Multichannel Analysis of Surface Waves (MASW) and Downhole Seismic Investigation at Duynefontyn, Western Cape

Open Ground Resources
2 November 2021

Multichannel Analysis of Surface Waves (MASW) and Downhole Seismic Investigation at Duynefontyn, Western Cape

Report 2758/2021

Presented to

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2 November 2021

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It should thus be noted that due to the nature of geophysical investigations and the non-uniqueness of geophysical interpretations, OPEN GROUND RESOURCES cannot be held responsible for any damages that may arise from correct or incorrect interpretation of geophysical results by OPEN GROUND RESOURCES or any other party.

Executive Summary

A total of 61 Multichannel Analysis of Surface Waves (MASW) profiles were conducted at the proposed Duynefontyn nuclear site located north of Koeberg Nuclear Power Station in the Western Cape including a total of 8 downhole seismic measurements to a depth of 80 metres.

The objectives of the seismic investigation were the measurement of shear wave velocities to a depth of 20 metres at the MASW locations and shear and compressional wave velocities to a depth of 80 metres at the downhole seismic locations.

Good data quality was observed for both the MASW and the downhole seismic investigations with prominent surface waves observed for the MASW measurements, and shear and compressional waves were observed to the target depth of 80 metres for the downhole seismic measurements.

Average shear wave velocities between 200 to 800 m/s were observed from surface to an average depth of 30 metres, with values as low as 100 and up to 1,000 m/s observed in specific areas as obtained from the MASW method. These velocities are correlated with sand and weathered rock at typical depths from surface to 30 metres. The downhole seismic results up to 30m depth show good agreement with the MASW results with shear wave velocities ranging from 100 to 1,000 m/s up to a depth of 30 metres.

Bedrock velocities obtained from the downhole seismic results varied between 3,000 and 4,500 m/s for the compressional and between 1,600 and 2,200 m/s for the shear wave velocities.

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Acronyms

OGR	-	Open Ground Resources
RTK	-	Real Time Kinematic
GPS	-	Global Positioning System
MASW	-	Multi-channel Analysis of Surface Waves
KNPS	-	Koeberg Nuclear Power Station
CW	-	Completely weathered
HW	-	Highly weathered
MW	-	Mediumly weathered
UW	-	Unweathered
SR	-	Soft rock
MHR	-	Medium hard rock
HR	-	Hard rock
VHR	-	Very hard rock

1. Introduction

Open Ground Resources was appointed by SRK Consulting (South Africa) (Pty) Ltd to conduct a geophysical investigation at the proposed Duynefontyn nuclear site located north of Koeberg Nuclear Power Station (KNPS) in the Western Cape.

The site is shown in **Figure 1** which is located mostly north of the existing power station although some measurements were also conducted south and east of KNPS.

The geophysical investigation comprised the Multichannel Analysis of Surface Waves (MASW) method at 57 locations and the downhole seismic method at 8 borehole locations.

The geophysical investigation was conducted from 12 to 28 August 2021.

2. Survey Objectives

The survey objectives for the MASW measurements were to measure shear wave velocities up to minimum depth of 20 metres at the locations measured. The objective of the downhole seismic investigation was to map both compressional (p-wave) and shear (s-wave) velocities to a depth of 80 metres.

3. Geology and Existing Information

The Malmesbury Group with thick sands overlying sandstone, shale, siltstone and greywacke characterize the site geology.

Not to Scale

Figure 1. Site Location	Eskom Duynefontyn Site MASW and Downhole Seismic Geophysical Investigation	Project 2758/2021 October 2021	OPEN GROUND RESOURCES

4. Geophysical Techniques

4.1 MASW

Multichannel Analysis of Surface Waves (or MASW) utilizes dispersion of surface waves to produce a surface wave velocity cross-section of the subsurface. Longer wavelengths travel deeper into the subsurface than shorter wavelengths and therefore travel at different velocities depending on the subsurface velocity.

By generating a range of short and longer wavelengths, one can thus sample the subsurface to different depths. The velocities of different wavelengths can be determined by calculating the phase difference between two receivers for each wavelength generated. Using a multi-channel system with 24 or more receivers a section of surface wave phase velocities as a function of depth and chainage can be produced.

Surface wave velocities are close related to shear wave velocities by Poisson's ratio (are slightly less than shear wave velocities). Using inversion methods, the surface wave phase velocities can be inverted to shear wave velocities. MASW can thus be used to map shear wave velocities as a function of depth and chainage, allowing for the calculation of the stiffness (maximum shear modulus G_{max}) of a site.

A multi-channel seismograph with an impact source like a sledgehammer is used. Shots are generated with a fairly tight spacing between shots (typically 1 to 5 times the geophone separation) to allow for essential coverage of all the depths of interest. For deeper penetration (for which low frequencies are needed) a source like a weight drop can be used. Data is acquired in a profile mode (similar to seismic reflection) and shear wave velocity cross-sections are produced as a final product.

MASW is an extremely attractive method as surface waves are easy to generate. It is therefore suitable in areas of high seismic background noise (such as industrial and built-up areas), which a technique like seismic refraction cannot be used.

MASW can be used in active and passive modes determined by the field setup and the source characteristics. An artificial source is used for the active method, such as a sledgehammer or weight drop, and the source is positioned at a certain offset distance from a linear array of receivers. Background noise, which may be man-made or natural events such as noise from waves or even earthquakes can be utilized as a source for the passive method, and the array be may a linear, cross, circular, etc.

The advantage of the passive array is the potential to increase penetration as background sources typically have lower frequency surface waves than what can be induced using a man-made source. The active method offers the ability to measure a continuous shear wave velocity section by moving (rolling) of the linear array and the source, allowing the measurement of lateral velocity changes. A combination of the passive and active methods may thus be used for site investigation depending on the objectives of the investigation, and the site conditions.

4.2 Downhole Seismic

The down-hole seismic technique is used to map p and s-wave velocities along the depth of a borehole using a source on surface. A 3-component geophone is typically used in the borehole which may be clamped mechanically or by using an inflatable bladder to the side of the borehole. Vertical impact shots are recorded by the vertical geophone to measure the p-wave velocities and horizontal geophones record horizontally polarized shear waves which are generated by striking the ground surface horizontally. A heavy plank coupled to the ground by a vehicle is typically used as a shear wave source although mechanical wedges or semi-vertically strike plates can also be used.

Horizontally polarized shear waves are usually acquired in two directions perpendicular to the borehole and the results are imposed on one another as the shear waves would typically show signal polarity reversal and can therefore be more accurately identified compared to a single direction horizontal shear wave record.

The interpretation method depends on the quality of the data observed. The average velocity method is most commonly used by which average velocities are determined for linear sections on the time-depth curve. The interval method can be used when with good data quality to determine discreet velocities for each depth interval.

Depth intervals used typically depends on the resolution requited and the thickness of layers to be resolved. Generally, intervals of 0.5 to 1.0 metres are used for depths up to 30 metres, with larger increments used with increase in depth.

The application of the technique is described in the ASTM standard D7400.

4.3 Seismic Velocities

Typical seismic velocities for common lithologies are shown in **Figure 2**.

Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm³)
Scree, vegetal soil	300-700	100-300	1.7-2.4
Dry sands	400-1200	100-500	1.5-1.7
Wet sands	1500-2000	400-600	1.9-2.1
Saturated shales and clays	1100-2500	200-800	2.0-2.4
Marls	2000-3000	750-1500	2.1-2.6
Saturated shale and sand sections	1500-2200	500-750	2.1-2.4
Porous and saturated sandstones	2000-3500	800-1800	2.1-2.4
Limestones	3500-6000	2000-3300	2.4-2.7
Chalk	2300-2600	1100-1300	1.8-3.1
Salt	4500-5500	2500-3100	2.1-2.3
Anhydrite	4000-5500	2200-3100	2.9-3.0
Dolomite	3500-6500	1900-3600	2.5-2.9
Granite	4500-6000	2500-3300	2.5-2.7
Basalt	5000-6000	2800-3400	2.7-3.1
Gneiss	4400-5200	2700-3200	2.5-2.7
Coal	2200-2700	1000-1400	1.3-1.8
Water	1450-1500	-	1.0
Ice	3400-3800	1700-1900	0.9
Oil	1200-1250	-	0.6-0.9

Figure 2. Typical Seismic Velocities

5. Data Acquisition & Survey Methodology

5.1 Survey Methodology

Multisource (MM) MASW surveys were conducted on 6 positions to allow for statistical analysis of shear wave velocity measurements which did not form part of the objective of this investigation. A total of 8 source locations were conducted at each of these survey locations, including two end-shot locations which can be used to obtain an indication of compressional p-wave velocity using the Seismic Refraction method.

A total of 55 Single Source MASW surveys was conducted which consisted of a single shot location for at each traverse location.

Table 1 summarizes the equipment and survey settings utilized for the respective techniques.

