BODIE TECHNOLOGY, INC.
The Noisy Data Experts®

Synthesizing a Realistic Transient Acceleration Shock Signal to Represent and Bound Diverse Oscillatory Shock Time-Histories

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Overview

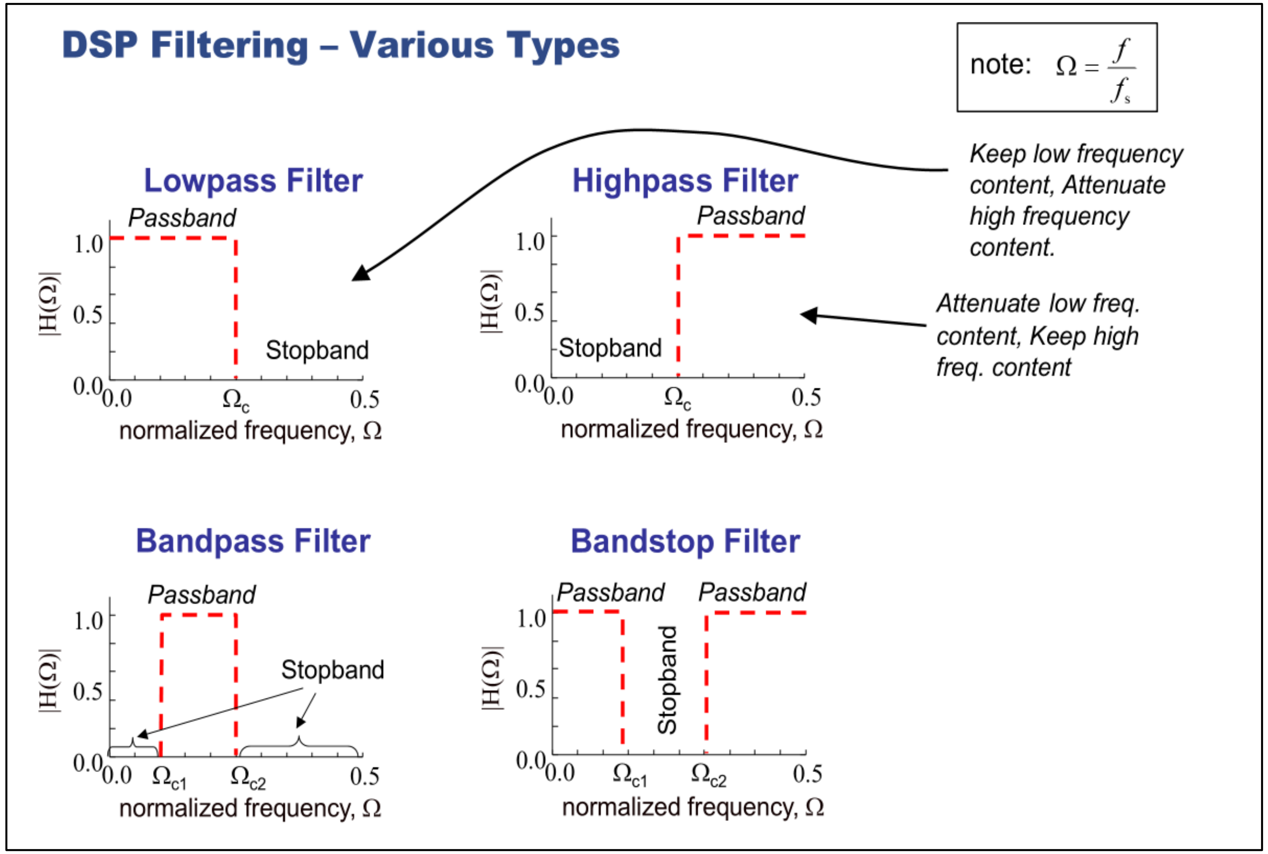
- The Goal, Key Challenges, and a Plan – How are we going to do what the presentation's title says.
- Dealing with problematic raw measurement data – AKA Salvaging.
- Characterizing each signal via its PVSS.
- Computing a statistically-based bounding curve for all the PVSS responses in each direction.
- How to synthesize a credible oscillatory transient signal for a target PVSS.
  - The approach.
  - Demonstrations.
- Conclusions / Key Achievements.

The Goal, Key Challenges, and a Plan

- **Goal:** Synthesizing a Realistic Transient Acceleration Shock Signal to Represent and Bound Diverse Oscillatory Shock Time-Histories
  - Applicable to naval, aerospace, or other industries. Intended to facilitate cost-effective and risk-appropriate mechanical shock testing using transient shaker-shock.
- **Challenges**
  - Typical repositories of measured shock data have zero-shifts and other distortions making them unsuitable as signals to drive shaker-shock tests themselves.
  - How to statistically bound a library of diverse transient signals into a single representative signal?
- **The Plan**
  - Implement preprocessing steps that effectively salvage large numbers of raw signals, making them plausible for further analysis by applying advanced filtering, integration, differentiation, and other specific manipulations.
  - Characterize each salvaged signal via its PVSS response and then compute a statistically-based envelope (bound) of all the curves to serve as a target PVSS.
  - Synthesize a credible bounding transient shock signal using scaled versions of a select few bandpass filtered signals from the greater repository of signals.
    - Utilize shape-based merit ranking of the PVSS curves over a few user-defined frequency ranges as the method of selecting the “seed” signals to aggregate for the synthesis.
    - Make additional bandpass adjustments as needed, and if needed utilize a few Shaker Wavelets too.

Terminology

- **Bi-directional** filter – The data is passed through the filter twice: first in the forward direction, then the result is reversed and filtered again, and then the result is reversed to yield a dataset in the original direction. This achieves a filtered result with no time delays (so-called zero-phase filter).
- **LP, HP, BP, BS** filters
  - Lowpass, Highpass, Bandpass, Bandstop
- **PVSS** – Pseudo-Velocity Shock Spectra
- **AUT** – Article Under Test
- Response directions of components or subcomponents in an AUT
  - **FB** – Front-to-Back
  - **SS** – Side-to-Side
  - **V** – Vertical
- Types of Shock Tests
  - **HW** – Heavyweight (MIL-DTL-901)
  - **MW** – Medium Weight (MIL-DTL-901)
  - Others



This is the Repository We Start With – a Mix of Test Types and Response Directions: FB, SS, V

- Over 40 measured shocks.
- Multiple test types and testing sources/vendors.
- Three Response Directions.
- **How to create three statistically representative time-domain shocks for all of this???**
  - **One for each direction.**

Note: To avoid duplicate signal names, each folder of files has a *UniqueID_map* table that defines a descriptive ID name for each signal that is unique across all the folders in the repository.

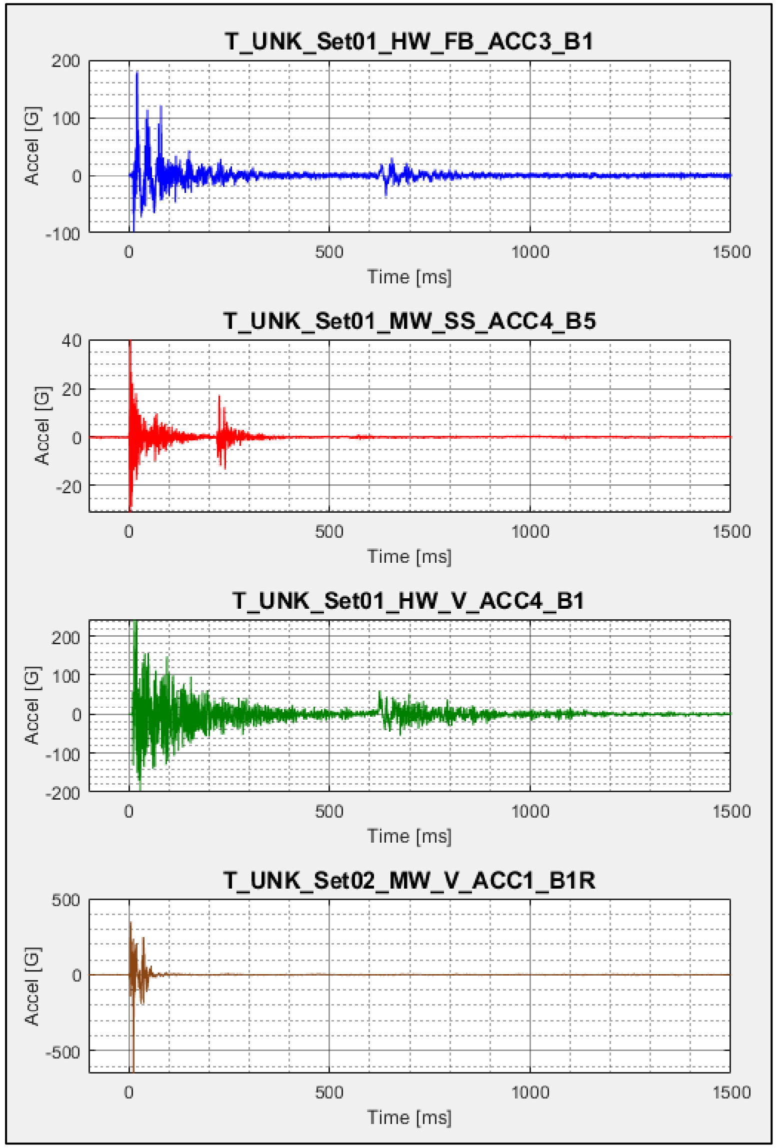
Set01

7381-A02S4AF.txt	7381-A02S4RAF.txt	9961-A02S4.txt
9961-A03S4.txt	HW_FB_ACC1.txt	HW_FB_ACC2.txt
HW_FB_ACC3.txt	HW_FB_ACC4.txt	HW_FB_ACC5.txt
HW_SS_ACC1.txt	HW_SS_ACC2.txt	HW_SS_ACC3.txt
HW_SS_ACC4.txt	HW_SS_ACC5.txt	HW_V_ACC1.txt
HW_V_ACC2.txt	HW_V_ACC3.txt	HW_V_ACC4.txt
HW_V_ACC5.txt	MW_FB_ACC1.txt	MW_FB_ACC2.txt
MW_FB_ACC3.txt	MW_FB_ACC4.txt	MW_FB_ACC5.txt
MW_SS_ACC1.txt	MW_SS_ACC2.txt	MW_SS_ACC3.txt
MW_SS_ACC4.txt	MW_SS_ACC5.txt	MW_V_ACC1.txt
MW_V_ACC2.txt	MW_V_ACC3.txt	MW_V_ACC4.txt
MW_V_ACC5.txt	UniqueID_map.csv	

Set02

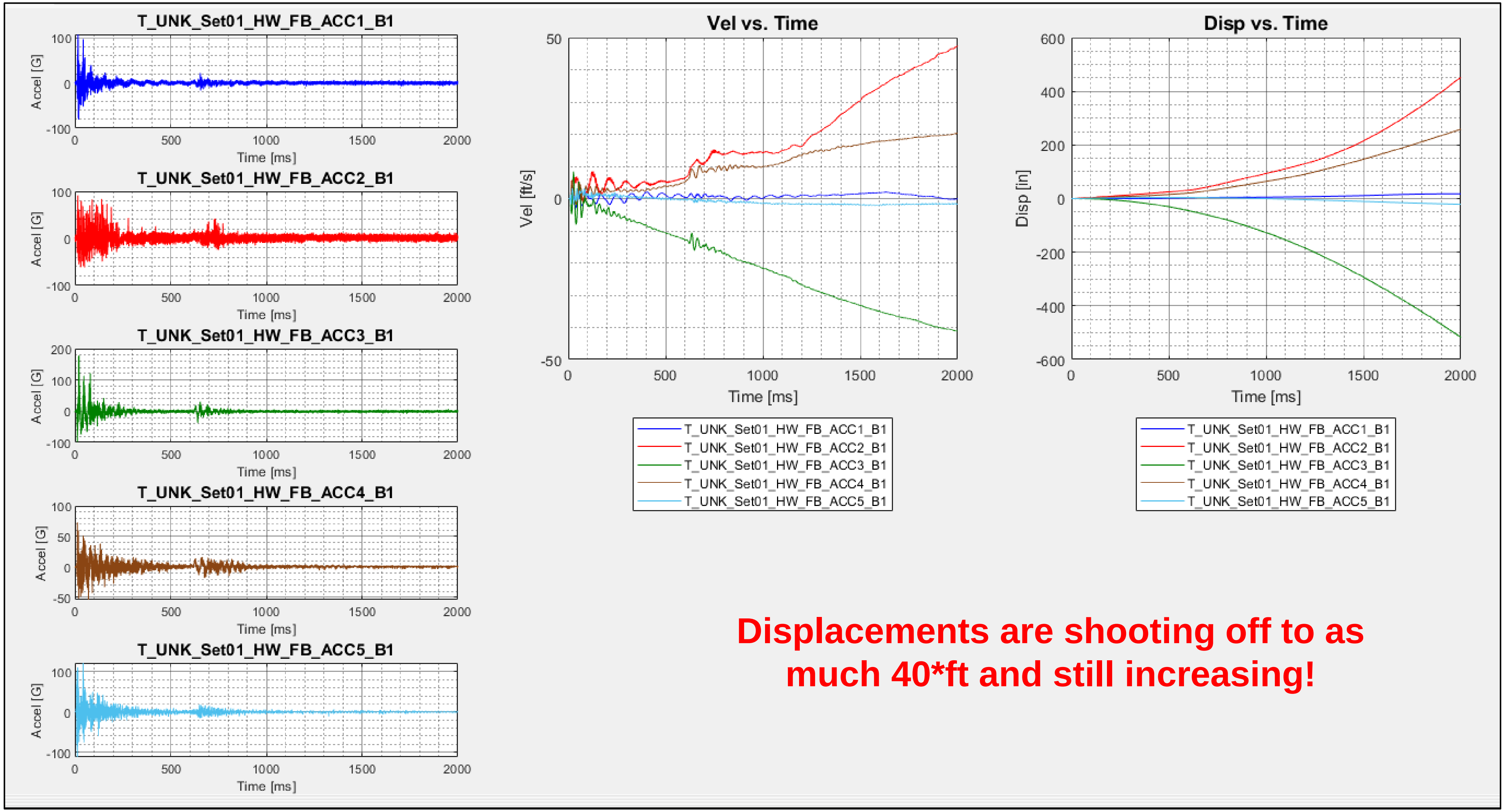
HW_FB_ACC3.txt	HW_FB_ACC4.txt	HW_SS_ACC3.txt
HW_SS_ACC4.txt	HW_V_ACC3.txt	HW_V_ACC4.txt
HW_V_ACC5.txt	MW_FB_ACC6.txt	MW_SS_ACC6.txt
MW_V_ACC1.txt	MW_V_ACC6.txt	UniqueID_map.csv

Exemplar Raw Signals



Raw Measurement Data is NOT Credible Relative to Velocity & Displacement

- Raw Heavyweight data.
- **FB** Response Dir.
- Acceleration seems OK.
- Time-integrating to Velocity and Displacement yield implausible results.
- Even if this data was somehow considered plausible, it could NOT be used to drive a mechanical shaker.

