A High-Level Tool for Bit-level SEU Sensitivity Analysis of DSP Filters

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Overview

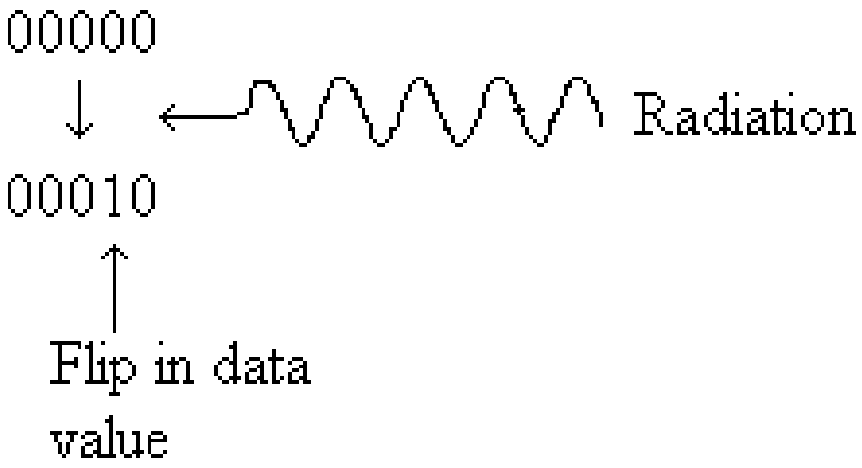
- Motivation
- Problem Formulation
- Proposed Approach
- Implementation
- Experimental Results
- Conclusions and Future Work

Space Electronic Systems – Radiation Effects

- **Space Electronic Systems**
  - Radiation effects can be fatal to the mission
- **System hardening by redundancy**
  - Triple Modular Redundancy (TMR)
    - Spatial TMR incurs 200% area overhead
    - Temporal TMR incurs 200% performance overhead
- **Redundancy is too costly!!**
  - Can we do better?
  - Can we exploit the function properties?

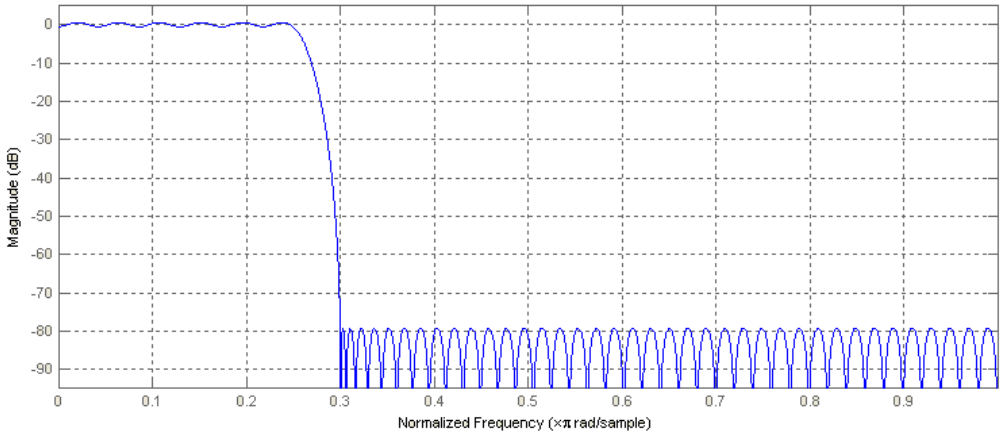
Single Event Upset (SEU)

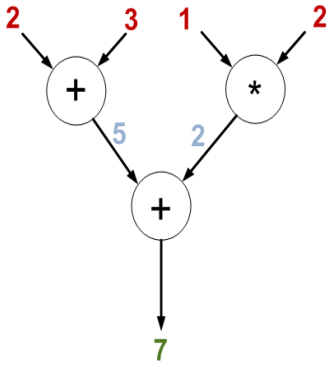
- **A momentary flip in a bit value due to radiation**
- **If latched can become permanent**

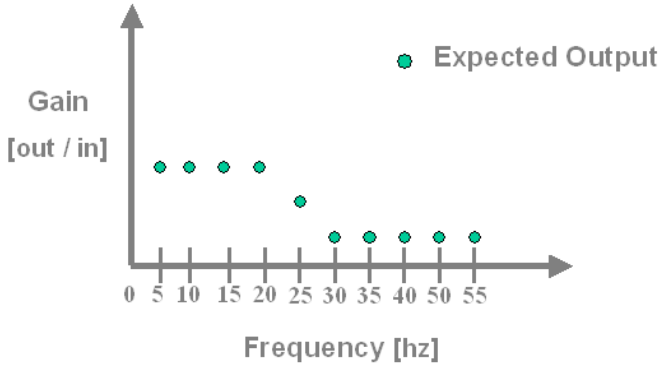


Digital Signal Processing (DSP) Filters

- **DSP Filters widely used in space missions widely**
  - noise removal
  - tuning to frequency ranges of interest
  - signal extraction, etc
- **Representation**
  - Data Flow Graph
- **Filter characteristics**
  - Frequency Response
  - Normalized (typically)







Problem Formulation

Given a DSP Filter, identify the SEU sensitive nodes of the Filter

- Such sensitive nodes can then be hardened

Scope of this work

- **Functionality:** Limited to DSP FIR Filters
- **Radiation Effects**: Single Event Upsets
- **Target Architecture**: None
    - Early analysis tool

Proposed Approach

Step 1: Examine the effects of an SEU on a filter.