Table 1. Summary of Geophysical Techniques

Technique	Traverse Length (m)	Comments
MASW Single Source Soundings	46	Equipment: Geode 24-channel seismograph Source: ESS-100 accelerated weight drop Geophones: 4.5Hz vertical Deployment type: Landstreamer Geophone separation: 2 metres Number of channels: 24 Source offset shot distance: 6 metres Number of shots: 5 individual records per shot location Record length: 2 seconds Sample interval: 0.125ms Delay: 0.5 seconds
MASW Multi Source Soundings	46	Equipment: Geode 24-channel seismograph Source: ESS-100 accelerated weight drop Geophones: 4.5Hz vertical Deployment type: Landstreamer Geophone separation: 2 metres Number of channels: 24 Source offset shot distance: 5, 10 and 20 metres on both sides of the spread, thus six shot locations per spread position Seismic refraction shot locations at 1m from both sides of the spread with 0.5 seconds record length and 0.0315 ms sample interval. Number of shots: 5 individual records per shot location MASW Record length: 2 seconds MASW Sample interval: 0.125ms MASW Delay: 0.5 seconds

Downhole Seismic	Borehole depth = 80 metres	Equipment: Geode 24-channel seismograph Source: ESS-100 Accelerated Weight Drop (AWD) and 6.2 kg sledge hammer Shots: Vertical + Two opposite horizontal Borehole geophone: Geostuff BKG5, 3 component geophone Shot offset distance from borehole: 2 metres Number of channels: 3 0 – 5m: depth intervals of 0.5 metres 5 – 24m: depth intervals of 1 metres 24 – 50m: depth intervals of 2 metres 50 – 80m: depth intervals of 3 metres Stacking: 3 – 10 Record length: 0.5 seconds Sample interval: 0.0315 ms Delay: 0.01 seconds

The vehicle mounted ESS-100 weight drop source is shown in **Figure 3.** The landstreamer at 2m geophone separation is shown in **Figure 4.** The downhole survey in operation at borehole BH47 is shown in **Figure 5**.

Figure 3. ESS-100 AWD Source

Figure 4. MASW Landstreamer

Figure 5. Downhole Seismic Survey at BH47

5.2 Surveying and Referencing

Surveying of geophysical locations was done using a Trimble R8 GPS in VRS mode in the LO-19 projection and WGS-84 datum. Both the beginning and end of each MASW spread were surveyed as well as the shot locations.

5.3 Survey Positions

The positions of the MM traverses are presented in **Figure 6** with all the MASW locations presented in **Figure 7**.

The downhole seismic borehole positions are shown in **Figure 8**.

Not to Scale

Figure 6. Location of Multi Source MASW Traverses	Eskom Duynefontyn Site MASW and Downhole Seismic Geophysical Investigation	Project 2758/2021 October 2021	OPEN GROUND RESOURCES

Figure 7. All MASW Locations

Eskom Duynefontyn Site
MASW and Downhole Seismic
Geophysical Investigation

Project 2758/2021

October 2021

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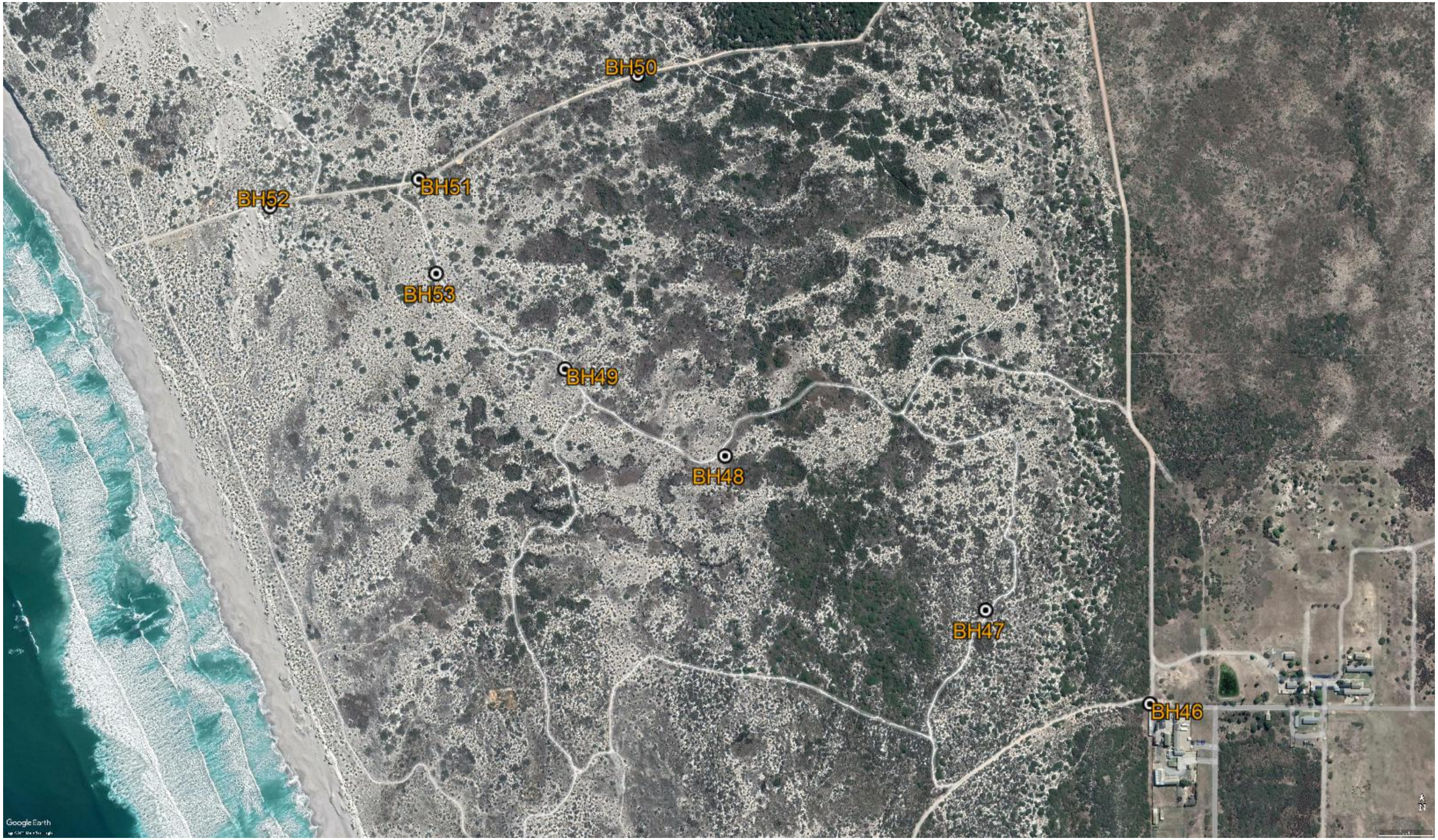


Not to Scale

Figure 8. Location of Downhole Seismic Surveys	Eskom Duynefontyn Site MASW and Downhole Seismic Geophysical Investigation	Project 2758/2021 October 2021	OPEN GROUND RESOURCES

6. Geophysical Data Processing

6.1 MASW

The MASW data was processed using SurfSeis 6 software to produce shear wave velocity models. Very good data quality was generally observed with the overtone image and inverted shear wave velocity models presented in **Appendix 1**.

6.2 Downhole Seismic

Downhole seismic data was processed using Geometrics PSLog software.

7. MASW Results

The MASW results for all the Multisource MASW results (MM1 to MM6) and the Single Source (MI1 to MI55) are presented in **Appendix 1**. The phase velocity image with picked dispersion curve (Overtone Image) well as the velocity model for each corresponding dispersion curve are presented.

Good quality dispersion curves were observed with depth penetration varying between 17.5 and 30 metres. Higher confidence is generally attributed to depths to 20 metres with less confidence to 30 metres due to the decrease in confidence in the identification and accuracy of the surface wave mode in the lower frequency (deeper penetration) region.

Shear wave velocities ranging from 100 to 1,000 m/s were observed with all the combined inverted shear wave velocities plotted in **Figure 9**. A simple exponential trendline was plotted to provide an indication of the average shear wave velocity trend with depth.