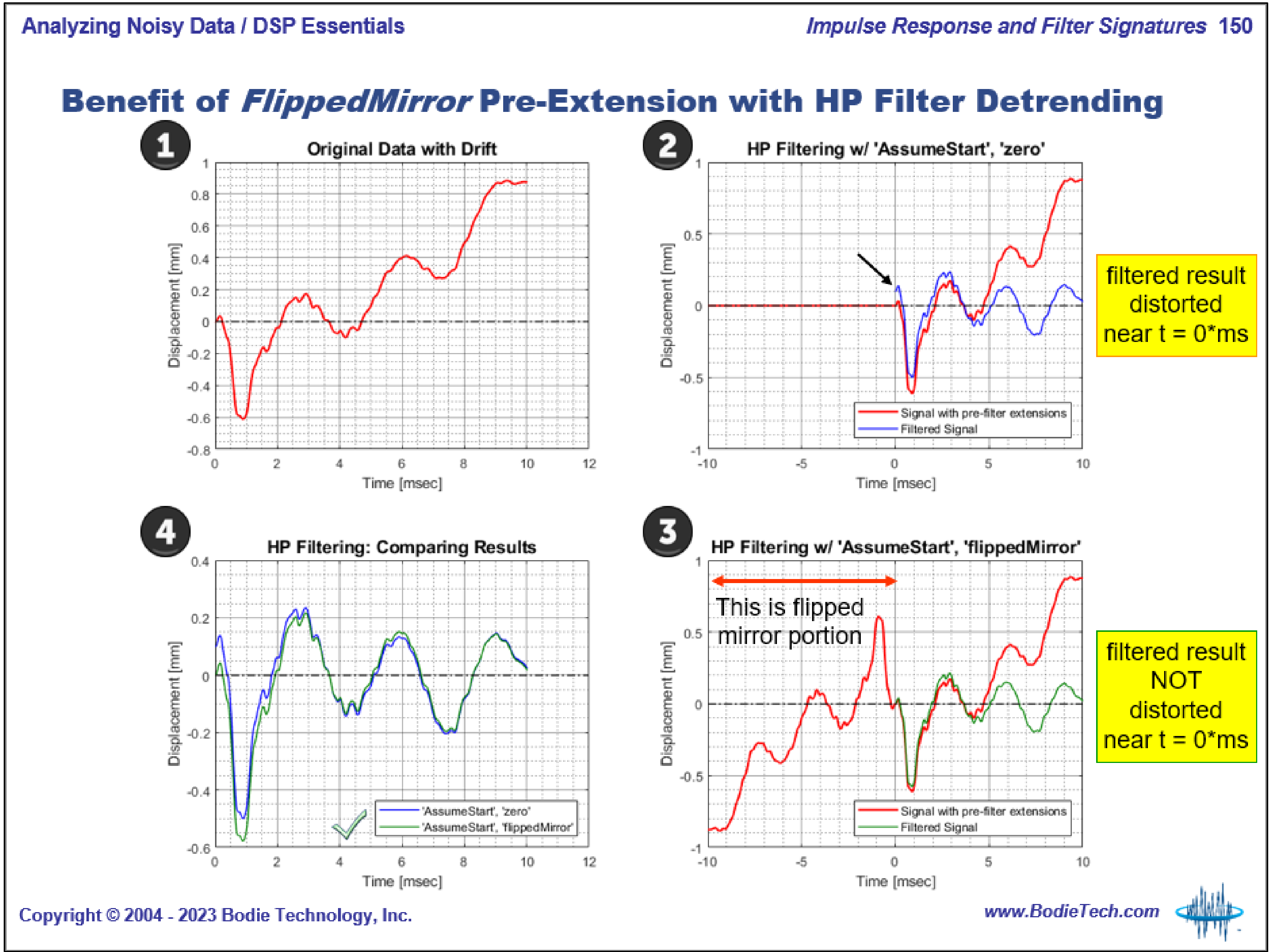


Salvaging Algorithm to Address Implausible Raw Data

- Need robust, non-burdensome, semi-automatic algorithm with a few user-controllable parameters, but not too many.
  - Must be able to process large repositories of data without constant user baby-sitting and intervention.
- **Our Approach:**
  - An automatic algorithm trims the raw acceleration data to where the "action starts".
  - The trimmed acceleration is then pre-extended with zero amplitude by a small amount so that bi-directional filters that are later applied can properly complete their back-pass. The extension length is proportional to a scale factor (typically 3) divided by `fc_LP` (a lowpass cutoff frequency that will be applied shortly).
  - Integrate the trimmed and pre-extended acceleration time-history to velocity vs. time.
  - Apply a bi-directional highpass filter using a flipped-mirror starting assumption to the velocity to remove the drifting behavior.
    - Physics of most , but not all, of the test types would dictate that the velocity should start at zero and end at zero (or oscillating around zero). Additionally, to be useable on a shaker, this condition must be met.
    - The flipped-mirror starting assumption minimizes the HP-filter distortion that would otherwise occur at the start of the signal.
  - Apply a bi-directional lowpass filter with zero starting assumption to bound frequency to max desired level.
  - Apply a taper to the start of the resulting signal to ensure the velocity starts at zero and its derivative (acceleration) starts at zero.
  - Recompute Acceleration and Displacement from the Salvaged Velocity time-history.

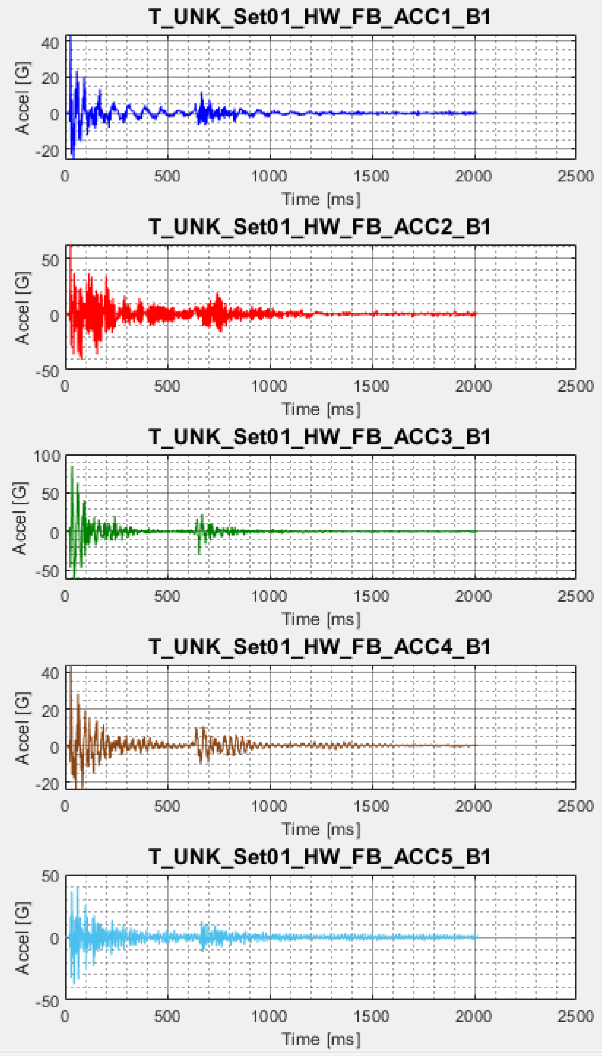
Benefits of a Flipped Mirror Starting Assumption with HP Filters on Shock Data

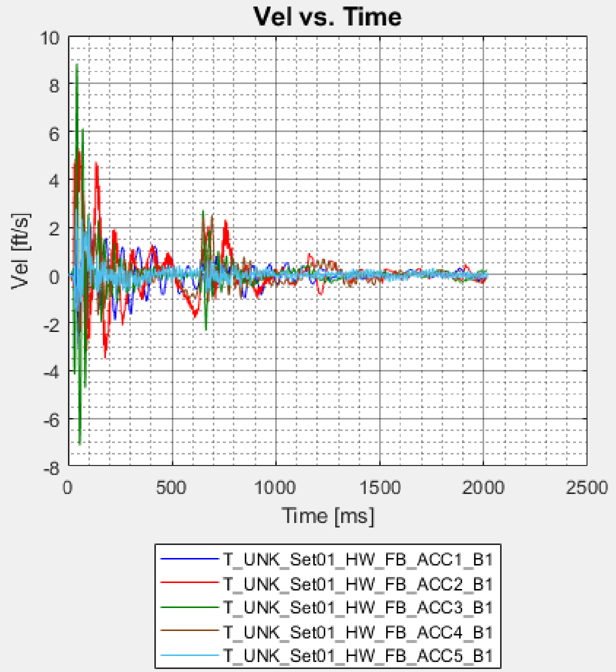
- The depiction to the right is an image from the training class ***DSP Essentials***, Courtesy of Bodie Technology, Inc.
- The displacement signal in graph #1 starts at zero but is clearly drifting.
  - We know the signal's value prior to its start has zero amplitude (it was at rest).
- Graph #2 shows a classic bi-directional HP filtering result that yields a non-zero starting value and a decreased max response at the first peak.
- Graph #3 demonstrates the flipped-mirror starting assumption.
- #4 compares the two approaches.

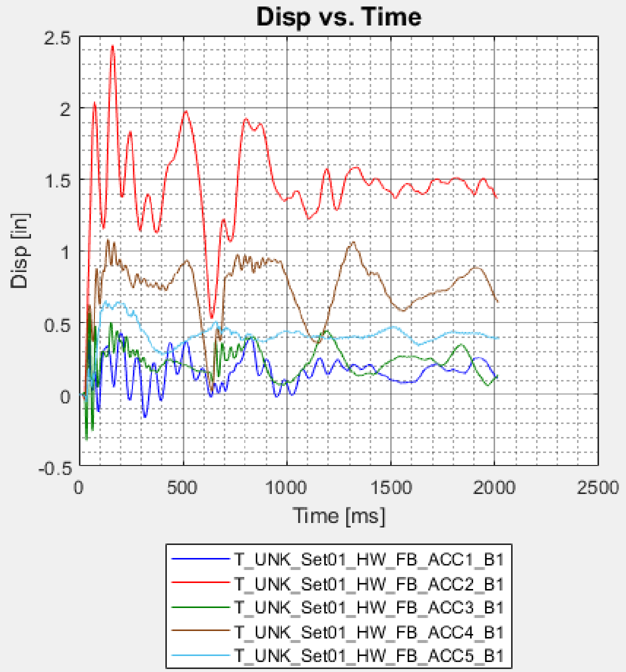


Salvaged Data is Now Credible Relative to All 3 Kinematic Measures

- Salvaged Heavyweight data.
- **FB** Response Dir.
- Data filtered with fc_HP = 2*Hz, fc_LP = 250*Hz.
- All three kinematic measures are plausible.
- Data could drive a mechanical shaker that has sufficient capabilities.





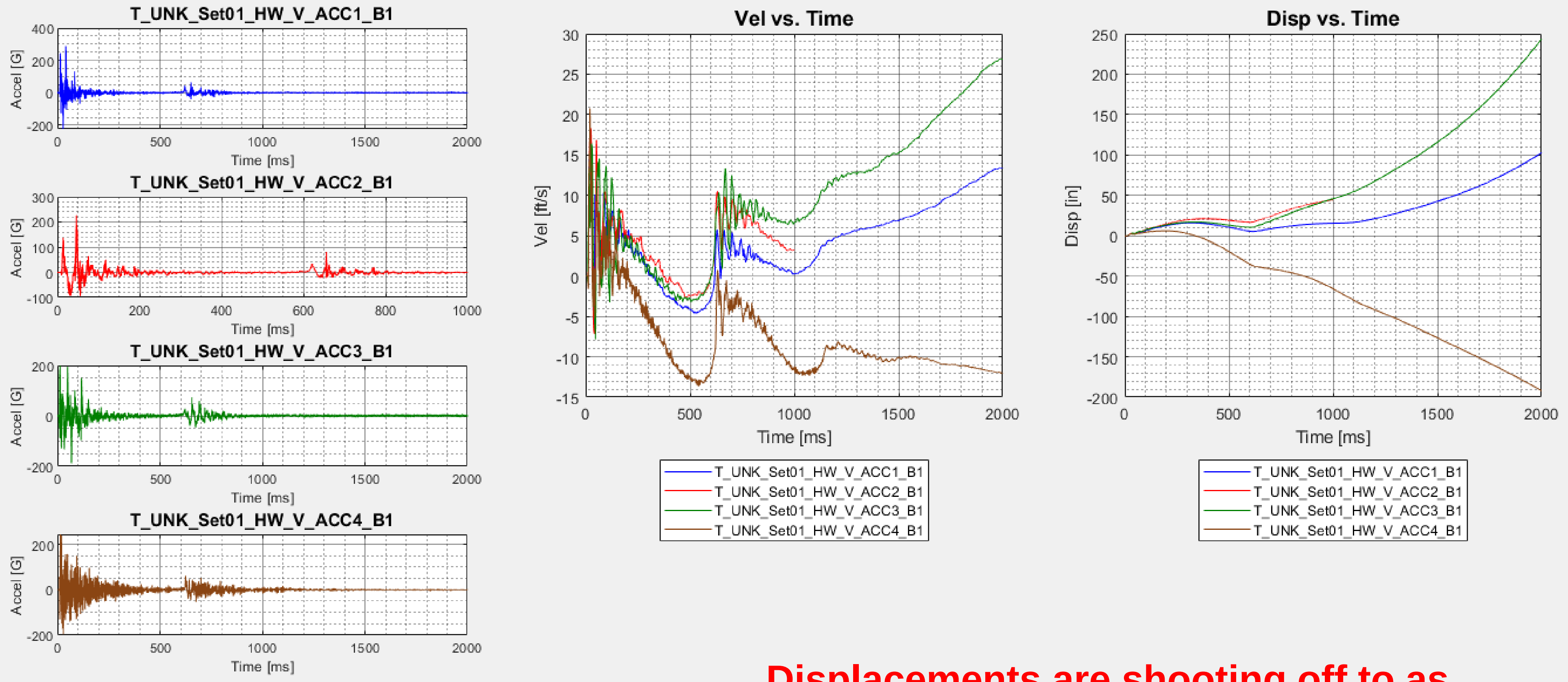


Temporal Moments from Salvaged Accel
fc_HP = 2*Hz, fc_LP = 250*Hz

	Mag_eff [G]	Centroid [ms]	RMSdur [ms]	Skewness [ms]	Kurtosis [ms]
T_UNK_Set01_HW_FB_ACC1_B1	8.571	172.7	261.5	365.1	487.1
T_UNK_Set01_HW_FB_ACC2_B1	16.34	245.5	279.5	358.1	476.1
T_UNK_Set01_HW_FB_ACC3_B1	23.48	128.0	195.4	284.9	378.4
T_UNK_Set01_HW_FB_ACC4_B1	9.550	219.5	288.4	358.5	458.1
T_UNK_Set01_HW_FB_ACC5_B1	9.855	258.3	367.6	490.5	631.8