Step 2: Compare these effects with normal filter behavior.

Proposed Approach

Step 1: Examine the effects of an SEU on a filter.

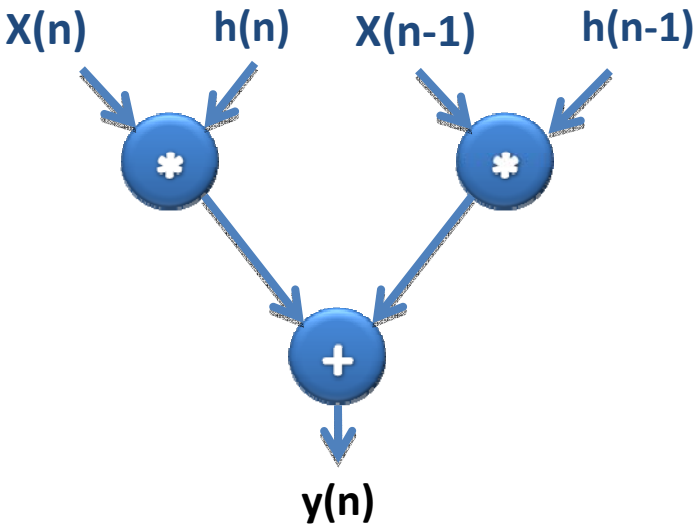
- How do we…
  - Represent a filter?
  - Model an SEU on a filter?
  - Examine the effects of an SEU on a filter?

Step 2: Compare these effects with normal filter behavior.

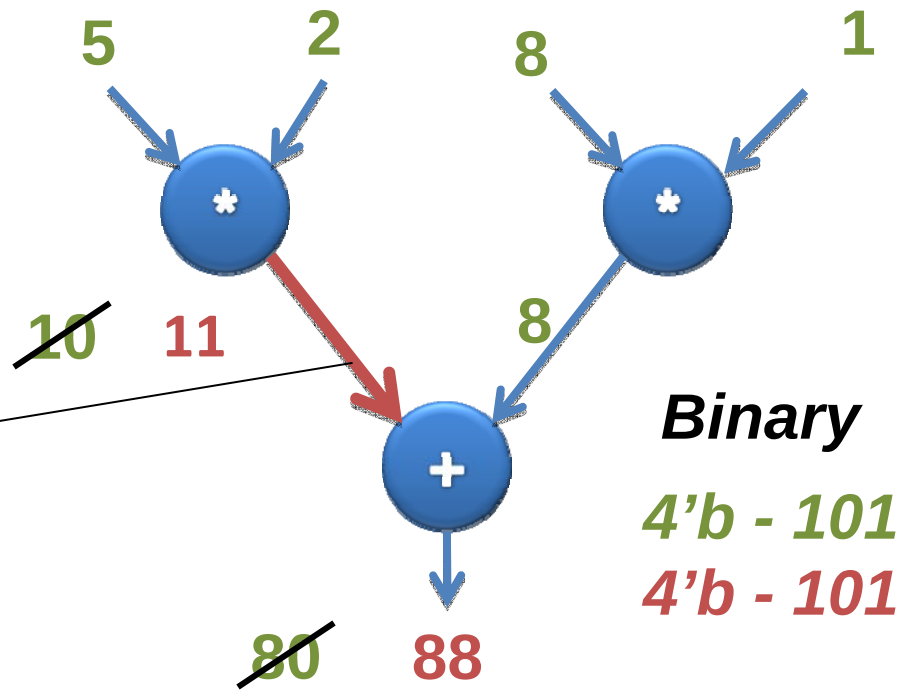
- How do we compare behavior?

Step 1: SEU Effect on DSP Filter

- Represent a filter with a data flow graph.



- Model an SEU by flipping edge bit values.



