively collected on every device in order to understand the impact towards upset.

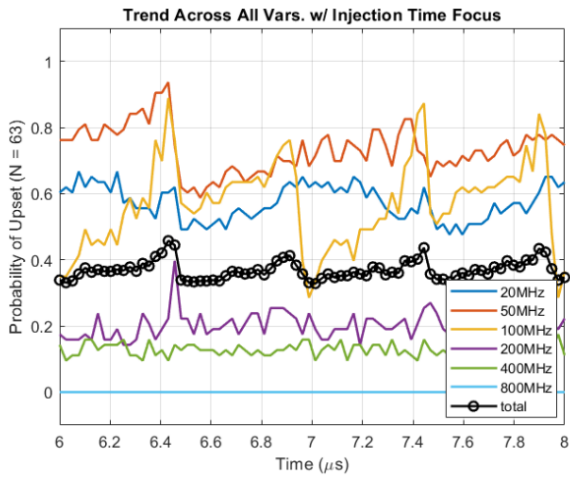


Figure 12: MCU1 Probability of Upset vs. Injection Time by Frequency

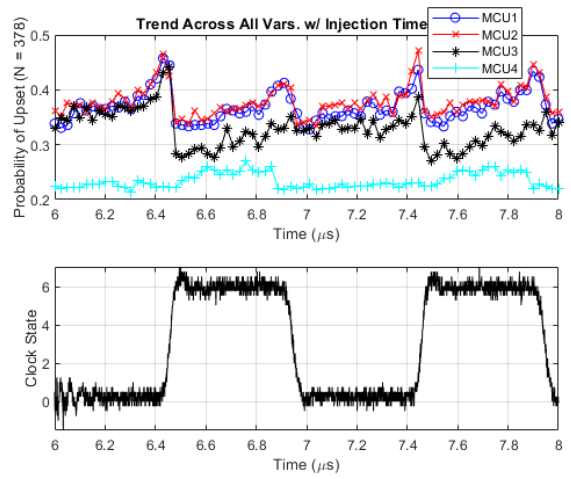


Figure 13: MCU1-4 Probability of Upset vs. Injection Time Trend Comparison

#### REFERENCES

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## **LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS**

AFRL	Air Force Research Laboratory
HPEM	High Power ElectroMagnetics
IEMI	Intentional ElectroMagnetic Interference
MCU	Microcontroller Unit
PoU	Probability of Upset
RDHE	High Power ElectroMagnetics Effects Branch
RF	Radio Frequency

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