More Problematic Raw Data from the V Response Direction

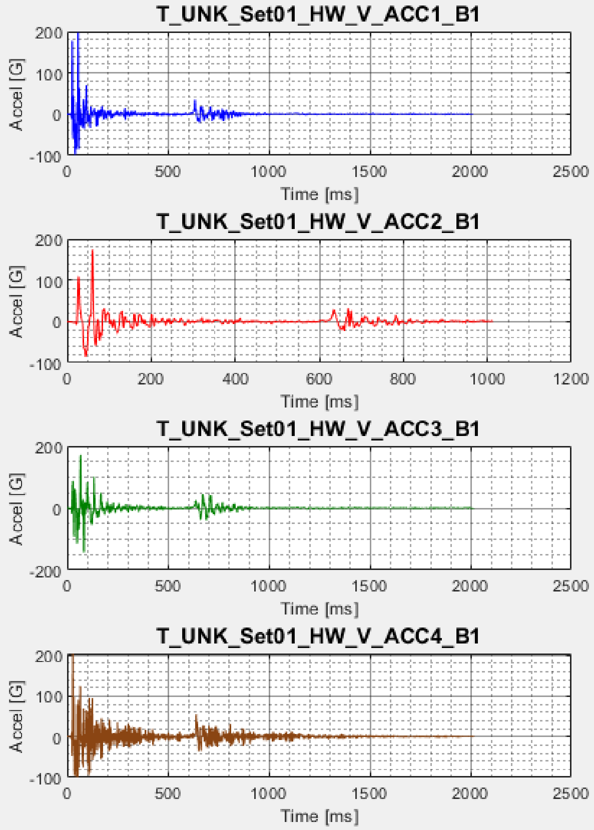
- Raw Heavyweight data.
- **V** Response Dir.
- Acceleration seems OK.
- Time-integrating to Velocity and Displacement yield implausible results.
- Even if this data was somehow considered plausible, it could NOT drive a mechanical shaker.

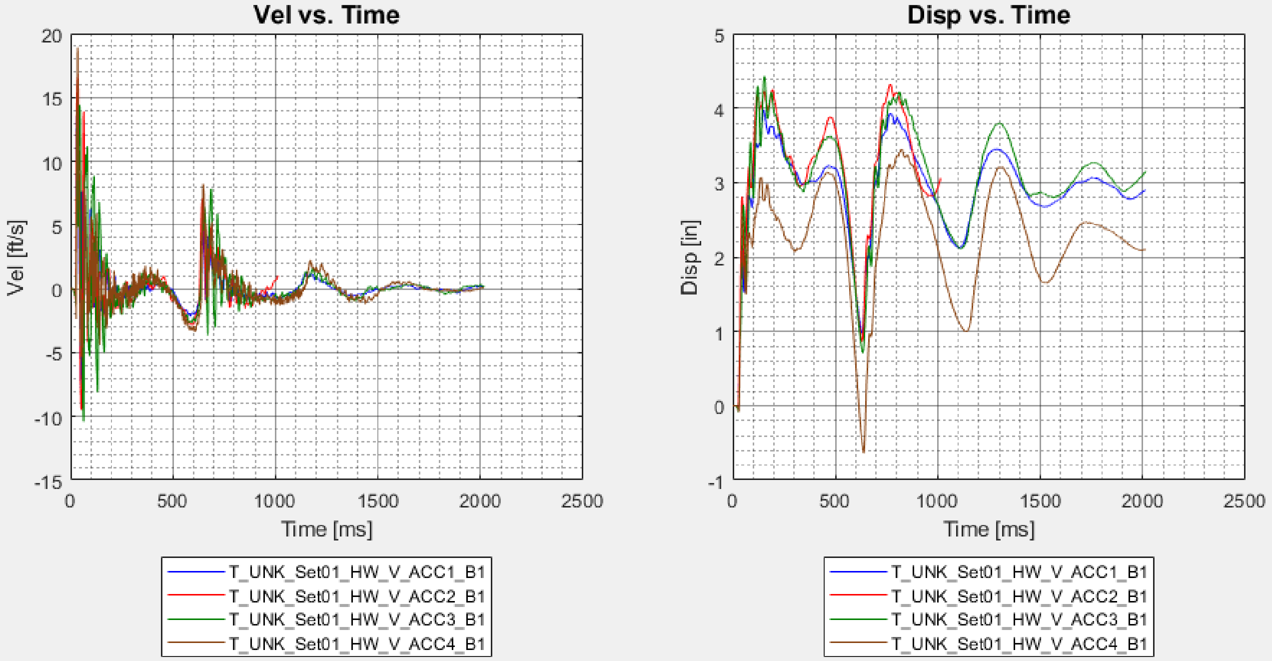


Displacements are shooting off to as much 20*ft and still increasing!

Salvaged V Data is Now Credible Relative to All 3 Kinematic Measures

- Salvaged Heavyweight data.
- **V** Response Dir.
- Data filtered with fc_HP = 2*Hz, fc_LP = 250*Hz.
- All three kinematic measures are plausible.
- Data could drive a mechanical shaker that has sufficient capabilities.



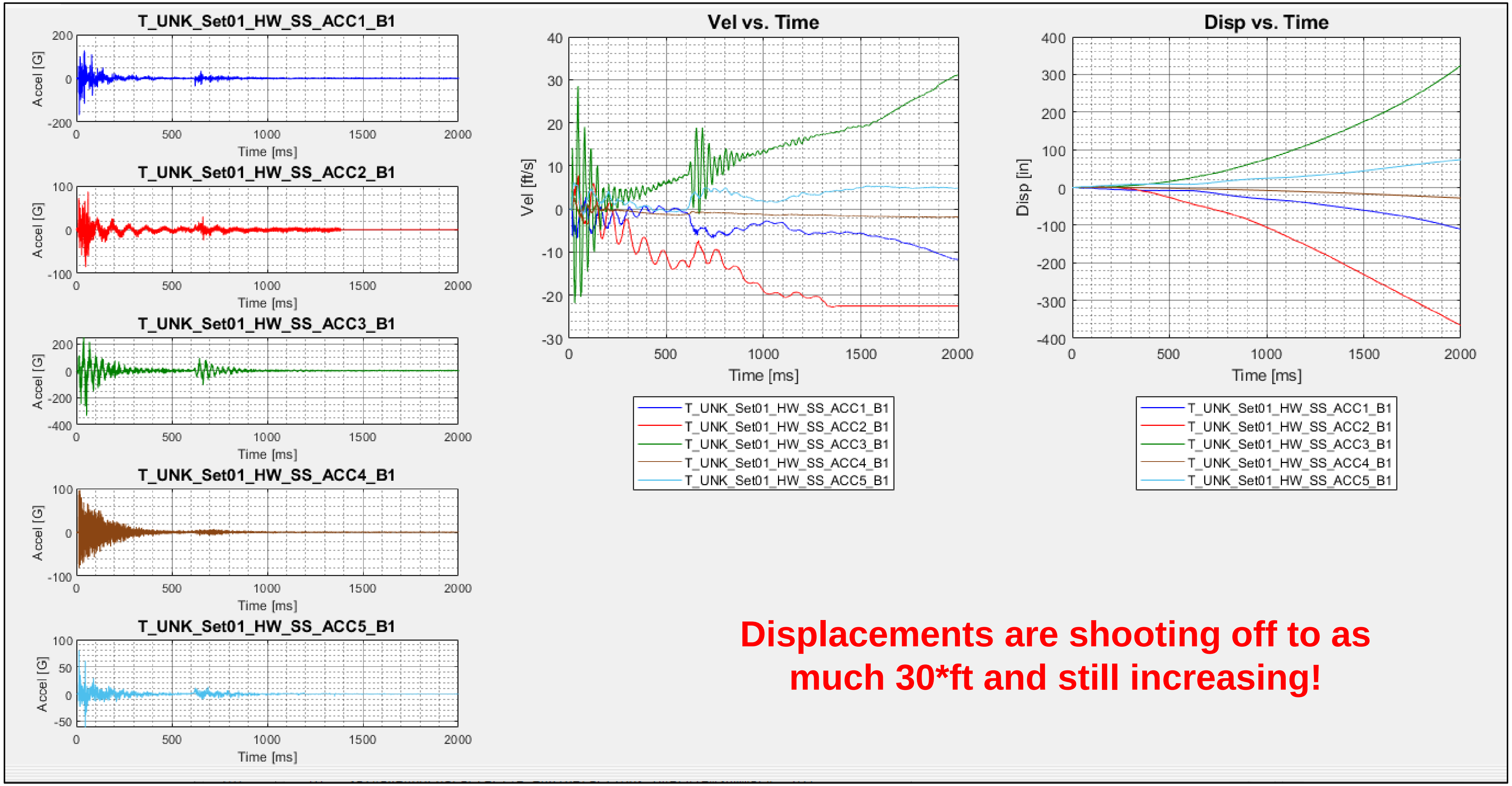


Temporal Moments from Salvaged Accel
fc_HP = 2*Hz, fc_LP = 250*Hz

	Mag_eff [G]	Centroid [ms]	RMSdur [ms]	Skewness [ms]	Kurtosis [ms]
T_UNK_Set01_HW_V_ACC1_B1	38.25	101.4	172.8	261.0	341.8
T_UNK_Set01_HW_V_ACC2_B1	38.05	111.0	172.4	246.8	307.7
T_UNK_Set01_HW_V_ACC3_B1	42.67	166.1	220.9	287.8	360.9
T_UNK_Set01_HW_V_ACC4_B1	43.17	182.9	249.1	328.6	421.6

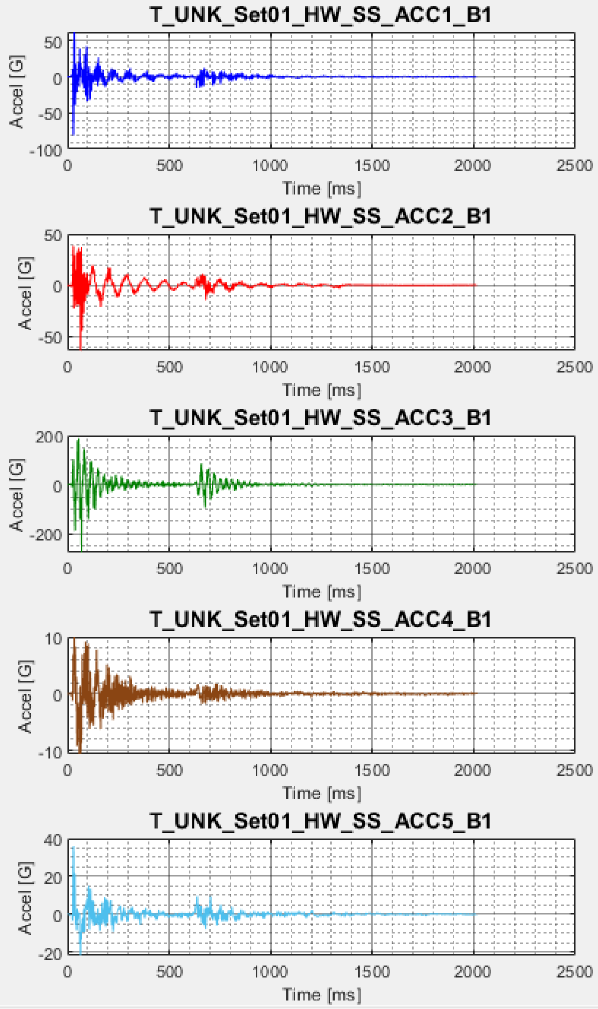
More Problematic Raw Data from the SS Response Direction