An SEU occurred on the LSB of this edge

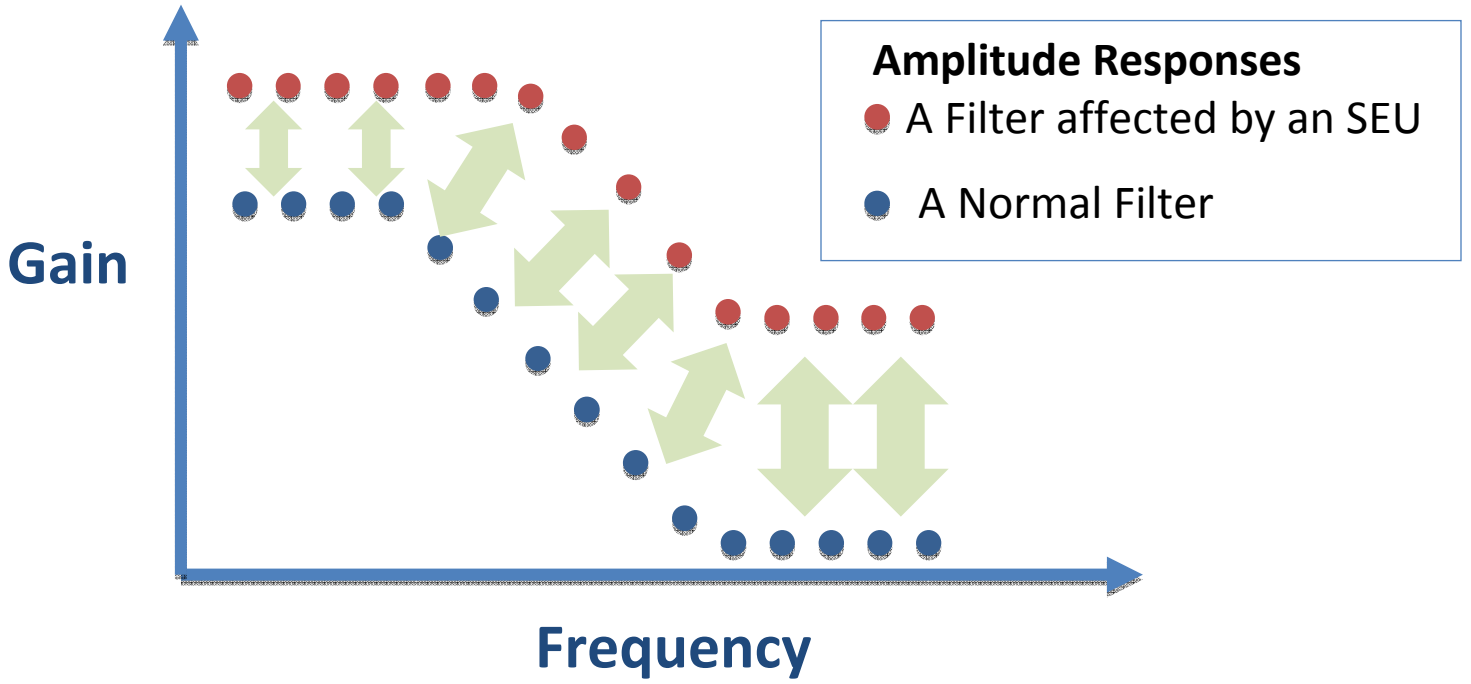
Binary

4'b - 1010

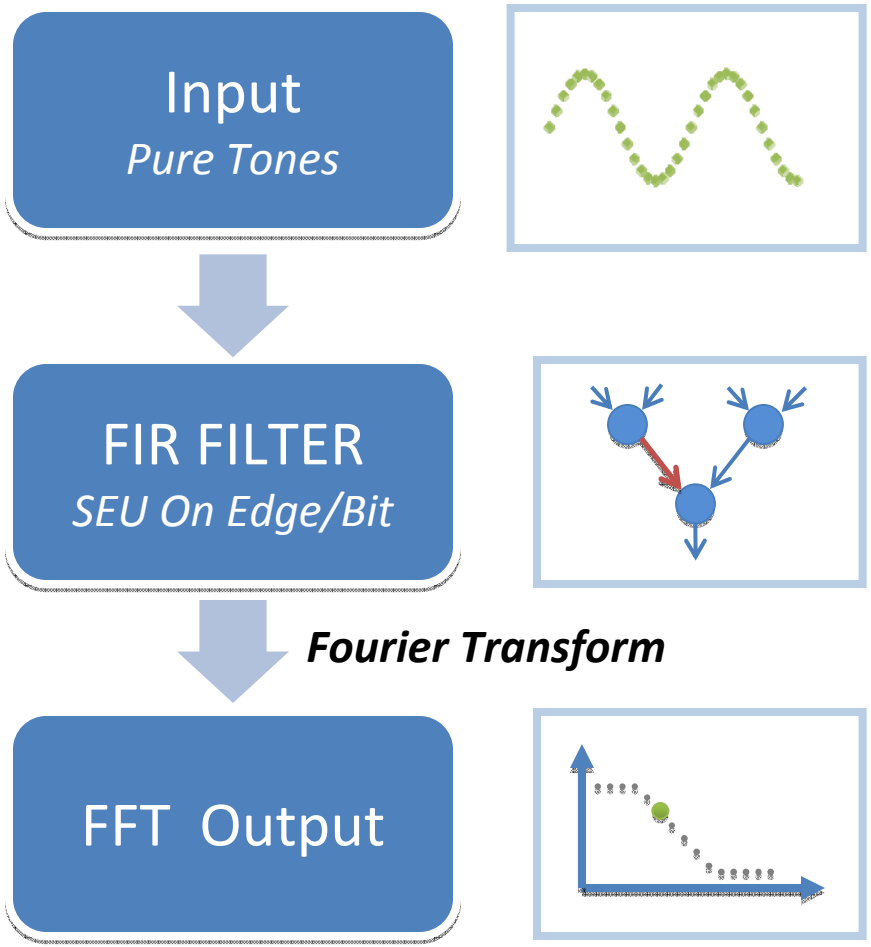
4'b - 1011

Step 2: Comparing Frequency Response

- **Compare filter behavior by using root mean square error on amplitude responses.**