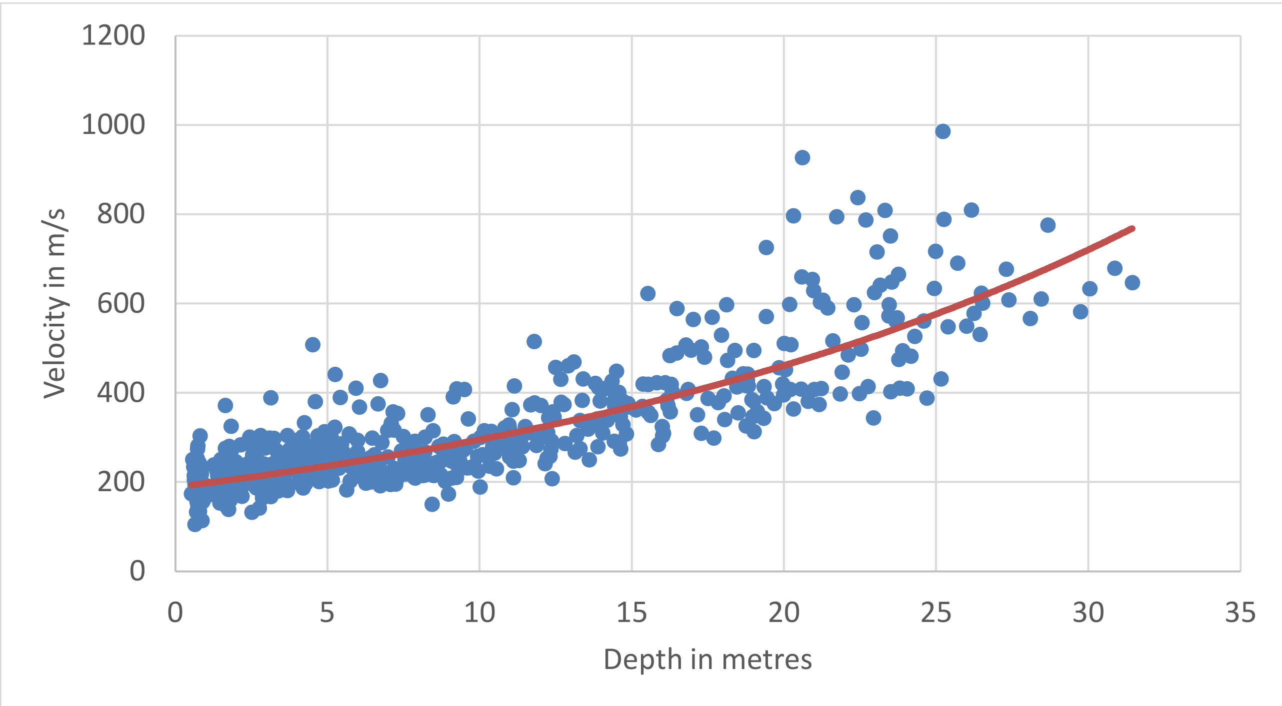


Figure 9. MASW Shear Wave Velocities

8. Downhole Seismic Results

A total of eight (8) downhole measurements were performed at boreholes BH46 to BH53 to a depth of approximately 80 metres.

The data quality varied on site with excessive 'ringing' of the seismic signal observed at some depth locations, possibly suggesting poor grouting at these depths. Ingress of water into the boreholes has also been observed on site with boreholes filling up with water overnight over depths of tens of metres, which can also be attributed to lack of grout at certain depths. However, it was possible to remove some of the unwanted signal ringing by filtering of the data to improve the quality of the data, especially for picking of the shear wave energy.

The downhole results are presented using both a layered model and an interval velocity model as indicated in **Figure 10** for borehole BH46. The layer model is generated by considering changes in the velocity gradient with depth and then assigning a depth and velocity to this layer. The interval velocities are automatically calculated by plotting the differences between the arrival times for each depth to calculate the velocity change between two depths. The interval velocities may thus show more subtle changes in velocities and may resolve thinner layers but are noisier due to the presence of errors in accurate picking of arrival times as well as other factors which influence the accuracy of the method. The interval velocities have been smoothed but do contain spikes in velocity which should be ignored for interpretation purposes.

<u>BH46:</u>

The downhole velocity model for BH46 shows a shallow high velocity p-wave layer at 3.3m depth (1,459 m/s) and another velocity increase at 12.2m depth for both p and s-wave velocities. The interface at 38m depth show a significant increase in both p and s-wave velocities and is interpreted as the depth at which the shale is possibly less weathered and fractured as the shear velocity of 1,191 m/s is suggesting relatively competent rock. The increase at 65.3m is interpreted as the shale/sandstone interface with velocities of 1,768 and 4,254 m/s observed for the s and p-waves respectively.

<u>BH47:</u>

A p-wave velocity increase at 4.1m depth is observed which is interpreted as the shallow water table. A minor increase in velocities is observed at 18.8m depth with a more significant velocity increase at 34.6m depth which is interpreted as the siltstone / sandstone interface. Velocities of 2,168 and 3,973 m/s are observed for the s and p-waves respectively for the sandstone layer. The interval velocities show a increase at 40m depth, with better correlation with the borehole results which indicate the siltstone / sandstone interface at 38.5m depth.

BH48:

The layered model shows a velocity boundary at 25.4m with the interval velocities increasing sharply at a depth of 30 metres, most likely correlating with SW to MW, SR to VSR shale/sandstone. A sharp increase in both interval velocities at 35m depth, especially with shear wave velocity increasing to more than 1,000 m/s is correlated with UW, MHR to HR shale. Further increase in velocities at 42m depth can be correlated with UW, HR to VHR sandstone with layered velocities 4,453 and 1,882 m/s for p- and s wave velocities respectively.

BH49:

The velocity gradient at 27.9m depth can be correlated with the interface between sand and soft rock sandstone. The layered velocity interface at 41.4m depth is interrupted as the transition from MW to SW sandstone / shale with the interval velocities increasing at a depth of 50 metres which is interpreted as MW to SW, SR to HR sandstone. Layered velocities of 1,864 and 3,643 m/s are observed for the s and p-waves respectively for the sandstone layer from 41.4 to 80m depth.

BH50:

The sand / HW siltstone at 31.5m depth is observed as a layered interface at 34.0m depth. From 34 to 80m depth the layered model shows s and p-wave velocities of 1,653 and 2,951 m/s for the sandstone / shale layers.

BH51:

The layered velocity model shows an increase in velocity at a depth of approximately 24 metres with the interval velocities increasing at a depth of 30 metres for the shear wave velocities. Layered velocities of 1,866 and 3,440 m/s are observed for the s and p-waves respectively for the sandstone/shale layer from 23.8 to 80m depth.

BH52:

The drilling results for BH52 indicate sand to 22.5m depth, then UW, HR Sandstone up to 72.5m depth. The downhole seismic results are characterized by a simple 2-layer model with a significant increase in both p and s-wave velocity at a depth of 21.8m depth. The shallow high p-wave velocity layer at 2.1m suggest a shallow water table, with a resulting sharp increase in p-wave velocity but not in s-wave velocity. Sandstone p-wave velocities of 4,321 and shear wave velocities of 2,133 m/s were calculated respectively.

BH53:

No apparent velocity interface between the sand and the siltstone at 34.5m depth is observed. An increase in layered velocity at 46m depth, and interval velocity at 50m depth are interpreted as SW to UW siltstone / shale. Sandstone p-wave velocity of 3,387 and shear wave velocities of 1,584 m/s were respectively calculated from 46 to 80m depth, interpreted as a combination of siltstone, shale, and sandstone layers.

Summary:

The combined layered velocity models for all eight boreholes are presented in **Figure 18.** The p-wave velocity layers are presented in red and the s-wave velocity layers in blue. The following can be summarized from the results:

1. The sharp increase in p-wave model velocities at shallow depth of less than 5 metres are attributed to the shallow water table.
2. P-wave velocities of bedrock varies between 3,000 and 4,500 m/s.
3. S-wave velocities of bedrock varies between 1,600 and 2,200 m/s.
4. Anomalous shallow high velocities observed at BH52 correlate well with competent sandstone bedrock at a depth of 22 metres.
5. A transition zone between 25 to 45 m depth is observed where there is a general increase in both s and p-wave velocities where the lithology change from sand to weathered, jointed and soft rock.