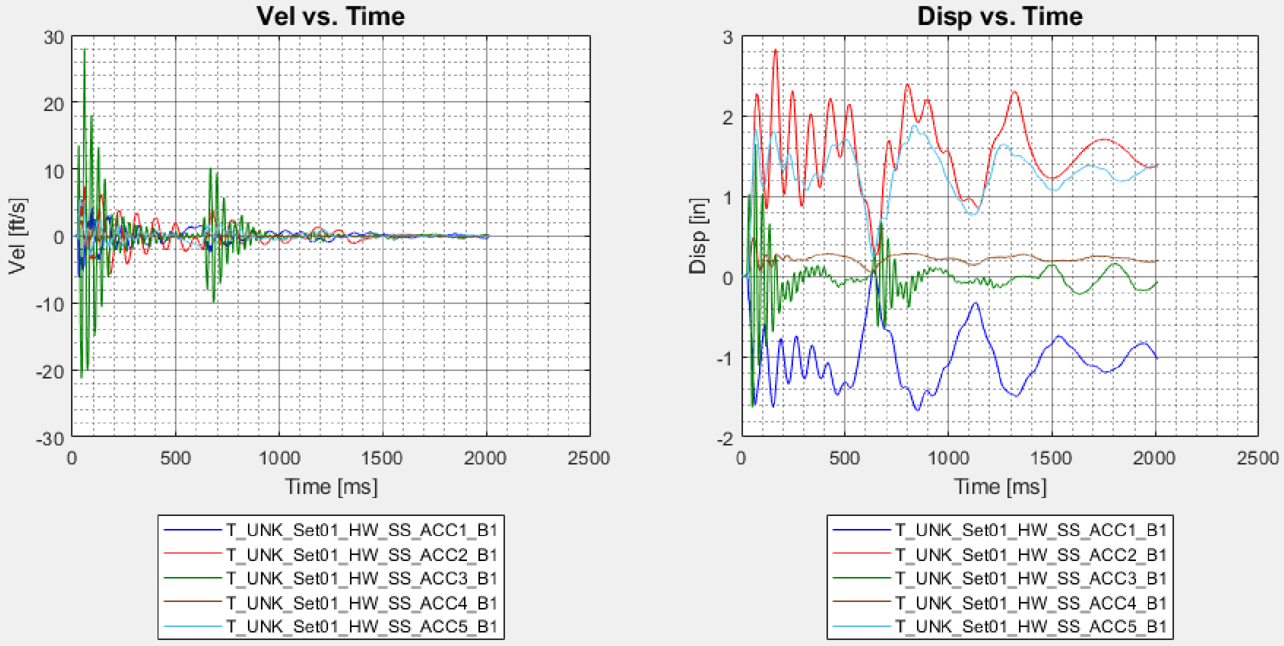
- Raw Heavyweight data.
- **SS** Response Dir.
- Acceleration seems OK.
- Time-integrating to Velocity and Displacement yield implausible results.
- Even if this data was somehow considered plausible, it could NOT drive a mechanical shaker.



Salvaged SS Data is Now Credible Relative to All 3 Kinematic Measures

- Salvaged Heavyweight data.
- **SS** Response Dir.
- Data filtered with fc_HP = 2*Hz, fc_LP = 250*Hz.
- All three kinematic measures are plausible.
- Data could drive a mechanical shaker that has sufficient capabilities.



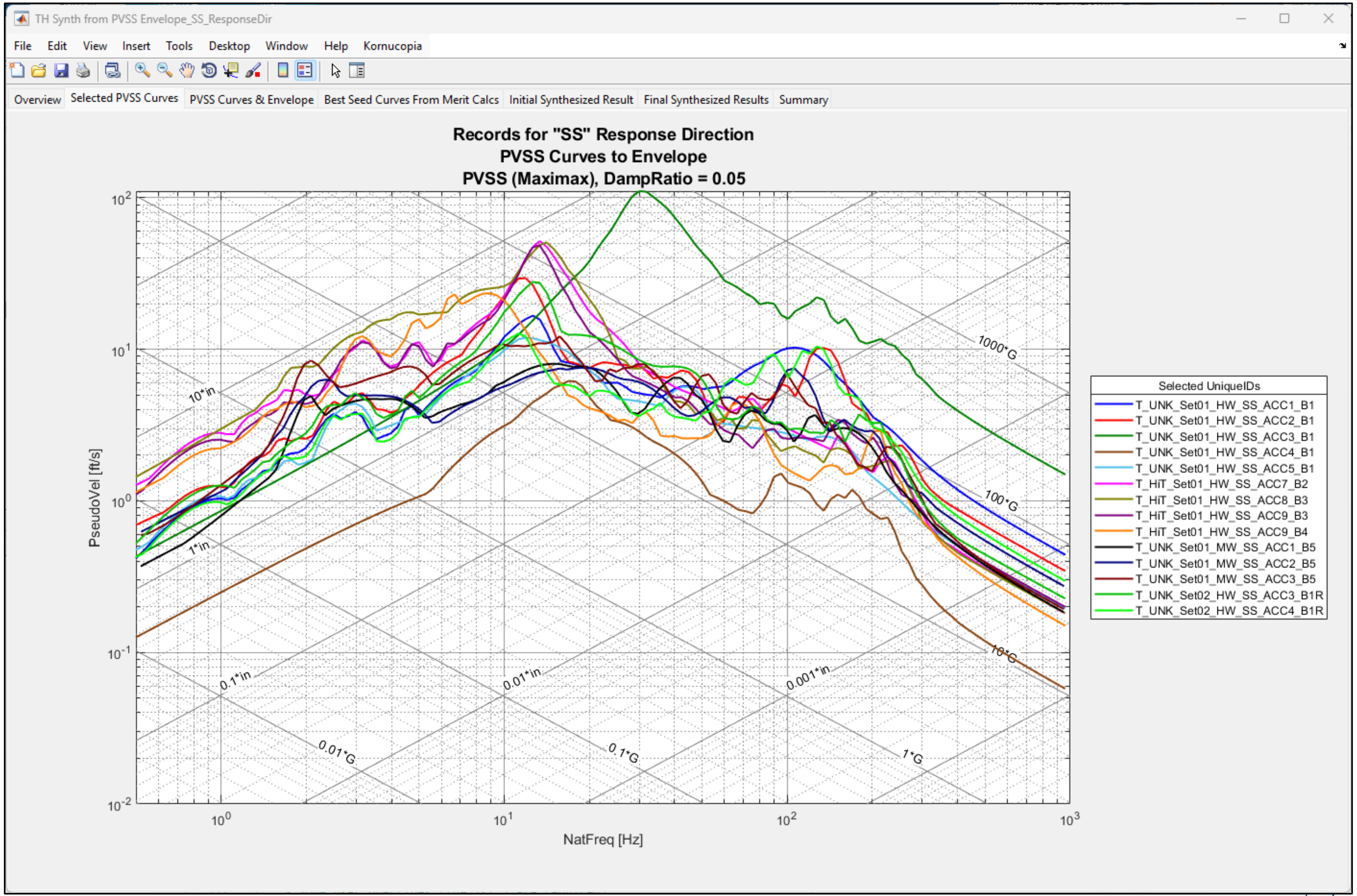


Temporal Moments from Salvaged Accel
fc_HP = 2*Hz, fc_LP = 250*Hz

	Mag_eff [G]	Centroid [ms]	RMSdur [ms]	Skewness [ms]	Kurtosis [ms]
T_UNK_Set01_HW_SS_ACC1_B1	16.91	143.9	212.8	302.0	400.1
T_UNK_Set01_HW_SS_ACC2_B1	16.78	167.6	200.2	269.9	351.7
T_UNK_Set01_HW_SS_ACC3_B1	71.08	175.3	229.6	286.1	350.0
T_UNK_Set01_HW_SS_ACC4_B1	4.428	141.8	177.9	285.2	401.3
T_UNK_Set01_HW_SS_ACC5_B1	7.216	201.7	268.7	344.6	447.4

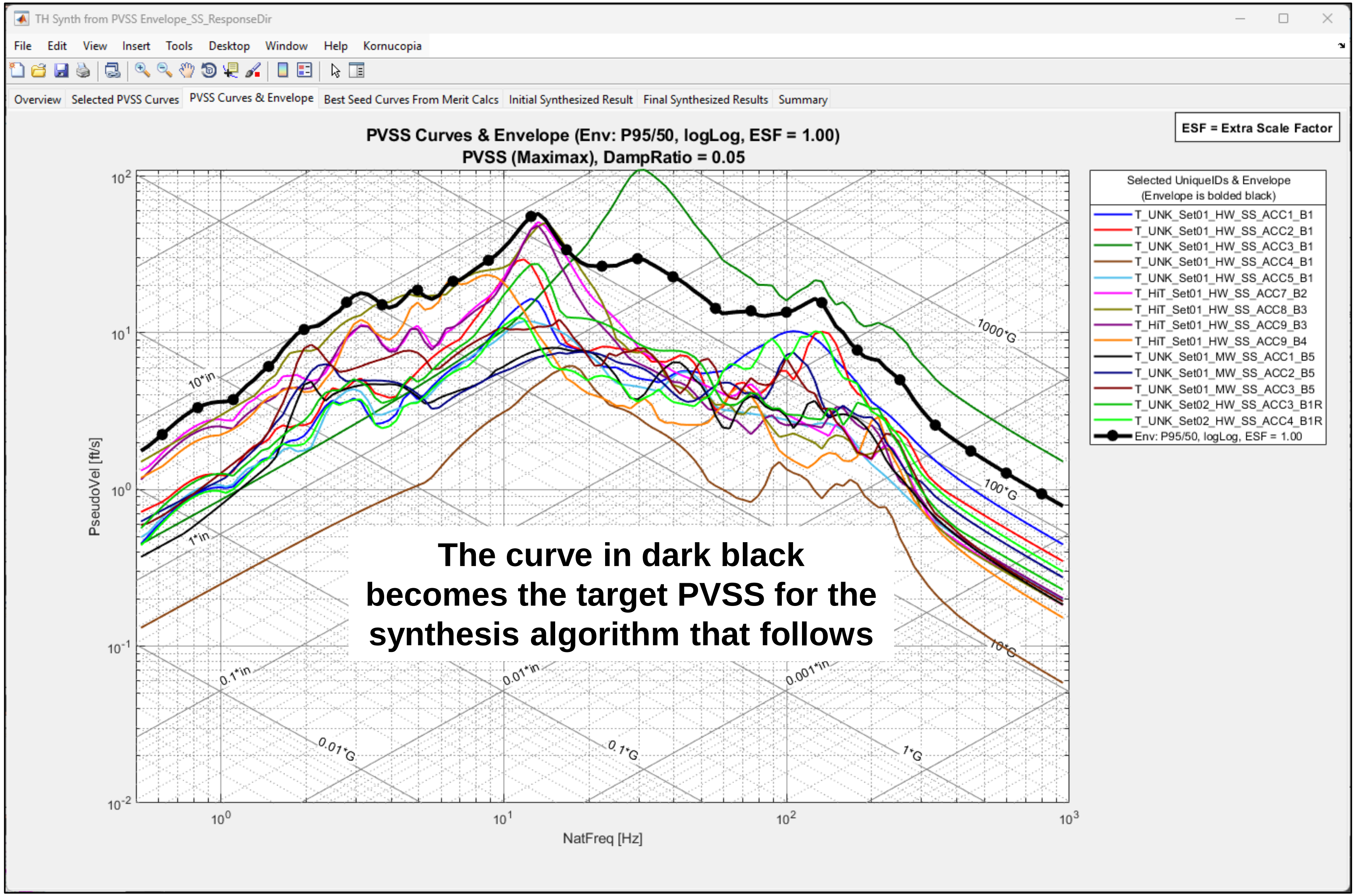
PVSS Plot of All the SS Response Direction Data in the Study

- Maximax PVSS curves for all 14 SS Response Direction signals.
  - PVSS curves all computed from salvaged signals.
- 3rd curve in list is noticeably different than the "pack".
  - We will simply let the statistics that are applied "account" for this.
  - The time-history data for this curve was taken from an accelerometer in an area of very high amplification.



Statistically Enveloping All the SS Response Direction PVSS Curves

- Several statistically-based enveloping methods could be applied. In this example a **P95/50 envelope** is computed.
  - Based on a one-sided normal tolerance limit approach to meet a 95-percentile limit with 50% confidence.
  - Statistical bounding calculations done in the log-log space as this is traditionally more likely to satisfy normality requirements of statistics.
    - Future efforts to explore this aspect of the analysis ongoing.

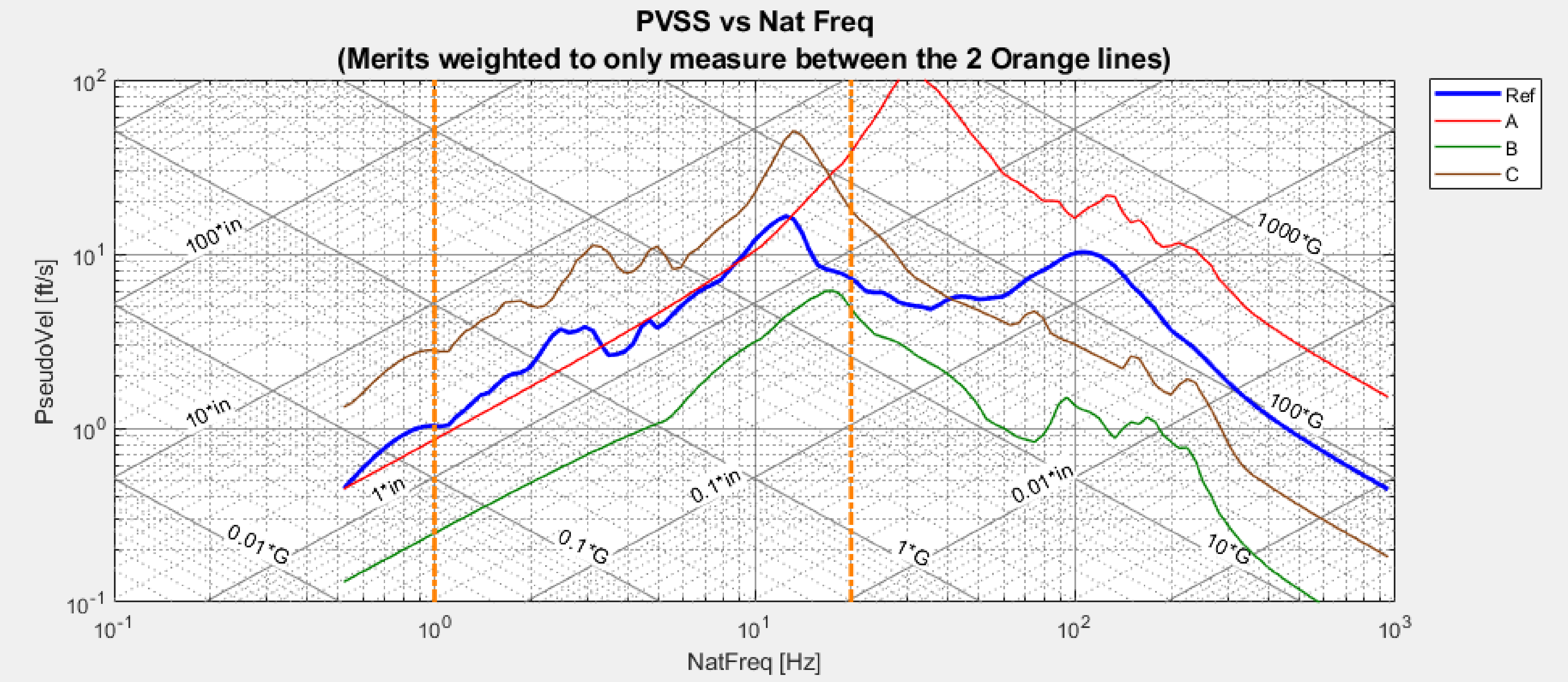


How to Create Representative Time History from Target PVSS Curve?