Analyzing a DSP Filter with an SEU



SEU Sensitivity Analysis

```
SEU Analyze(Filter, Frequency Range)
begin
  Normal_Response =  FrequencyResponse(Filter, FrequencyRange);
  foreach edge in the DFG
    foreach bit in the edge
      SetSEU(edge,bit)
      SEU_Response = FrequencyResponse(Filter, edge, bit, Frequency Range)
      SensitivityList[edge, bit] =
            CompareFrequencyResponses(Normal_Response, SEU_Response)
      ClearSEU(edge,bit)
    end foreach
  end foreach
 return SensitivityList
end algorithm
```

Software Functions

- "Simulating" A Filter with a DFG
  - AIF File
  - Coefficient File
  - Sine Wave Generation
  - Generate the frequency response and compare the result with Matlab's Filter Designer Tool
- SEU Function
  - Store edge values as an integer variable
  - Add or subtract $2^{\wedge k}$ from edge value.

SEU Function

- **Introduces an SEU on a given bit of a given edge**
  - Example of concept: edge = 3; bit = 2;
    - Current value of edge = 0101
    - Shift
    - 0001
    - Check if LSB is even or odd
    - Flip the bit by adding or subtracting 2^{bit} to original value

```
// SEU function
   m = EdgeValue / (int)2^bit;
   if (m % 2 == 0)  //If m is even
        EdgeValue = EdgeValue + (int)2^bit;
   else  //else m is odd
        EdgeValue = EdgeValue - (int)2^bit;
   //Reset edge and bit to null
   edge = null;
   bit = null;
```

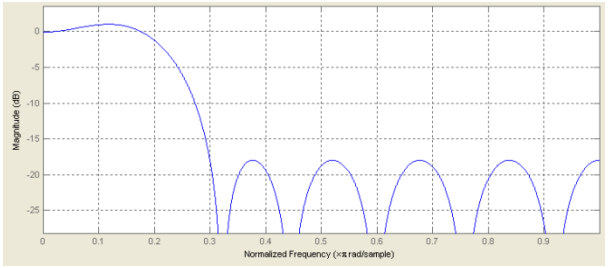
Software Implementation

- **Created a Java based program that reads in:**
  - .aif files describing the DFG Structure
  - .txt files containing coefficient list
- **Resources:**
  - Michael Thomas Flanagan's FFT Java Scientific Library**
    - Non-Commercial use only!
    - We recommend JMSL Numeric Library for commercial operation.
  - Java.Math Library
- **Program outputs a text file containing:**
  - Amplitude Response
  - RMSE values

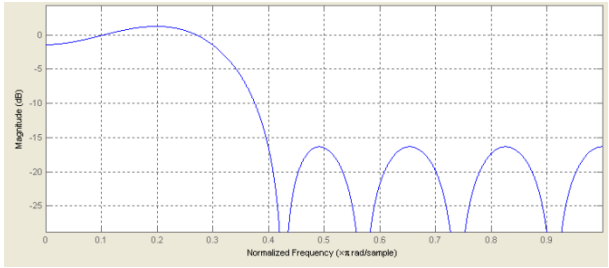
**Flanagan, Michael T. "Michael Thomas Flanagan's Java Library." Fourier Transforms. 18 Feb. 2006. University College London. 28 Mar. 2008 http://www.ee.ucl.ac.uk/~mflanaga/java/FourierTransform.html.

Experimental Validation

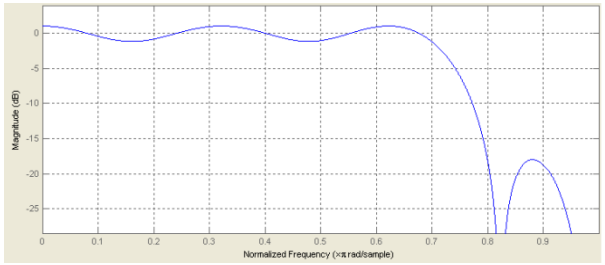
Filter Type	Low Range	Medium Range	High Range
Band Pass	10 – 20 KHz	100 – 200 KHz	1 – 2 MHz
High Pass	10 KHz	100 KHz	1 MHz
Low Pass	10 KHz	100 KHz	1 MHz