Figure 10. BH46 Velocity Models

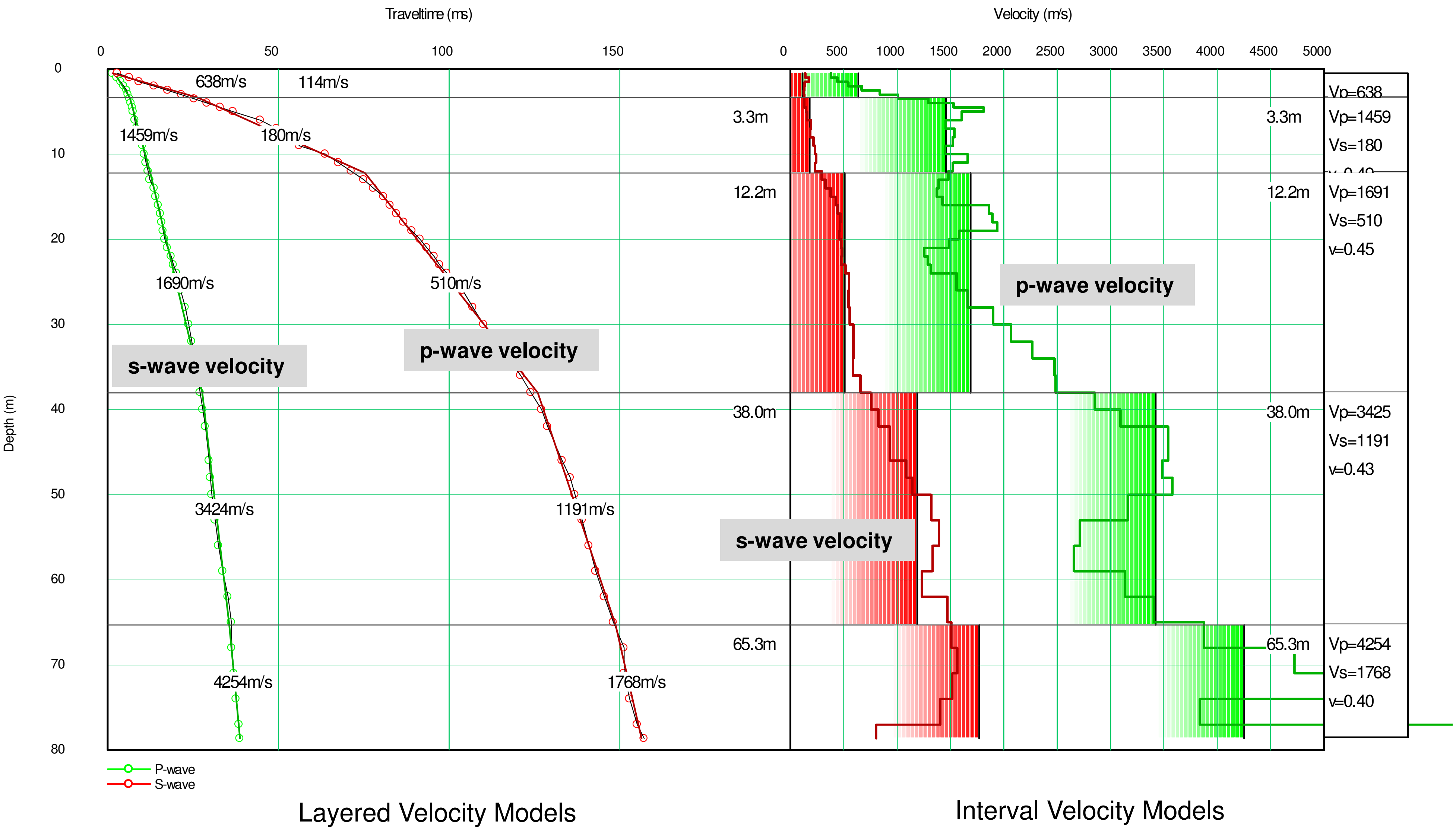


Figure 11. BH47 Velocity Models

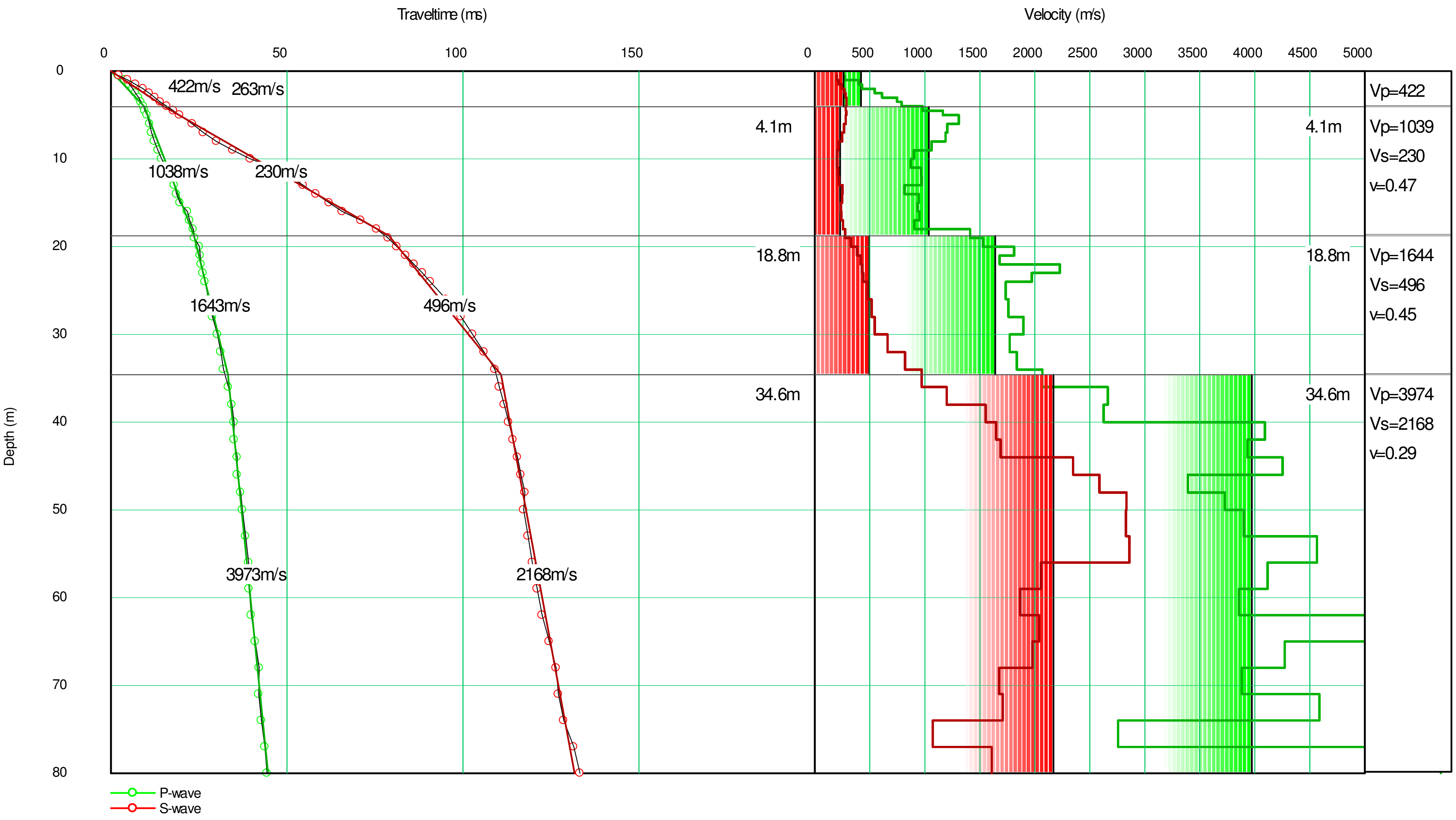


Figure 12. BH48 Velocity Models

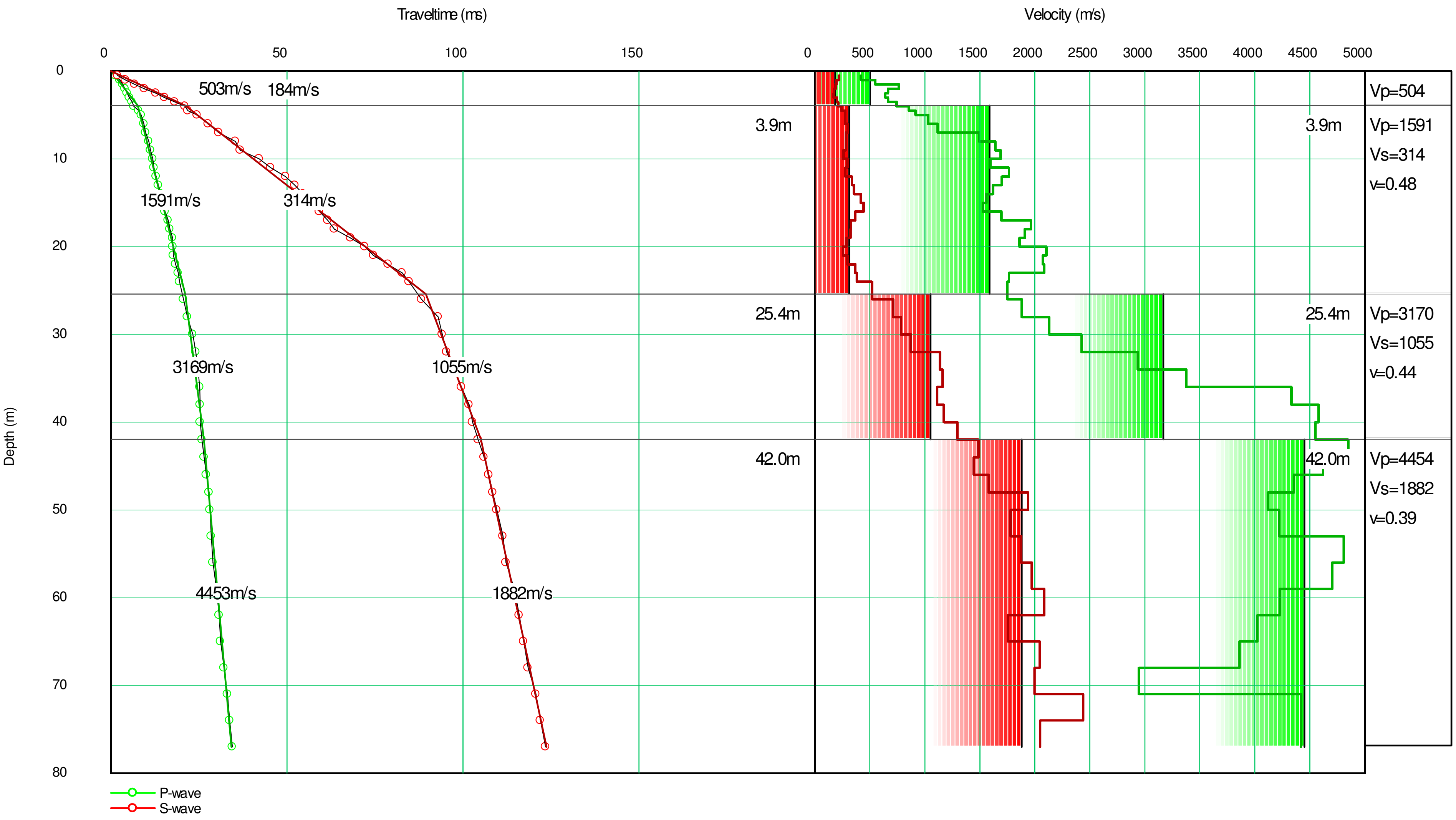


Figure 13. BH49 Velocity Models

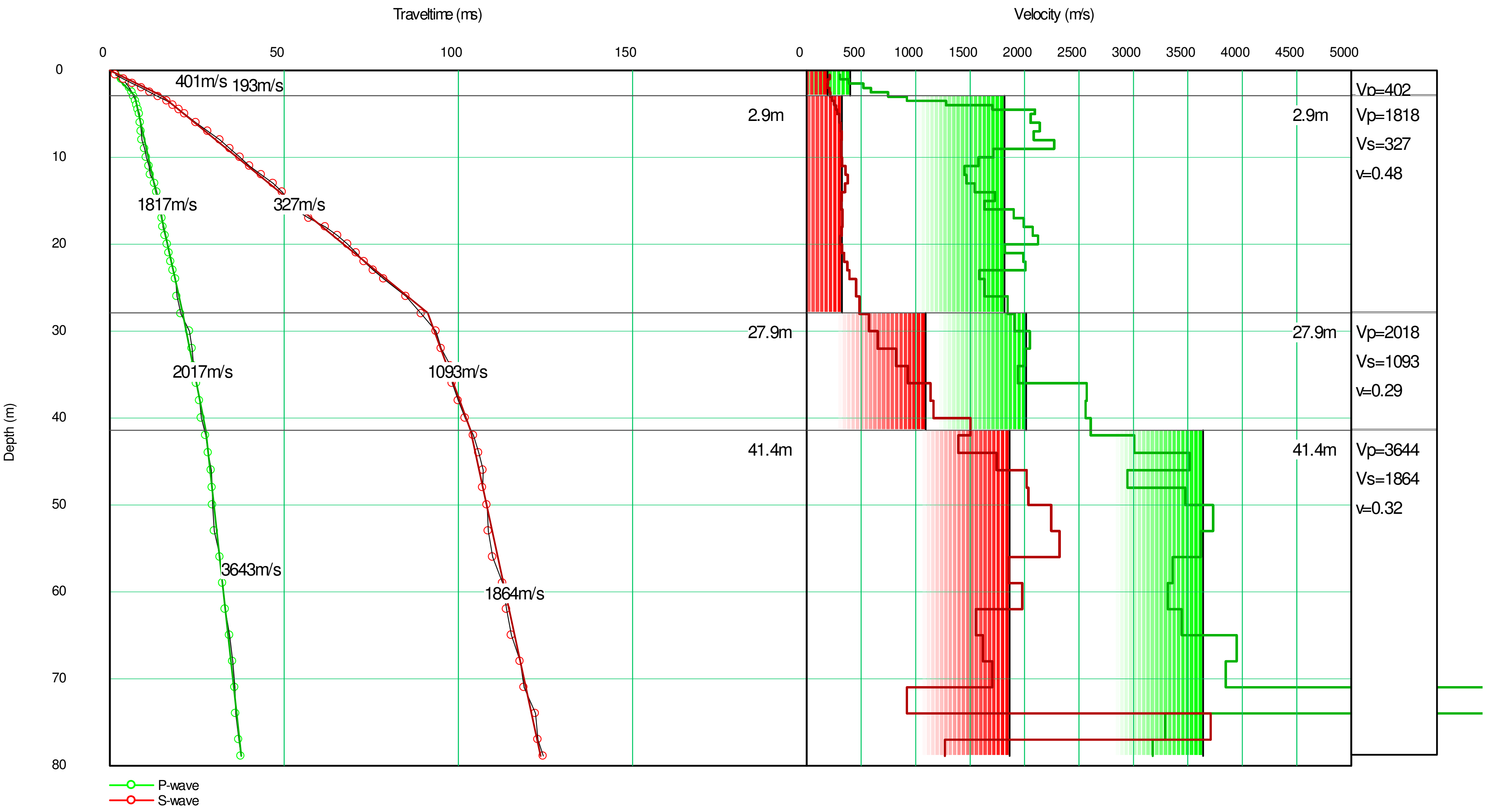


Figure 14. BH50 Velocity Models

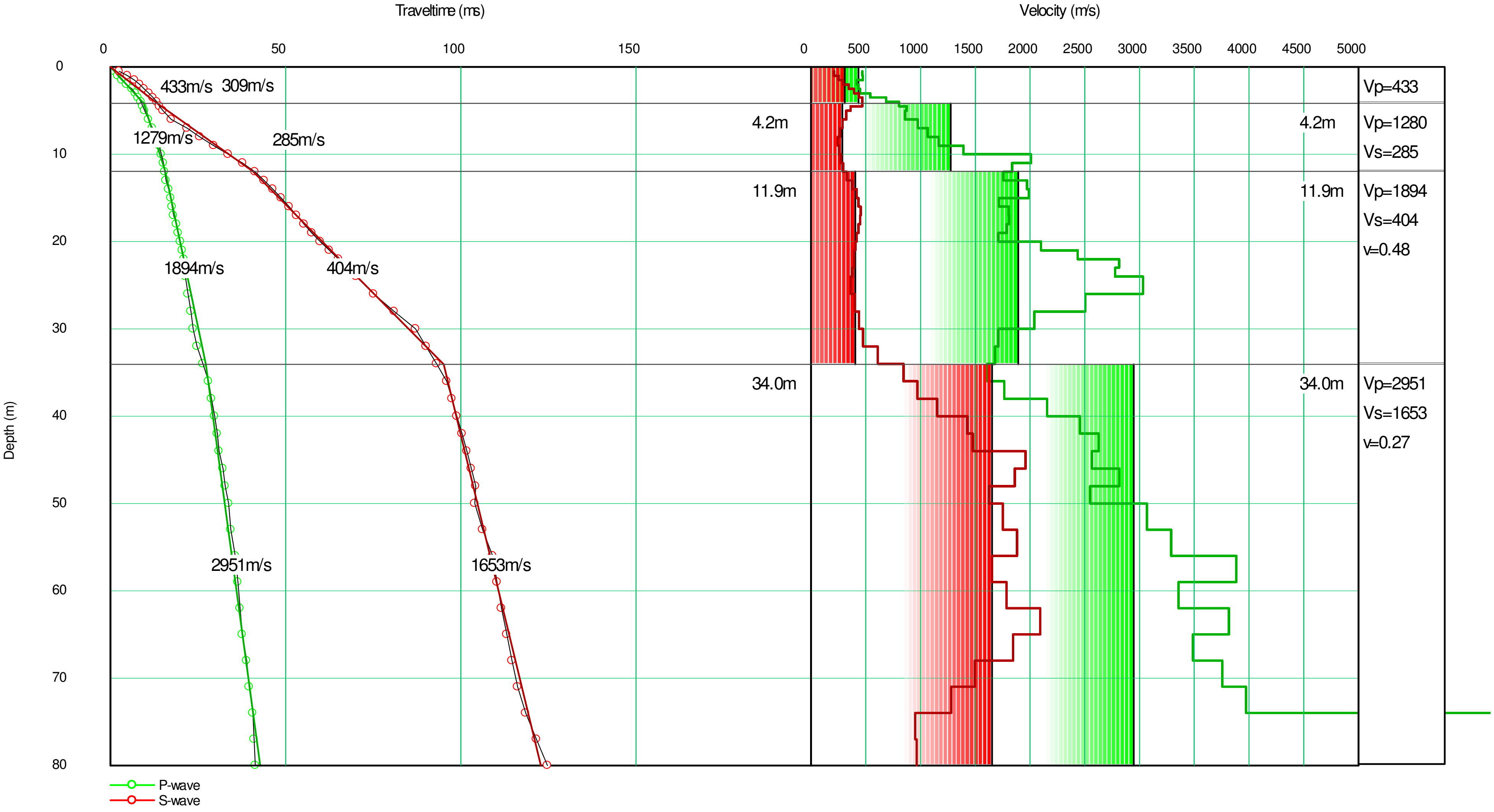