- Traditional approaches to this problem have utilized Monte Carlo approaches with damped sinusoids and wavelets.
  - These methods are computationally expensive and uncertain to converge.
  - They generally result in a transient signal that may meet the target PVSS but bear little to no resemblance to any actual acceleration signals in the repository.
- Dr. Bryan Joyce of Naval Surface Warfare Center Dahlgren Division (NSWCDD) demonstrated the benefits of a “filter+Add” method and a “Match Shape” method to select filtered *seed* signals from the repository of underlying signals to aggregate together for a synthesis algorithm.
  - Joyce, B., **Time Waveform Replication (TWR) Pulse Development from Multiple Test Records**, *93rd Shock and Vibration Symposium*, Oct. 2023.
- Our method generalized and extends on the NSWCDD approach:
  - We use the PVSS space instead of acceleration SRS space for computing a target characteristic curve. Our target curve is over then entire repository, not portioned populations as NSWCDD did.
  - We allow the user to specify a few natural frequency ranges in the PVSS space over which a shape-based merit measure is utilized to select best seeds to consider.
  - Acceleration time-histories of selected seed signals are bandpass filtered (with appropriate amplitude scaling).
    - Time delays can also be applied. These seeds are summed together to create an initial synthesized signal.
  - A check is made of the synthesized signal’s PVSS compared to the target PVSS with user-specified tolerance.
  - If needed, the user can specify additional BP frequencies and amplitude rescaling factors plus add a few Shaker Wavelets (if needed in rare cases) to achieve desired results.

Shape-Based Merit vs Traditional Merit Measures

- Compare 3 PVSS curves to a Ref Curve.
- Frequency range of interest between orange lines (1*Hz to 20*Hz). Use weighting to enforce this.
- Both **Shape-Base** and **Traditional Merit Measures** computed.
  - Traditional Merits computed in loglog mapping space.
- Shape-based measures “focus” on curve shape, not differences between values. Traditional Merits based on differences between values.
- Shape correct ranks curve **C** the best.



Shape-Based Measures of Merit & Scaling Factors

	S_NRMSE	S_NMAE	SSF_avg
A	0.7928	0.8609	1.032
B	0.8376	0.8882	3.795
C	0.8945	0.9134	0.4162

Traditional Measures of Merit (loglog mappingSpace)

	Rsq	NMAE	NRMSE	NRMSRE
A	0.6069	0.5146	0.3730	0.003409
B	-2.006	-0.9767	-0.7337	-9.440
C	-0.4983	-0.4048	-0.2240	-6.576

Traditional Normalized Merit Measures (Including Weighting)

Formulations from *Kornucopia® ML™*

- **Sum of weights and weighted mean of y_{ref}**

$$w_{sum} = \sum_{i=1}^{N} w_i \qquad \overline{wy_{ref}} = \frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} w_i \cdot y_{ref\,i}$$

- **Weighted Residual Sum of Squares, Total Sum of Squares, and R-squared**

$$RSS = \sum_{i=1}^{N} \left(w_i \cdot \left(y_i - y_{ref\,i} \right)^2 \right) \qquad TSS = \sum_{i=1}^{N} \left(w_i \cdot \left(y_{ref\,i} - \overline{wy_{ref}} \right)^2 \right) \qquad Rsq = 1 - \frac{RSS}{TSS}$$

- **Normalized Weighted Root Mean Square Error**

$$NRMSE = 1 - \frac{\sqrt{\sum_{i=1}^{N} \left(w_i \cdot \left(y_i - y_{ref\,i} \right)^2 \right)}}{\sqrt{\sum_{i=1}^{N} \left(w_i \cdot \left(y_{ref\,i} - \overline{wy_{ref}} \right)^2 \right)}} \qquad NRMSE = 1 - \sqrt{\frac{RSS}{TSS}}$$

- **Normalized Weighted Root Mean Square Relative Error**

$$RMSRE = \sqrt{\frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} \left(w_i \cdot \left(1 - \frac{y_i}{y_{ref\,i}} \right)^2 \right)} \qquad NRMSRE = 1 - RMSRE$$

- **Weighted Mean Absolute Error and its Weighted Normalized formula**

$$MAE = \frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} \left(w_i \cdot \left| y_i - y_{ref\,i} \right| \right) \qquad NMAE = 1 - \frac{\sum_{i=1}^{N} \left(w_i \cdot \left| y_i - y_{ref\,i} \right| \right)}{\sum_{i=1}^{N} \left(w_i \cdot \left| y_{ref\,i} - \overline{wy_{ref}} \right| \right)}$$

Shape-Based Merit Measures (Including Weighting)

Formulations from *Kornucopia® ML™*

- **Point Ratios, weighted PR, sum of the weights, and weighted mean of wPR**

$$PR_i = \frac{y_{ref_i}}{y_i} \qquad wPR_i = w_i \cdot \frac{y_{ref_i}}{y_i} \qquad w_{sum} = \sum_{i=1}^{N} w_i \qquad \overline{wPR} = \frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} wPR_i$$

- **Scale Factors**
  A few different options
  (We prefer SSF_{avg}).

$$SSF_{avg} = \overline{wPR} \qquad SSF_{rms} = \sqrt{\frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} \left(w_i \cdot PR_i^2\right)} \qquad SSF_{rrms} = \frac{\sqrt{\sum_{i=1}^{N}\left(w_i \cdot {y_{ref}}_i^2\right)}}{\sqrt{\sum_{i=1}^{N}\left(w_i \cdot y_i^2\right)}}$$

- **Log-transformed values for Point Ratios and a weighted mean of PR_{log10} values (This makes Merits invariant of constant scaling factor)**

$$PR_{log10_i} = \log_{10} PR_i \qquad \overline{wPR_{log10}} = \frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} \left(w_i \cdot PR_{log10_i}\right)$$

- **Shape-based merit measure for Normalized Mean Absolute Error**

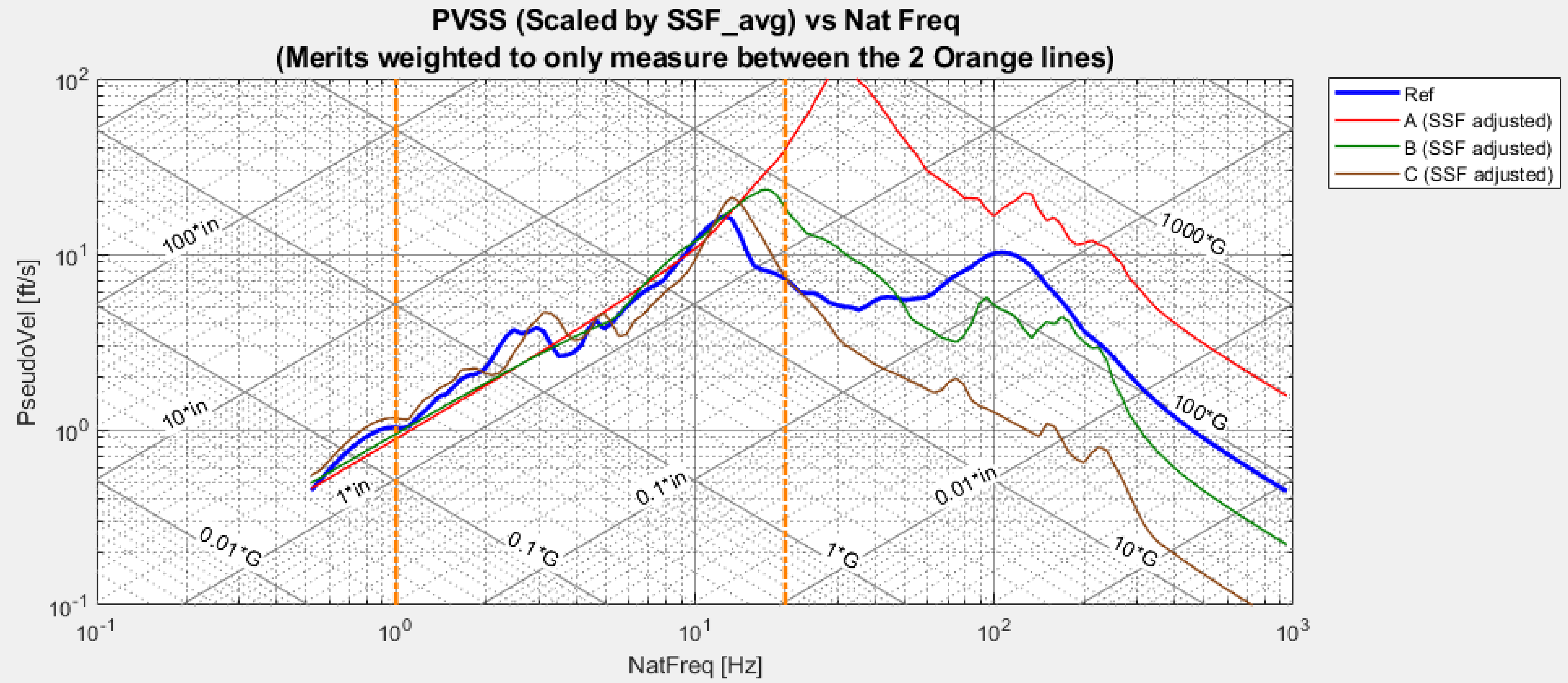
$$S\_NMAE = 1 - \left(\frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} \left(w_i \cdot \left|PR_{log10_i} - \overline{wPR_{log10}}\right|\right)\right)$$

- **Shape-based merit measure for Normalized Root Mean Square Error**

$$S\_NRMSE = 1 - \left|\sqrt{\frac{1}{w_{sum}} \cdot \sum_{i=1}^{N} \left(w_i \cdot \left(PR_{log10_i} - \overline{wPR_{log10}}\right)^2\right)}\right|$$

Shape-Based Merit vs Traditional Merit Measures (after rescaling via SSF_avg)

- The 3 curves are rescaled based on previous SSF_avg values.
- Frequency range of interest still between orange lines (1*Hz to 20*Hz).
- Same Shape-Based Merit values and rankings are computed as before.
  - The Shape-based formulation is invariant of a constant scaling factor.
- After scaling, Traditional Merits now rank the same as Shape-based Merits.
  - **C**, then **B**, then **A.**



Shape-Based Measures of Merit & Scaling Factors

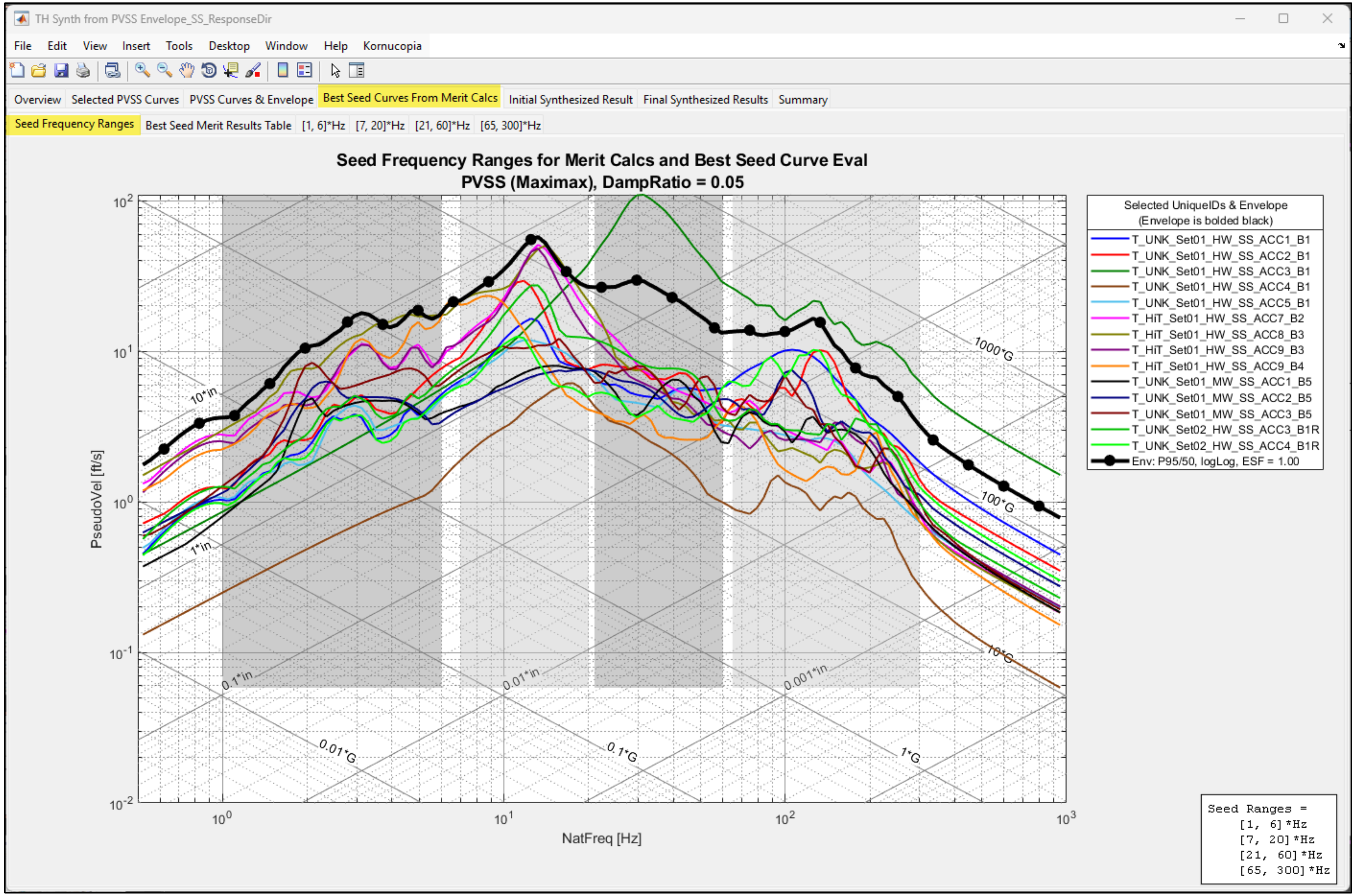
	S_NRMSE	S_NMAE	SSF_avg
A (SSF adjusted)	0.7928	0.8609	1.000
B (SSF adjusted)	0.8376	0.8882	1.000
C (SSF adjusted)	0.8945	0.9134	1.000