Low pass test #1.
Pass-band from 0 to 0.2

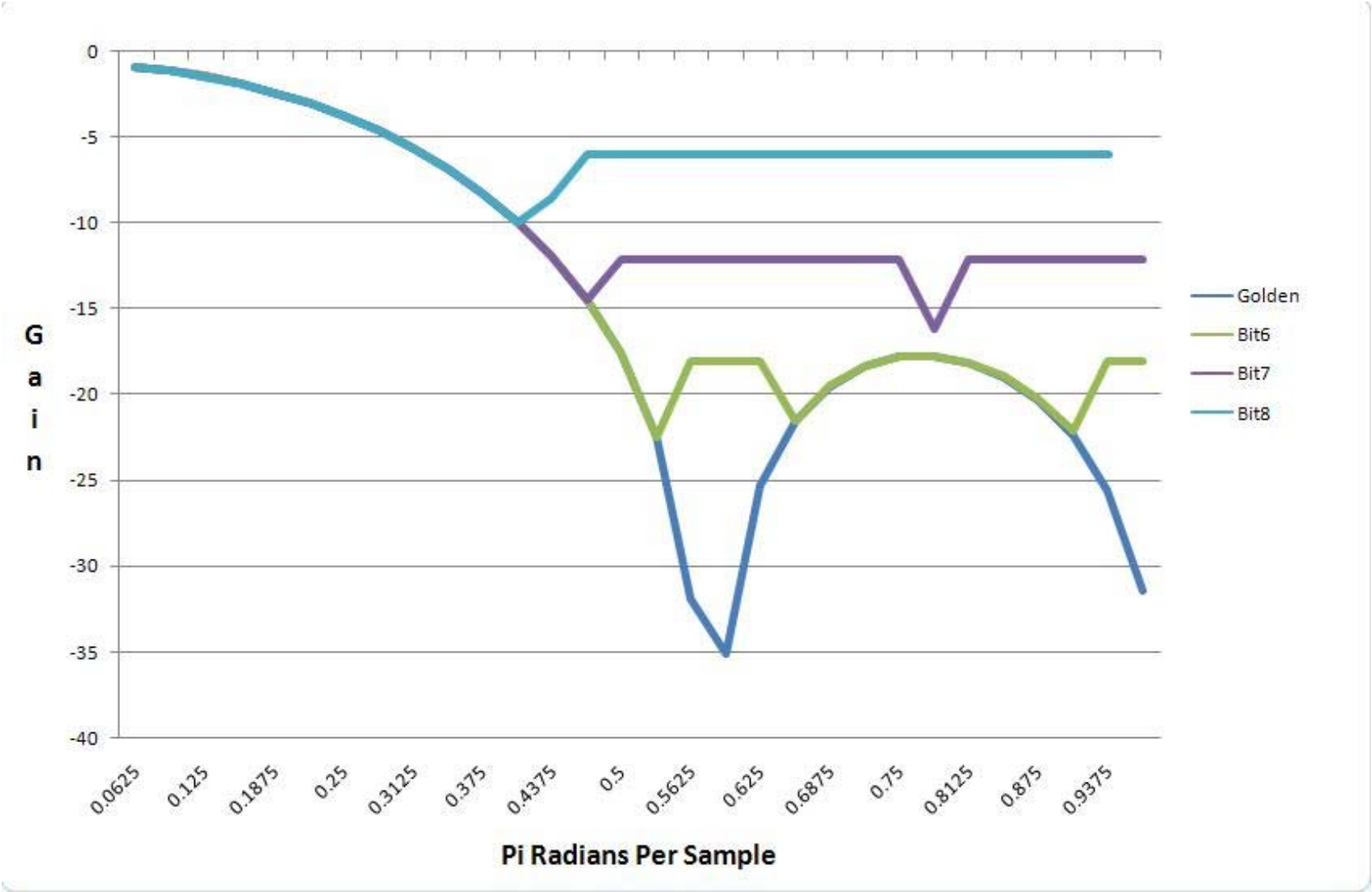


Low pass test #2
Pass-band from 0 to 0.3

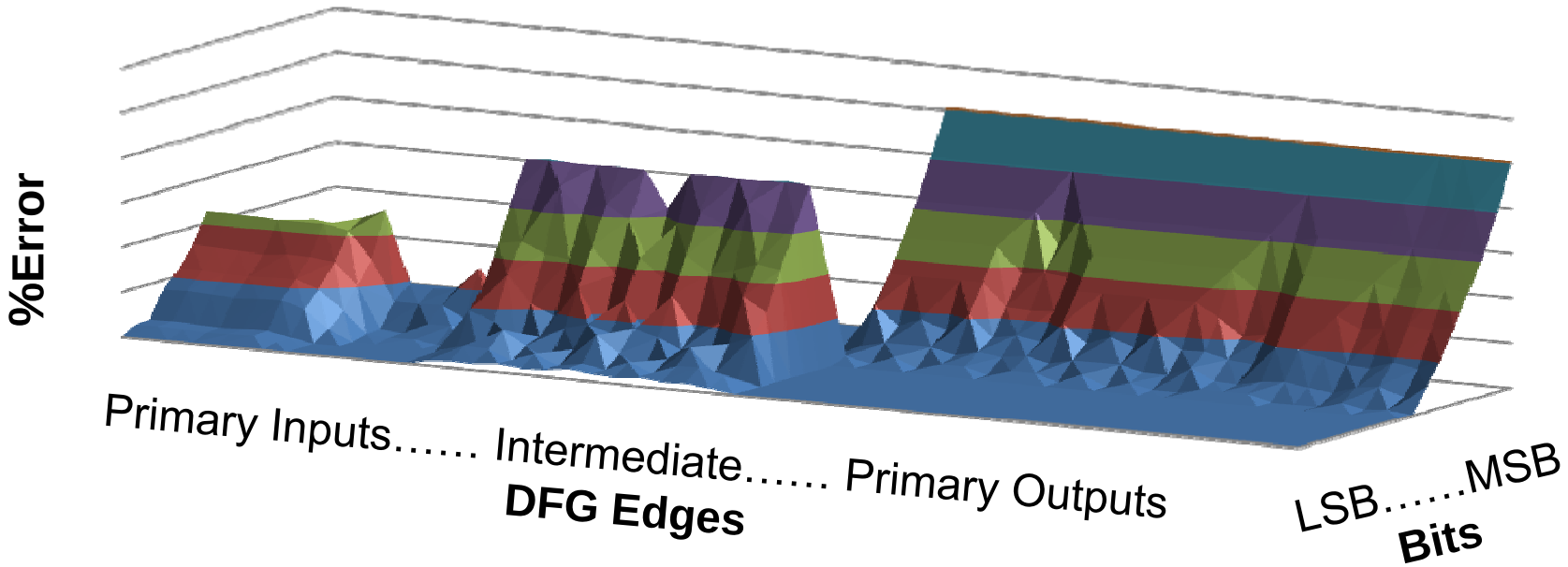


Low pass test #3.
Pass-band from 0 to 0.7

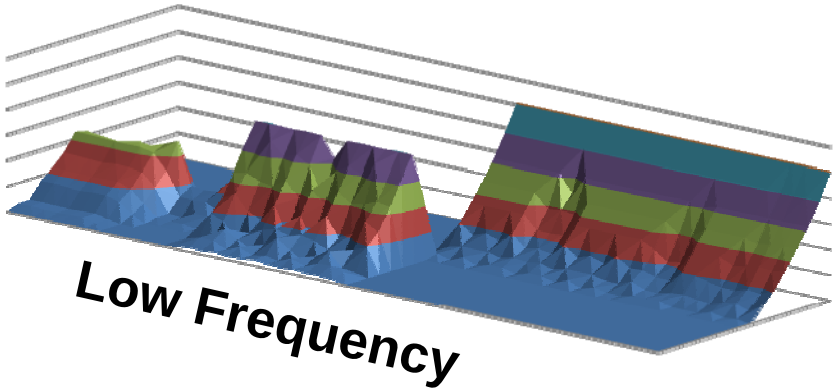
Effect of an SEU on Amplitude Response



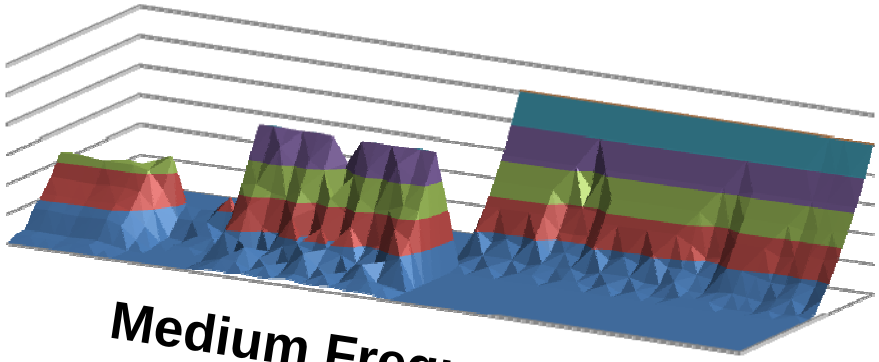
3D Error Plots



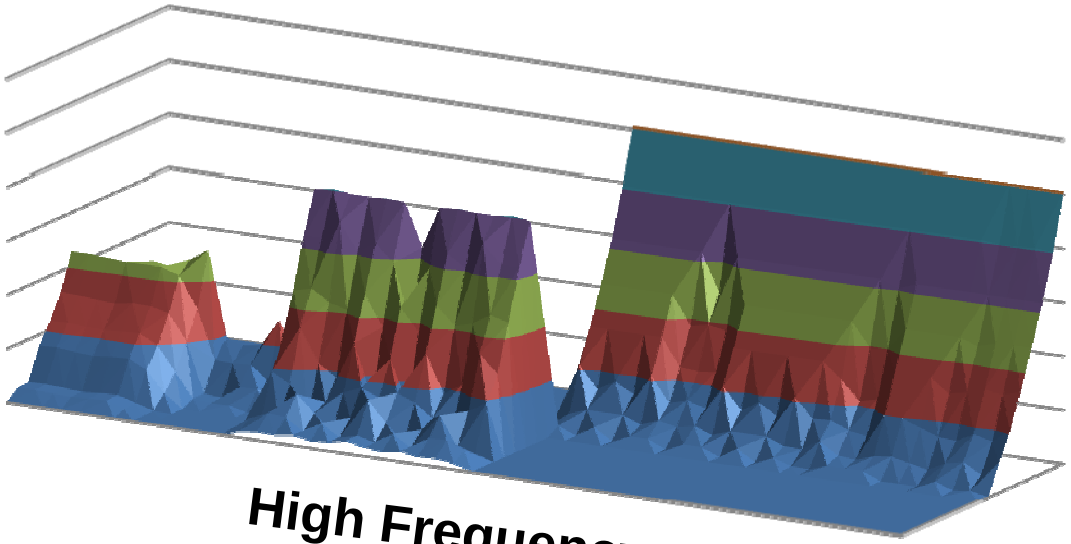
Test Results: Low Pass Filter



Low Frequency

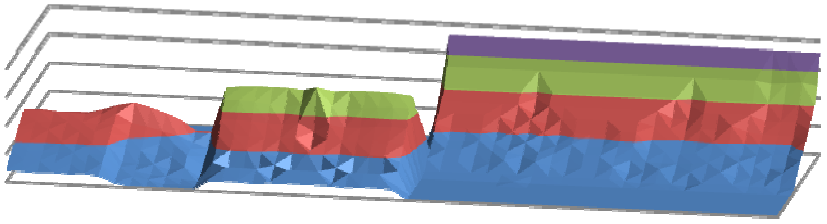


Medium Frequency

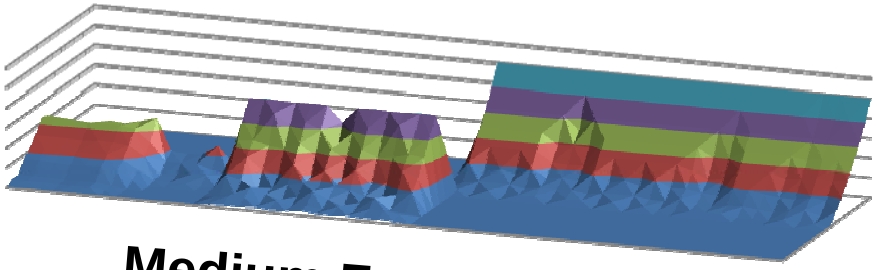


High Frequency

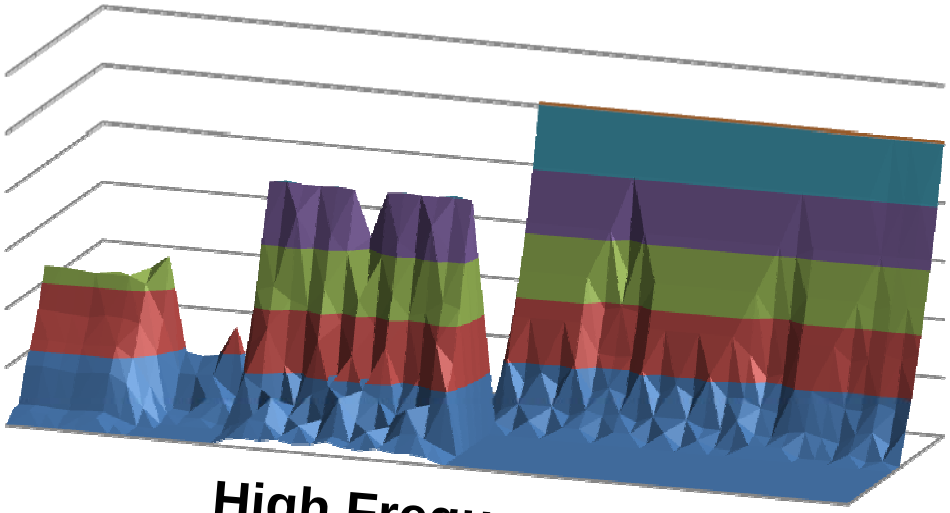
Test Results: High Pass Filter



Low Frequency