Figure 15. BH51 Velocity Models

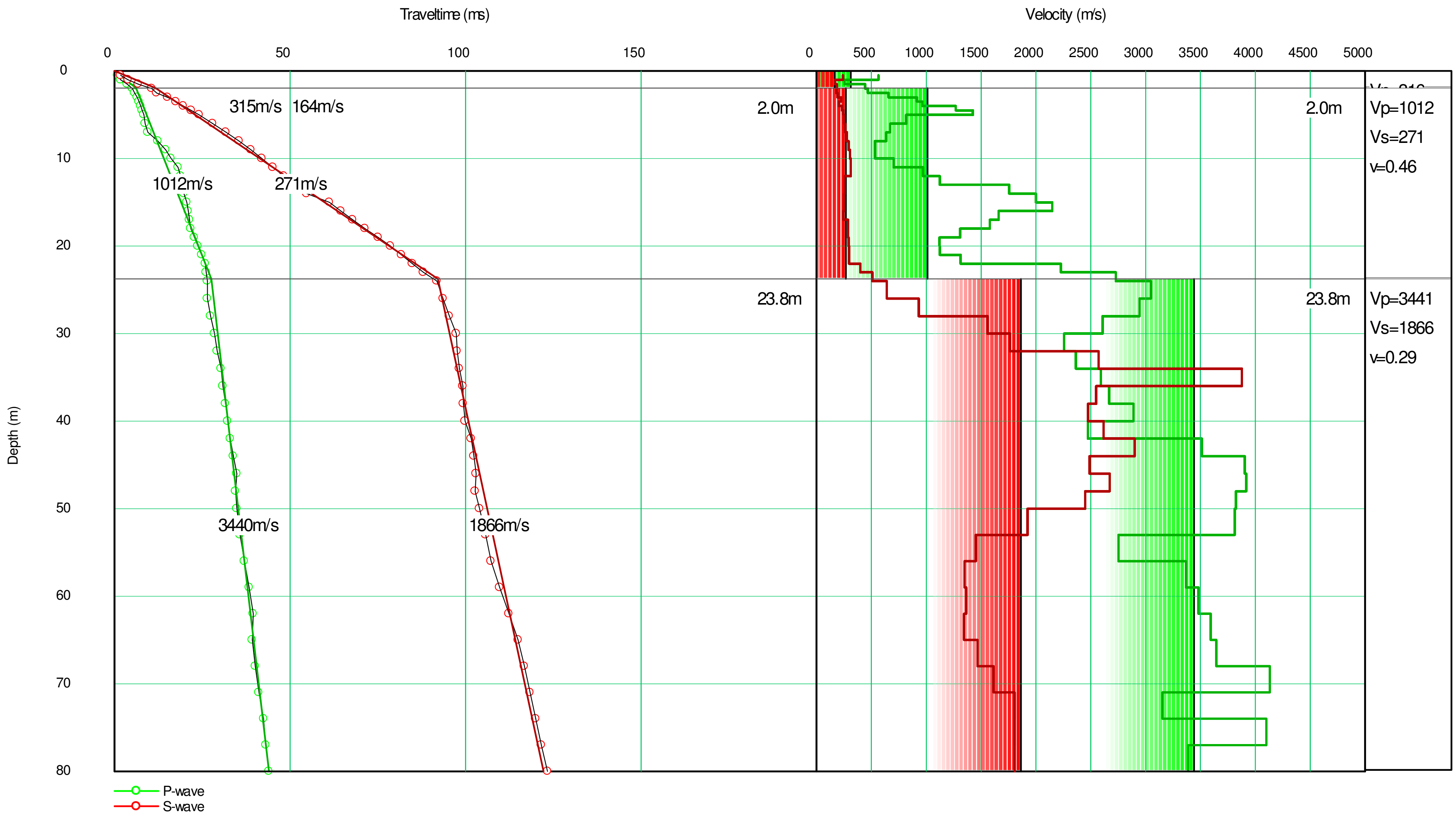


Figure 16. BH52 Velocity Models

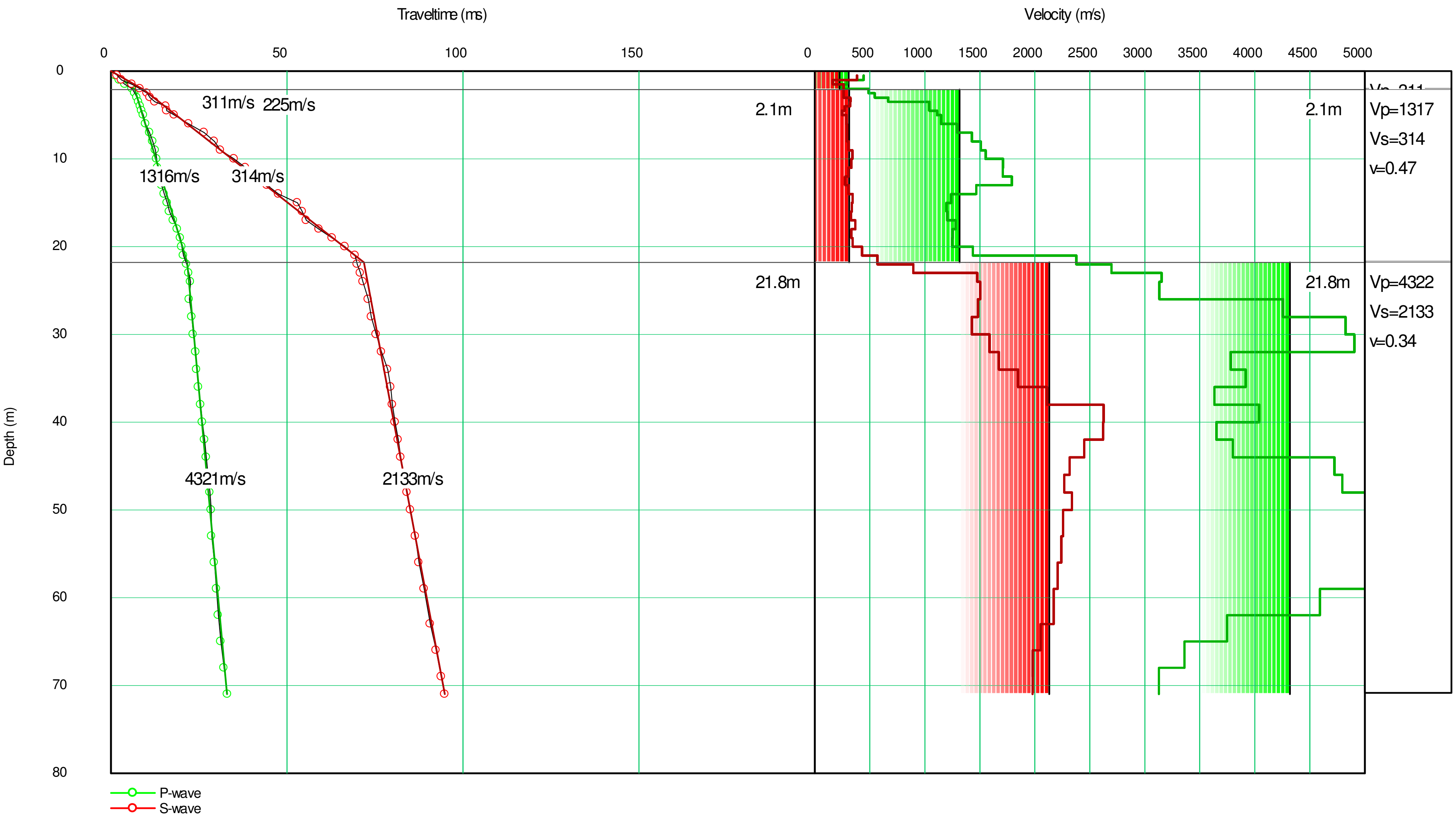


Figure 17. BH53 Velocity Models

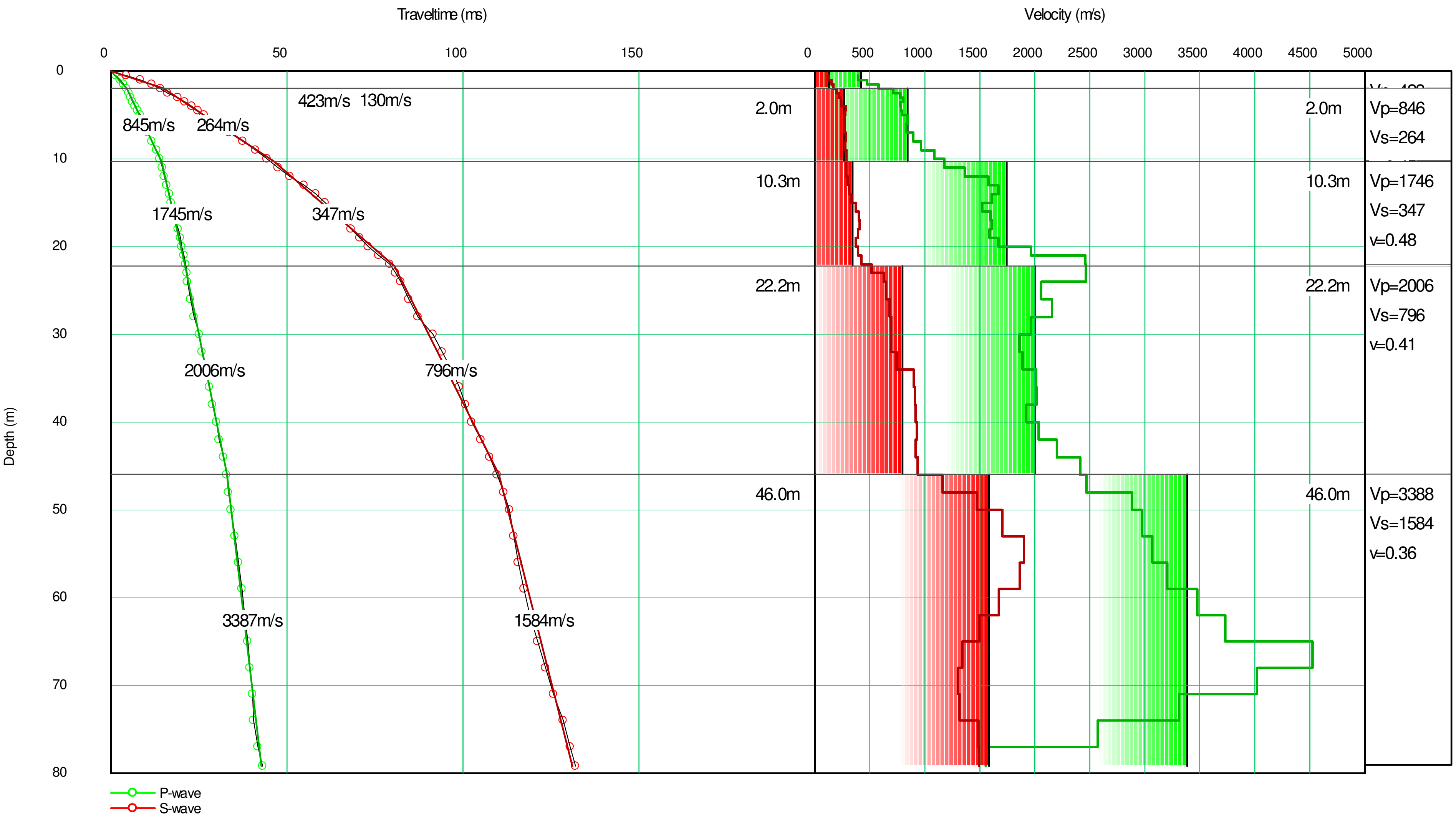
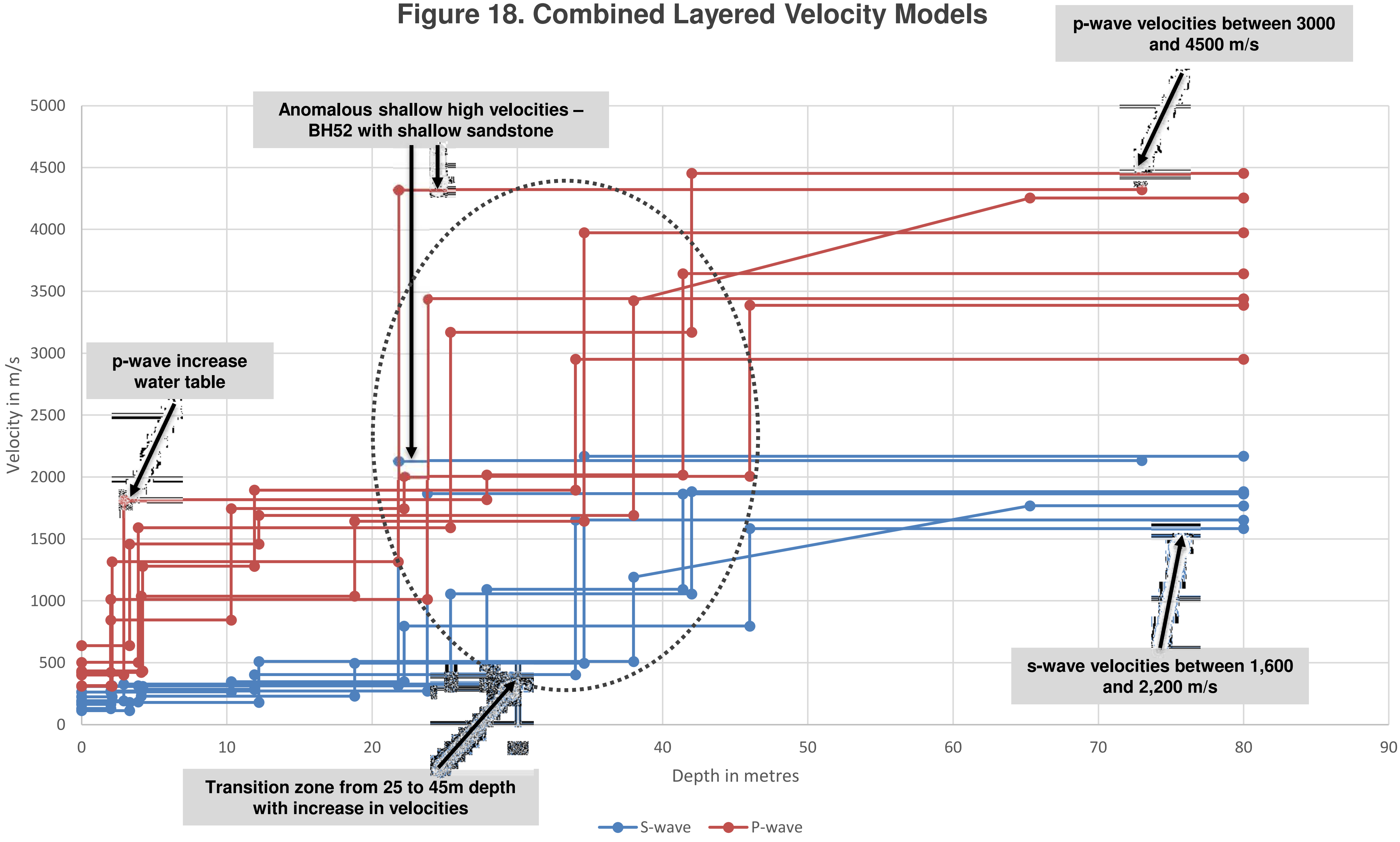


Figure 18. Combined Layered Velocity Models



9. Conclusions and Recommendations

Good data quality was observed for the MASW investigation with accurate shear wave models obtained from the results. Average shear wave velocities from 200 to 800 m/s were observed from surface to an average depth of 30 metres, with values as low as 100 and up to 1,000 m/s observed in specific areas as obtained from the MASW method. These velocities are associated with sand and high weathered and soft rock at typical depths from 0 to 30 metres.

The downhole seismic results up to 30m depth show good agreement with the MASW results with shear wave velocities ranging from 100 to slightly more than 1,000 m/s to a depth of 30 metres. The downhole seismic results measured p-wave velocities of bedrock between 3,000 and 4,500 m/s and s-wave velocities between 1,600 and 2,200 m/s.