Traditional Measures of Merit (loglog mappingSpace)

	Rsq	NMAE	NRMSE	NRMSRE
A (SSF adjusted)	0.5992	0.5177	0.3669	0.2298
B (SSF adjusted)	0.7557	0.6148	0.5057	0.6534
C (SSF adjusted)	0.8981	0.6821	0.6807	0.1188

Defining Frequency Ranges for Ranking Best Seeds Via Shape-Based Merits

- Results are for **SS** Response Direction.
- User defines a few frequency ranges (*shaded blocks*) based on the nature of the target PVSS shape.
  - Place ranges to approximately cover larger “bumps” in the PVSS target curve.
- Ranges can have gaps but should not overlap in general.
- Shape-based merit rankings over these ranges are computed.
  - Ranges will define initial bandpass filter frequencies to apply to seed signals.



Defining Frequency Ranges for Ranking Best Seeds Based on Shape-Merits

- Resulting Shape-based Merit rankings. Each of the 4 ranges has 3 top-ranked seeds identified.
  - Based on Merit value and time-histories on next slide, user picks 1 seed for each frequency range.

TH Synth from PVSS Envelope_SS_ResponseDir

File Edit View Insert Tools Desktop Window Help Kornucopia

Overview | Selected PVSS Curves | PVSS Curves & Envelope | Best Seed Curves From Merit Calcs | Initial Synthesized Result | Final Synthesized Results | Summary

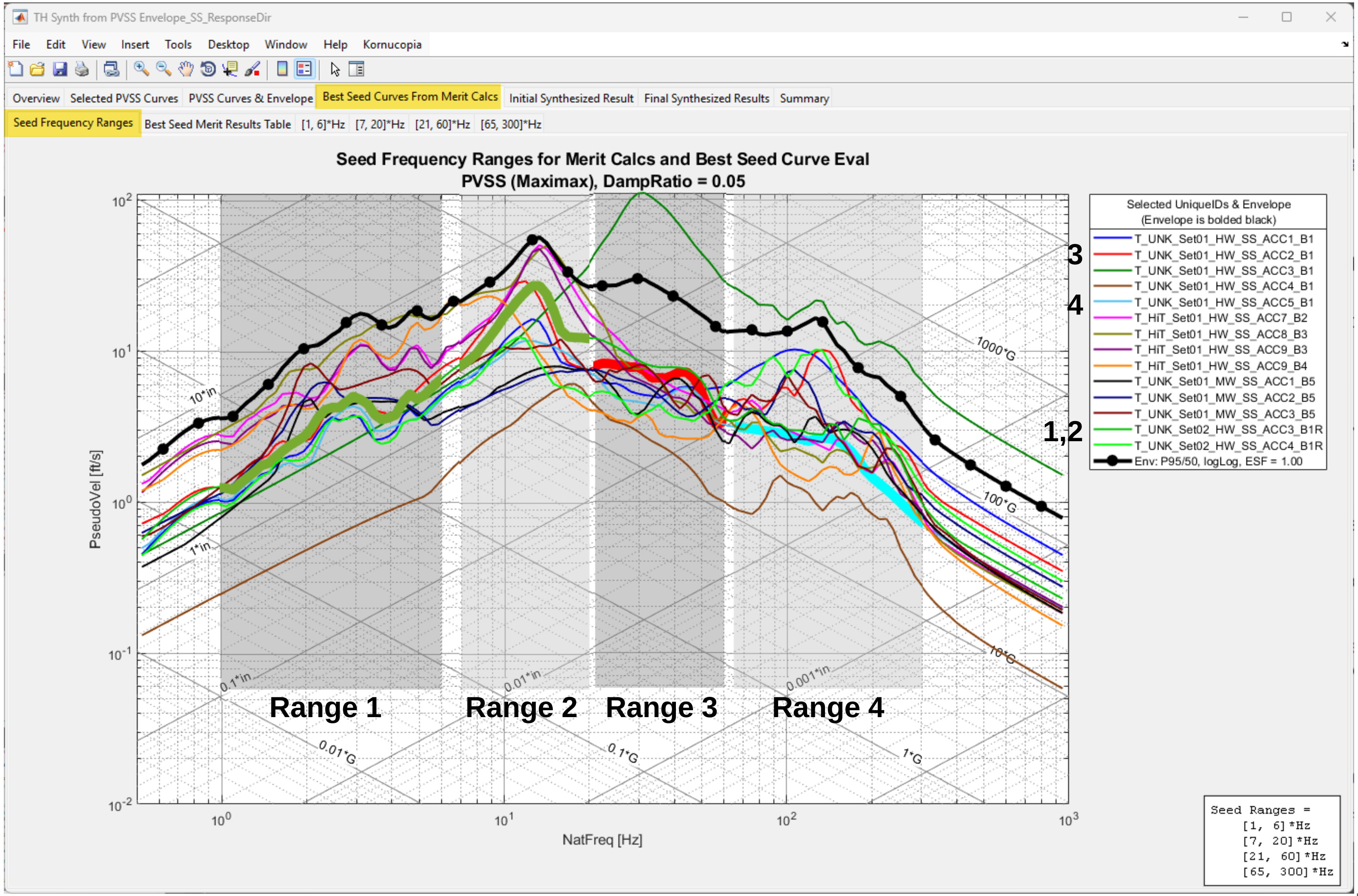
Seed Frequency Ranges | Best Seed Merit Results Table | [1, 6]*Hz | [7, 20]*Hz | [21, 60]*Hz | [65, 300]*Hz

Top 3 Seeds for Each Defined Frequency Range

	RangeNum	Seed_FreqRange	UniqueID	LocalMeritRank	Merit_val	SSF_val
Range 1	1	{'[1, 6]*Hz' }	{'T_UNK_Set02_HW_SS_ACC3_B1R'}	1	0.94817	3.4048
	1	{'[1, 6]*Hz' }	{'T_HiT_Set01_HW_SS_ACC8_B3' }	2	0.9428	1.1866
	1	{'[1, 6]*Hz' }	{'T_HiT_Set01_HW_SS_ACC9_B3' }	3	0.93943	1.8065
Range 2	2	{'[7, 20]*Hz' }	{'T_UNK_Set02_HW_SS_ACC3_B1R'}	1	0.9506	2.3071
	2	{'[7, 20]*Hz' }	{'T_UNK_Set01_HW_SS_ACC5_B1' }	2	0.94977	3.8105
	2	{'[7, 20]*Hz' }	{'T_UNK_Set01_HW_SS_ACC1_B1' }	3	0.9471	3.5299
Range 3	3	{'[21, 60]*Hz' }	{'T_UNK_Set01_HW_SS_ACC2_B1' }	1	0.9462	3.5811
	3	{'[21, 60]*Hz' }	{'T_UNK_Set02_HW_SS_ACC3_B1R'}	2	0.93643	2.975
	3	{'[21, 60]*Hz' }	{'T_UNK_Set01_MW_SS_ACC2_B5' }	3	0.91356	4.499
Range 4	4	{'[65, 300]*Hz'}	{'T_UNK_Set01_HW_SS_ACC5_B1' }	1	0.94877	4.7997
	4	{'[65, 300]*Hz'}	{'T_UNK_Set01_HW_SS_ACC1_B1' }	2	0.94639	1.7099
	4	{'[65, 300]*Hz'}	{'T_UNK_Set01_HW_SS_ACC3_B1' }	3	0.93271	0.64708

Top Ranking Seeds Via Shape-Based Merits

- Results are for **SS** Response Direction.
- Within each range, the bolded PVSS curve is the #1-ranged Shape-based curve for that range.



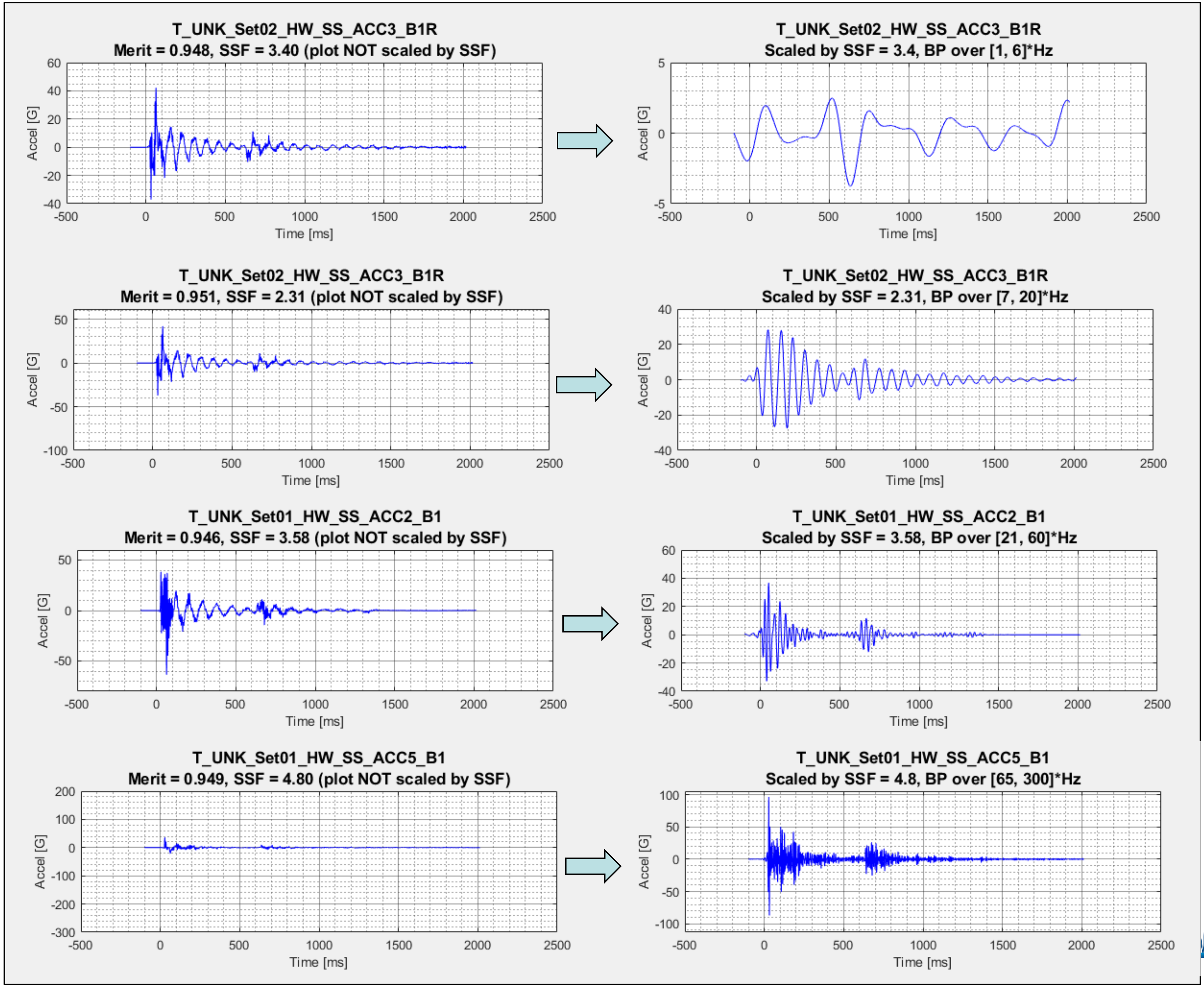
Best Ranked Signals & Their Bandpass Versions (SS Response Dir)