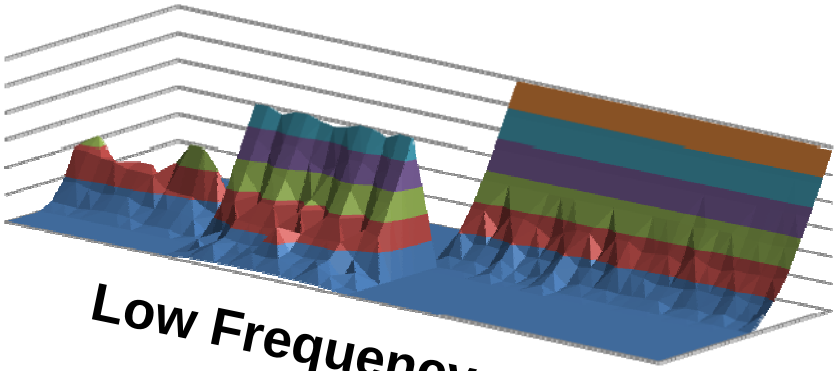


Medium Frequency

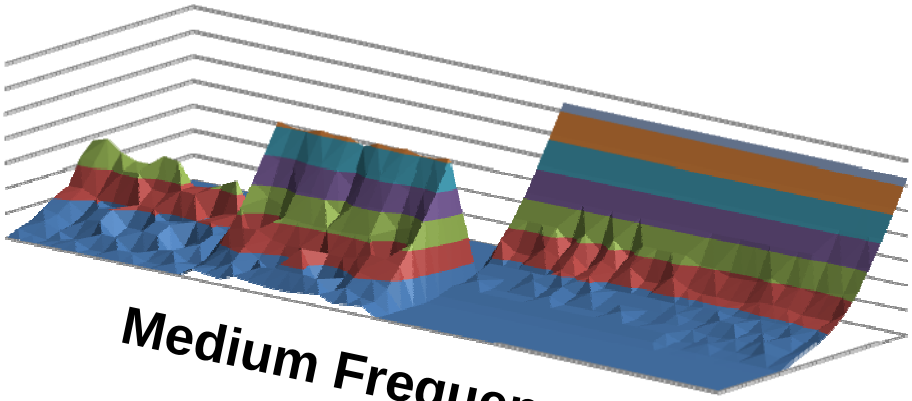


High Frequency

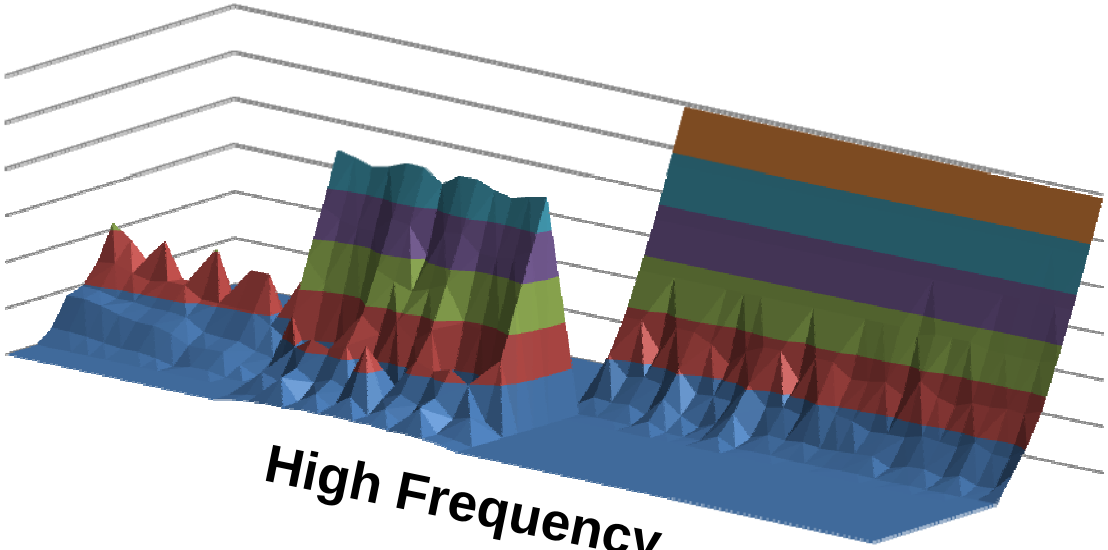
Test Results: Band Pass Filter



Low Frequency



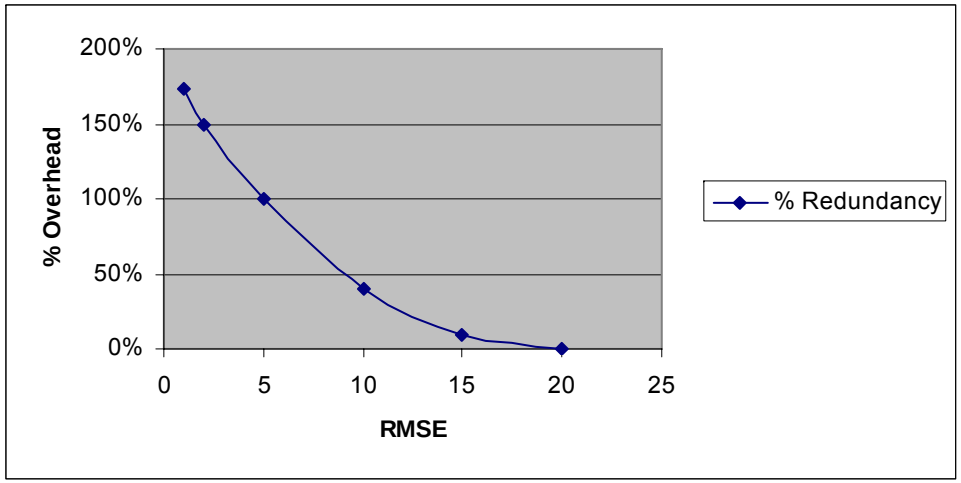
Medium Frequency



High Frequency

RMSE vs. Overhead

RMSE vs. Triple Modular Redundancy Highpass Filter, Total Edges (483)						
RMSE	≤ 1	≤ 2	≤ 5	≤ 10	≤ 15	≤ 20
# of Edges to Protect	418	359	242	97	25	0
Redundancy %	173%	149%	100%	40%	10%	0%



- **200% Redundancy is unnecessary for our test filters.**
- **High RMSE values can still result in acceptable filter behavior.**

SEU Analysis Tool – Implementation Summary

- **Automatic Filter Simulation** **Software that simulates a DSP filter via a DFG.**
  - Accept a data flow graph representation of DSP filter as input in AUDI Intermediate Format (AIF).
  - Provide correct output based on the test vector and filter in a format defined by the team.
- **Automatic Response Extraction** **Effects of SEU on Filters Performance**
- **Extensibility** **The software will be designed to be extensible by creating separate modules for input, simulation, and SEU sensitivity analysis.**
- **Extensive Documentation** **- Users and Developers.**
  - User documentation should include instructions on how to input the DFG, run the program, and interpret the output.
  - Developer documentation should include a list of classes and a description of their methods and properties, as well as an explanation on how and why they were designed.

Conclusions

- For DSP FIR Filters, full TMR may not necessary
- Overhead due to redundancy is a function of error tolerance on Filter Performance

Future Work

- **Program Extension**
  - Explore response comparison methods
    - Characteristic Comparison
    - Weighted
  - Phase Response
- **Test on different Filter forms**
  - Are some DSP Filter structures are better than others?
- **Batch support**

References

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