[1, 6]*Hz

[7, 20]*Hz

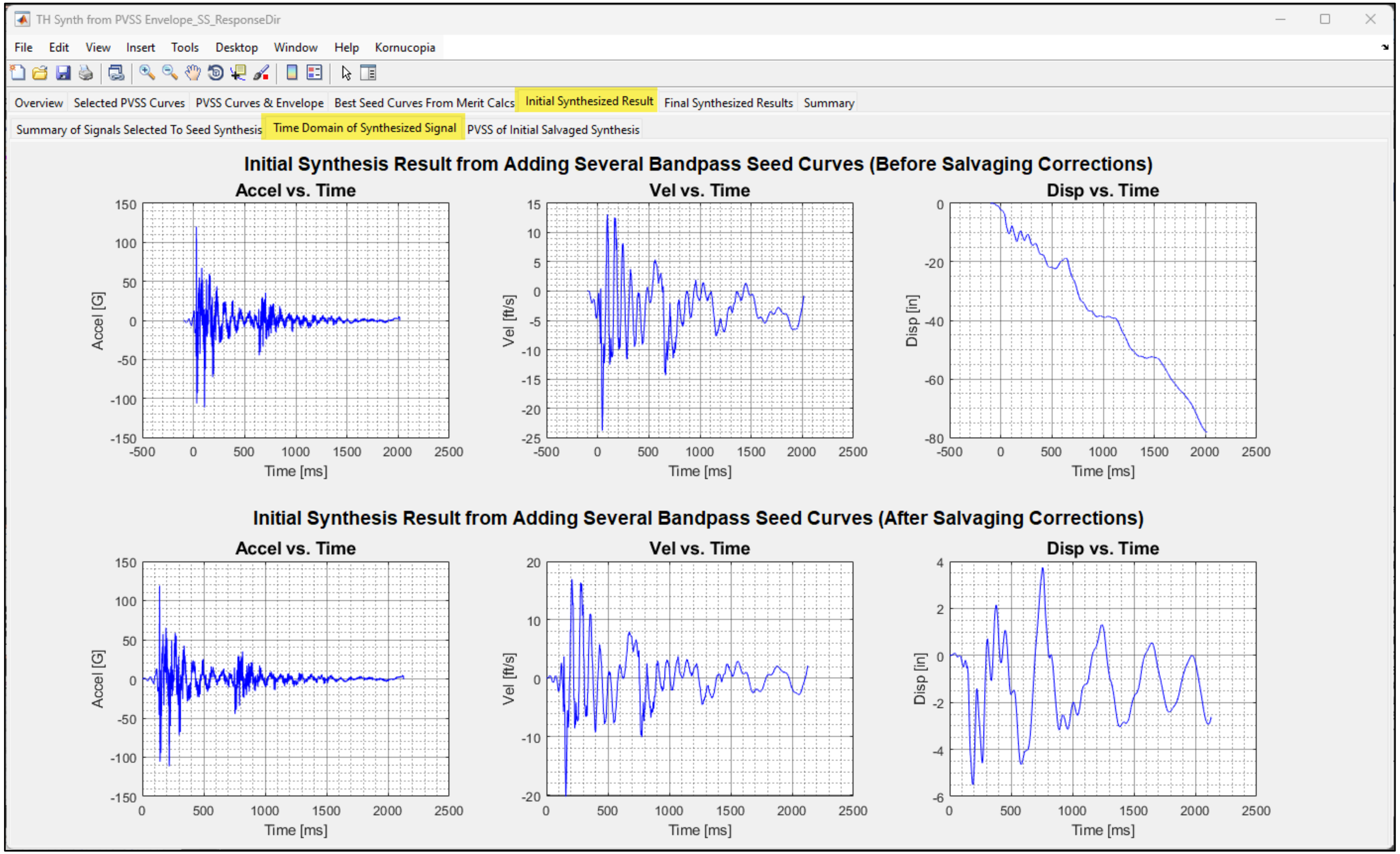
[21, 60]*Hz

[65, 300]*Hz



Adding the BP Filtered Top Seeds for Each of the 4 Ranges (SS Response Dir.)

- For aggregating the selected seeds together into a single synthesized signal, user has option of specifying time delays and additional scaling factors to each seed.
  - This is part of the manual tuning that is sometimes needed.
- The 2nd row of plots is after the synthesized signal is processed by the salvaging algorithm.
- In this example, no time delays are included but additional Amplitude Scaling Factors are applied as shown in the table.

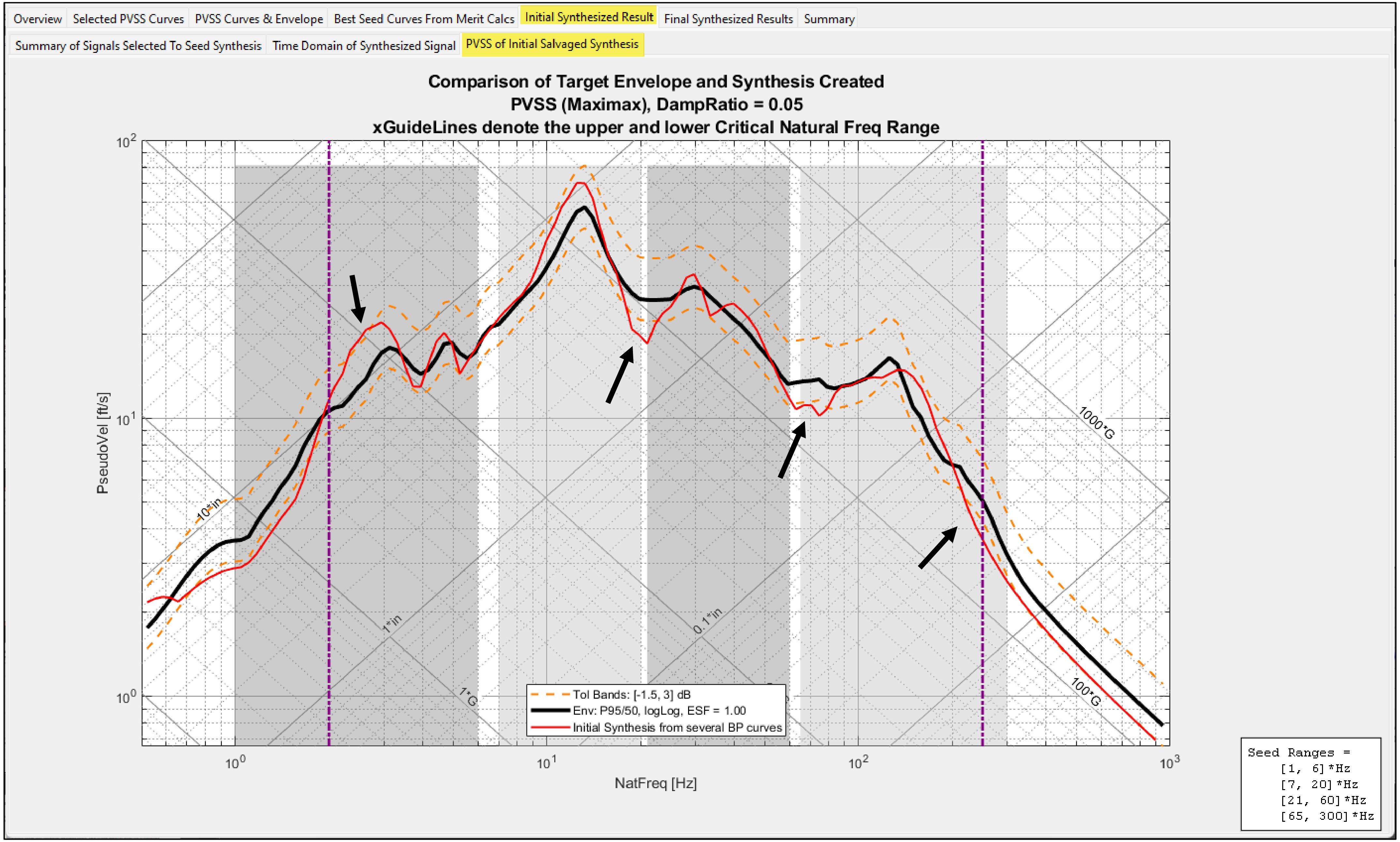


Signals Selected To Seed Synthesis

RangeNum	Seed_FreqRange	UniqueID	TimeDelay	SSF	ESF_Total	SF_Total
1	{'[1, 6]*Hz' }	{'T_UNK_Set02_HW_SS_ACC3_B1R'}	{'0*ms'}	3.4048	1.43	4.8689
2	{'[7, 20]*Hz' }	{'T_UNK_Set02_HW_SS_ACC3_B1R'}	{'0*ms'}	2.3071	1.1	2.5378
3	{'[21, 60]*Hz' }	{'T_UNK_Set01_HW_SS_ACC2_B1' }	{'0*ms'}	3.5811	1.32	4.727
4	{'[65, 300]*Hz'}	{'T_UNK_Set01_HW_SS_ACC5_B1' }	{'0*ms'}	4.7997	1.1	5.2797

Assessment of Synthesized Signal Relative to Target PVSS (SS Response Dir.)

- The initial assessment of the synthesized signal's PVSS relative to the target looks good, but it violates the tolerance bands in a few spots (see arrows).
- We only need to meet the tolerance band within the Critical Zone between the purple guidelines.



Optional Additional Adjustments to Improve Results

- For added flexibility, our algorithm incorporates the option of additional adjustments to the synthesized transient using a combination of the following two approaches. Any number of such adjustments can be specified and are processed sequentially.
- **BP Rescaling**
  - The user specifies one or more frequency ranges and amplitude rescaling factors, plus optional time delay to apply via a bandpass filtering technique to the synthesized signal. Cut it out, rescale, and put it back in.
- **BS & Wavelet**
  - The user specifies a frequency band to attenuate (bandstop) and replace with a Shaker Wavelet.

Inputs defining freq bands, rescaling factors and delays. Last row is an example of *BS & Wavelet* technique. The last 4 entries are wavelet params.

```
IO.settings.FinalResults.Adjustments = {
    '[5, 9]*Hz', '[1.7, 0*ms]'
    '[17, 23]*Hz', '[2.5, 0*ms]'
    '[27, 35]*Hz', '[1.2, 0*ms]'
    '[50, 85]*Hz', '[2.2, 0*ms]'
    '[90, 130]*Hz', '[0.8, 0*ms]'
    '[190, 400]*Hz', '[3.0, 0*ms]'
    '[110, 150]*Hz', '[85*G, 130*Hz, 7, 100*ms]'
    };
```

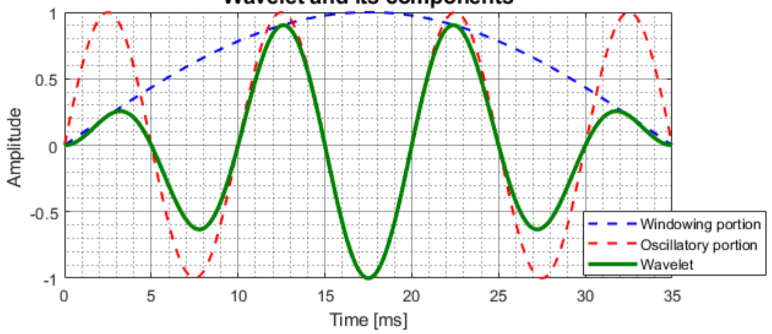
Shaker Wavelet Formulation

$$w(t) = \begin{cases} 0\cdot Amp, & \text{for } t<t_d \text{ or } t>(t_d+NHS/(2\cdot f_o)) \\ Amp\cdot \underbrace{\sin((2\cdot\pi\cdot f_o/NHS)\cdot(t-t_d))}_{\text{Windowing portion}}\cdot\underbrace{\sin((2\cdot\pi\cdot f_o)\cdot(t-t_d))}_{\text{Oscillatory portion}}, & \text{otherwise}\end{cases}$$

$w(t)$ = Wavelet
Amp = Amplitude
f_o = Primary freq.
NHS = # of half sines
t_d = Time delay

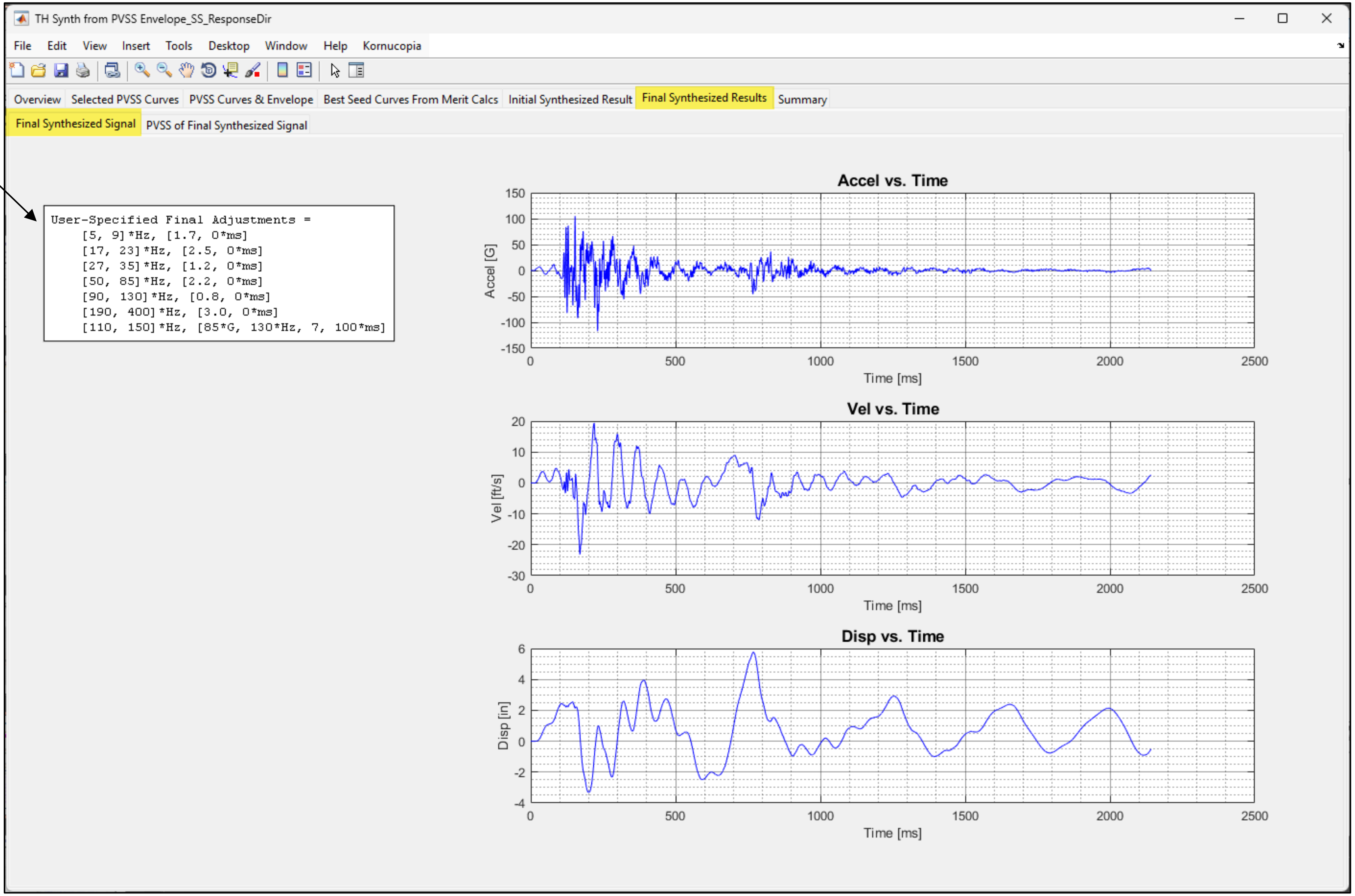
Wavelet Parameters
==================

Amp	fo [Hz]	NHS	Delay [ms]
1.000	100.0	7.000	0.000



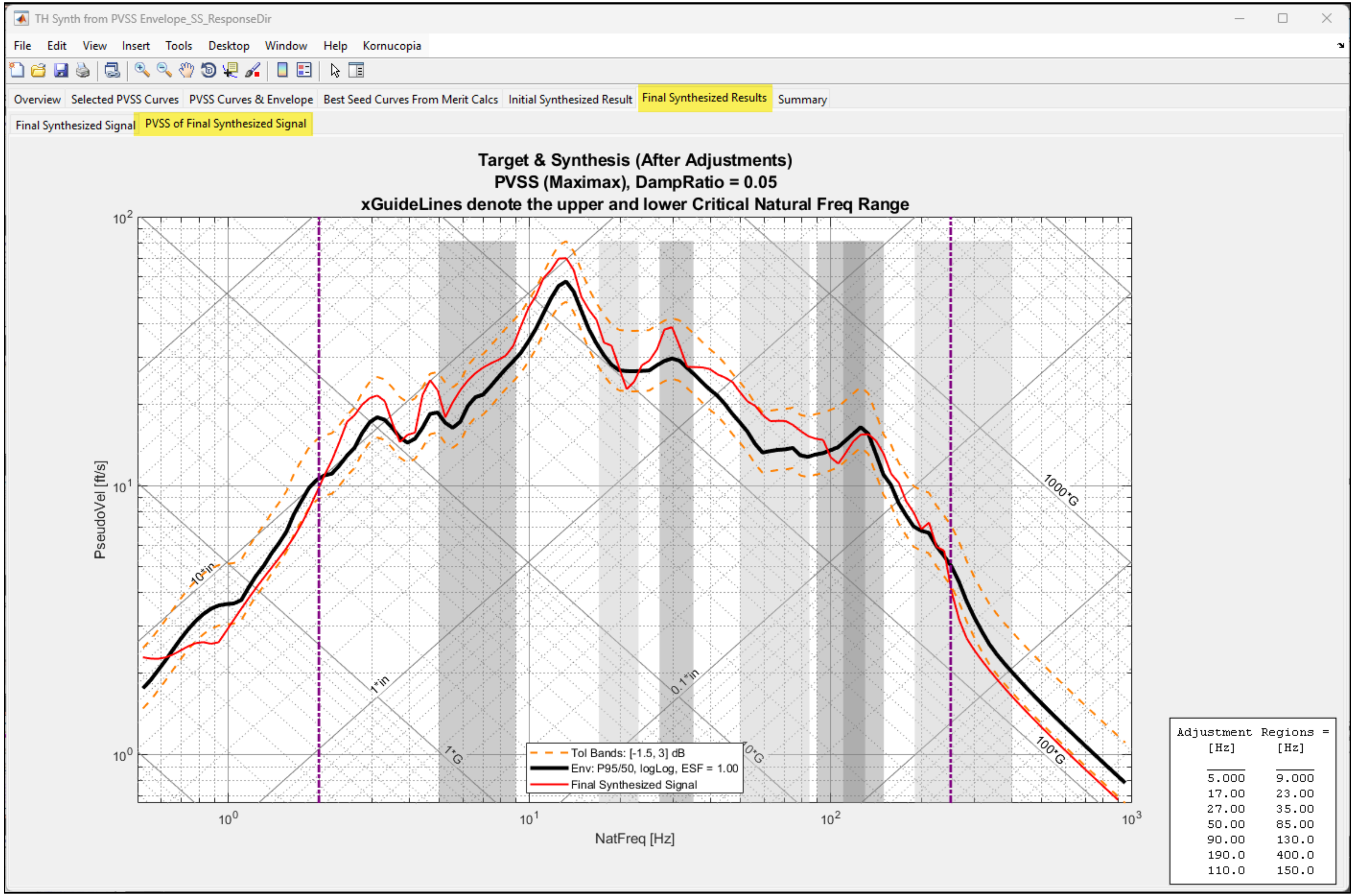
Final Synthesized Signal After a Few User-Specified Adjustments (SS Response Dir.)

- The user-specified adjustments are derived with a few manual iterations.
- The final synthesized signal looks credible in all three kinematic measures.
- The signal also looks realistic and resembles visually the types of signals in the repository.

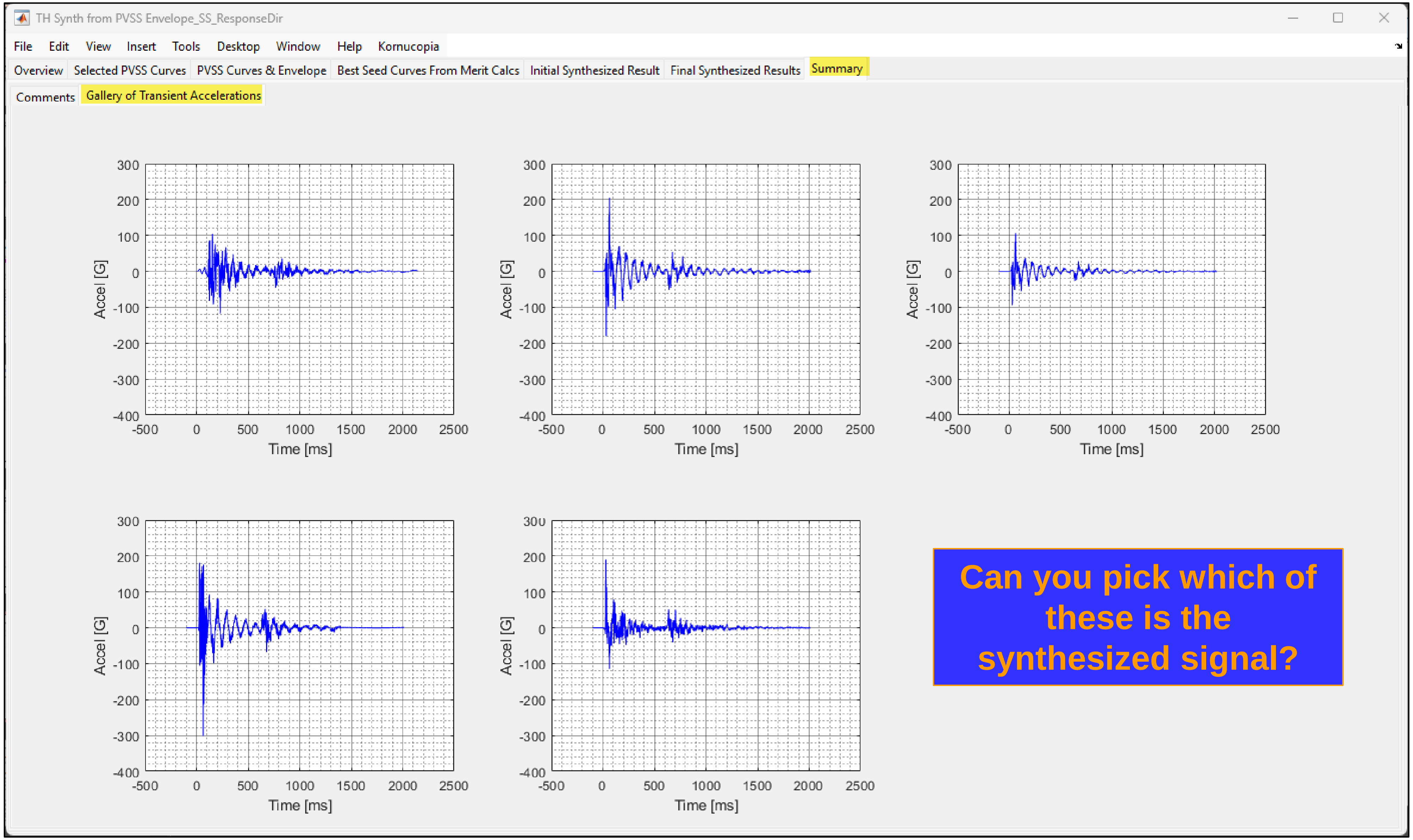


Final Assessment of Synthesized Signal (PVSS of SS Response Dir.)

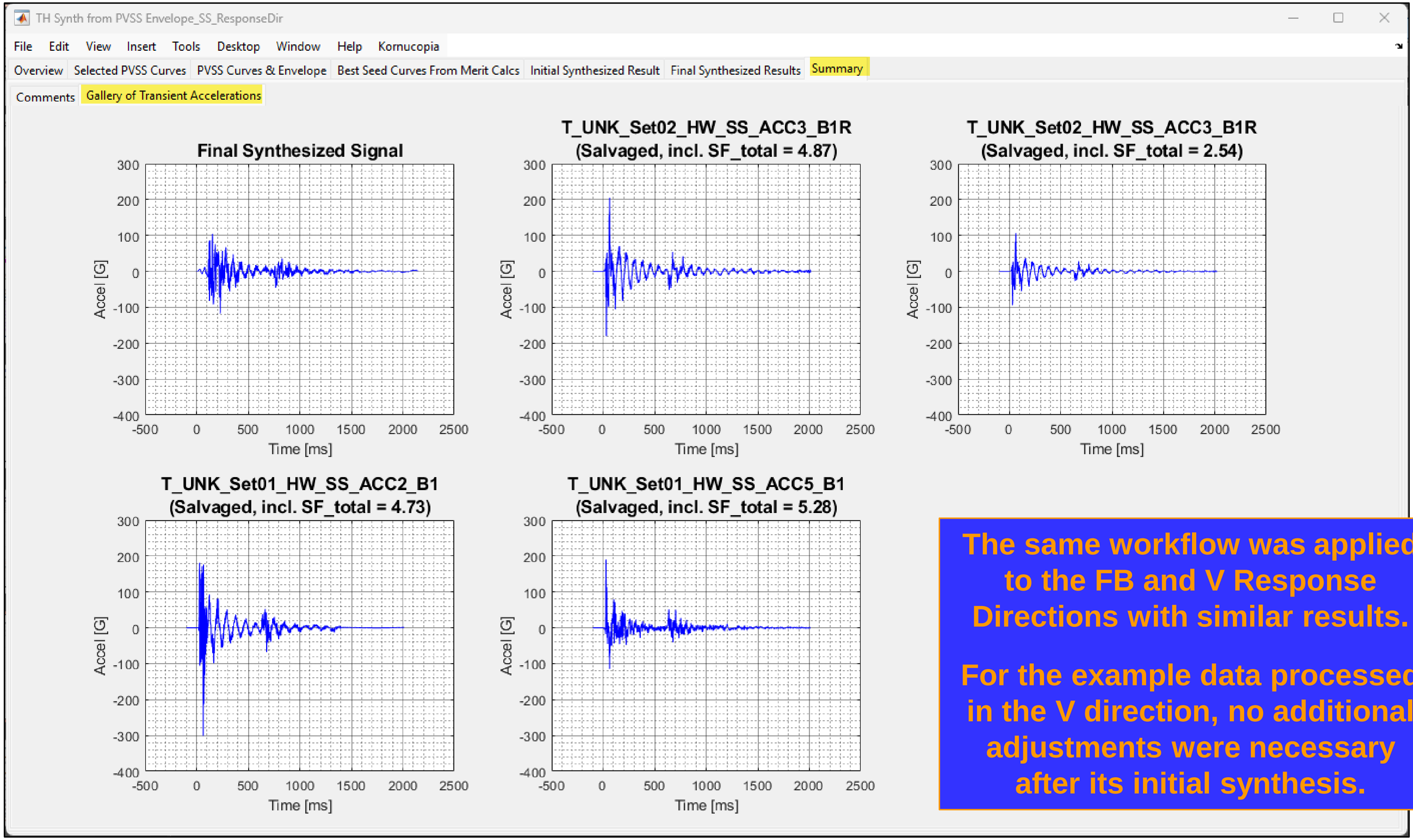
- The final version of the synthesized signal's PVSS now meets the target PVSS within the specified tolerance bands within the Critical Natural Frequency Range.
- Note: The tolerance bands used in the example are [-1.5, 3] dB. These are typical for many shock problems, but different tolerances may be required for specific projects.



Synthesized Signal is Virtually Indistinguishable From Underlying Test Signals



Synthesized Signal is Virtually Indistinguishable From Underlying Test Signals



The same workflow was applied to the FB and V Response Directions with similar results.

For the example data processed in the V direction, no additional adjustments were necessary after its initial synthesis.

Conclusions / Key Achievements

- **Data Organization and Preprocessing/Salvaging**
  - A robust method for organizing and preprocessing/salvaging large repositories of raw transient acceleration data was developed.
- **Characterization and Statistical Bounding**
  - Based on PVSS characterization, a statistically-based enveloping approach is used to create a target PVSS response that represents the entire dataset in the PVSS space. This target is one of the main components to the workflow's synthesis algorithm, ensuring that the synthesized time-history signal is a bounding representation of the underlying repository of acceleration time-histories from a frequency and damage potential perspective.
- **Synthesis of Shock Signals**
  - An enhanced synthesis methodology based on the NSWCDD "Filter+Add" method, incorporating PVSS characterizations, was developed and implemented.
  - The synthesis process uses shape-based merit ranking to select seed signals, applies bandpass filtering and amplitude scaling, and aggregates the filtered seeds to create a synthesized signal. The software offers the user several filter-based signal adjustment options as well as the use of Shaker Wavelets to help ensure the synthesized signal meets the target PVSS within user-definable tolerance bands.
  - Synthesized signals are usually visually indistinguishable from actual measured signals in the repository.
- All calculations presented were computed by ***Kornucopia® ML*** ™, for use with MATLAB®.
  - The workflow and software efficiently completes the whole analysis task, often in less than 15 minutes.