Yours sincerely

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10. References

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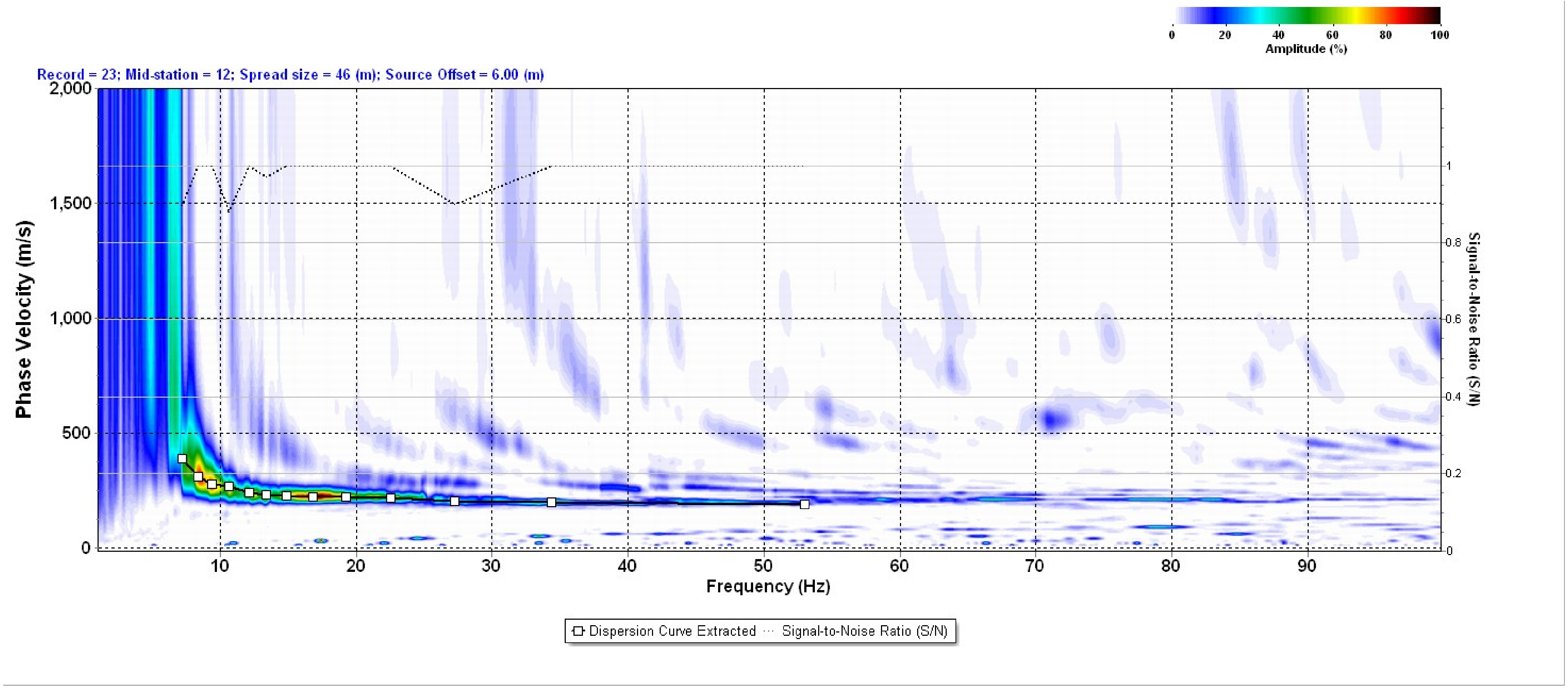
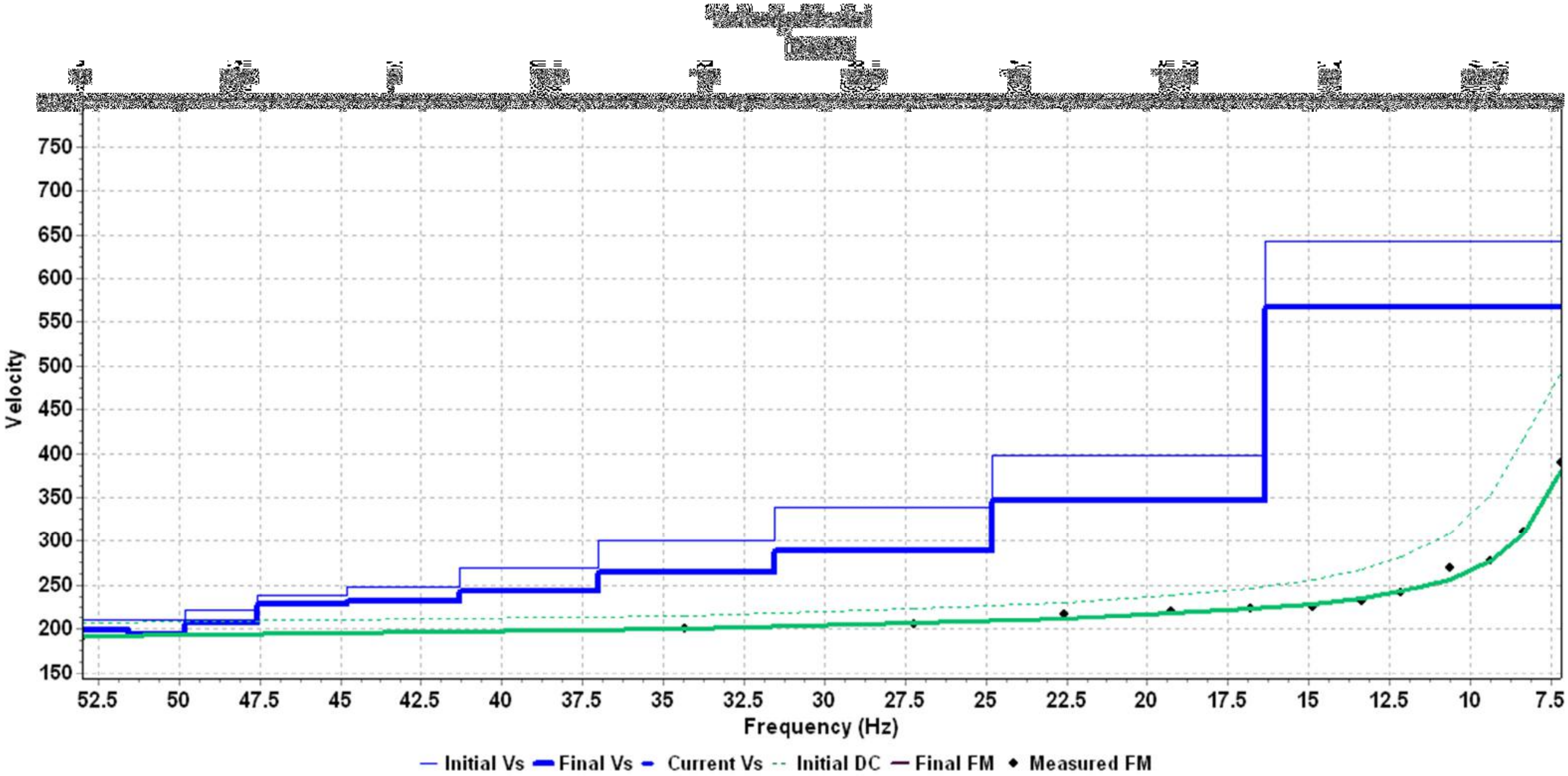
Appendix 1: MASW Overtone Images and Velocity Models

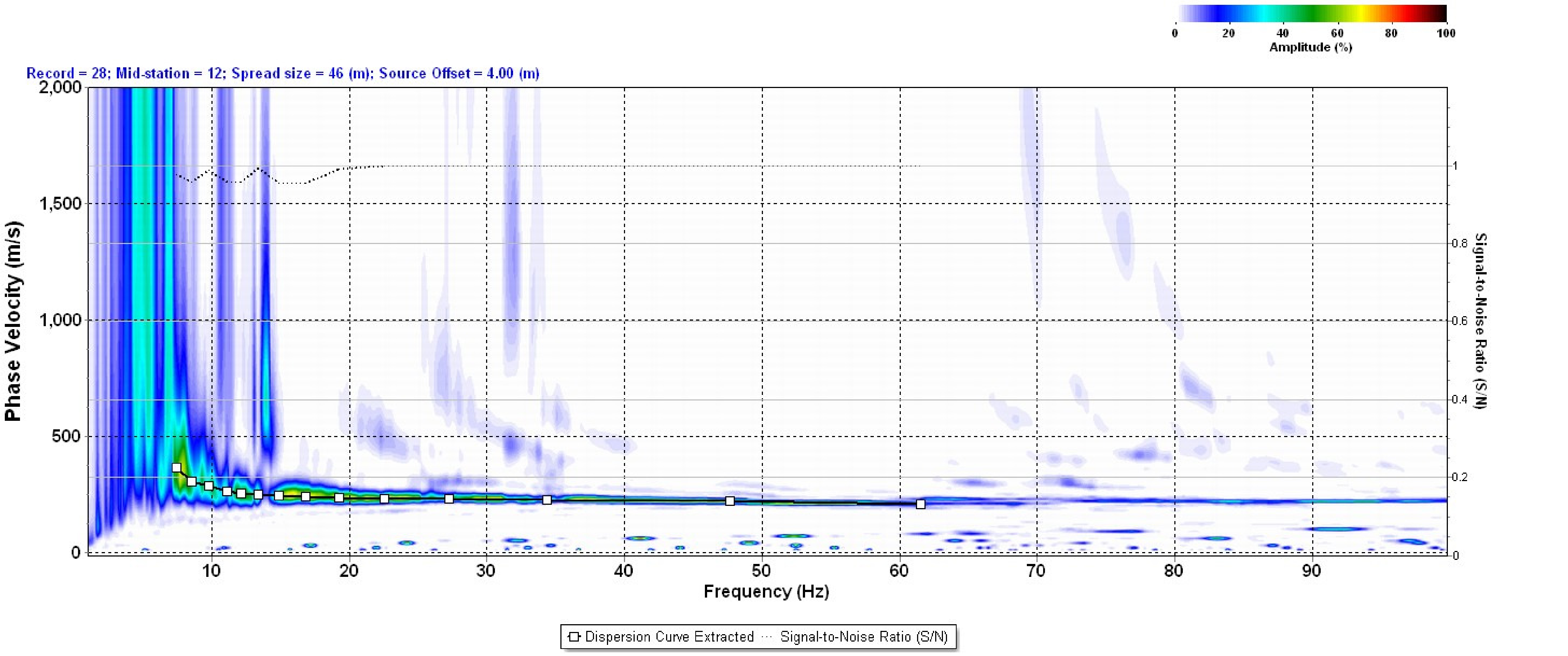
MM-1 Overtone Image



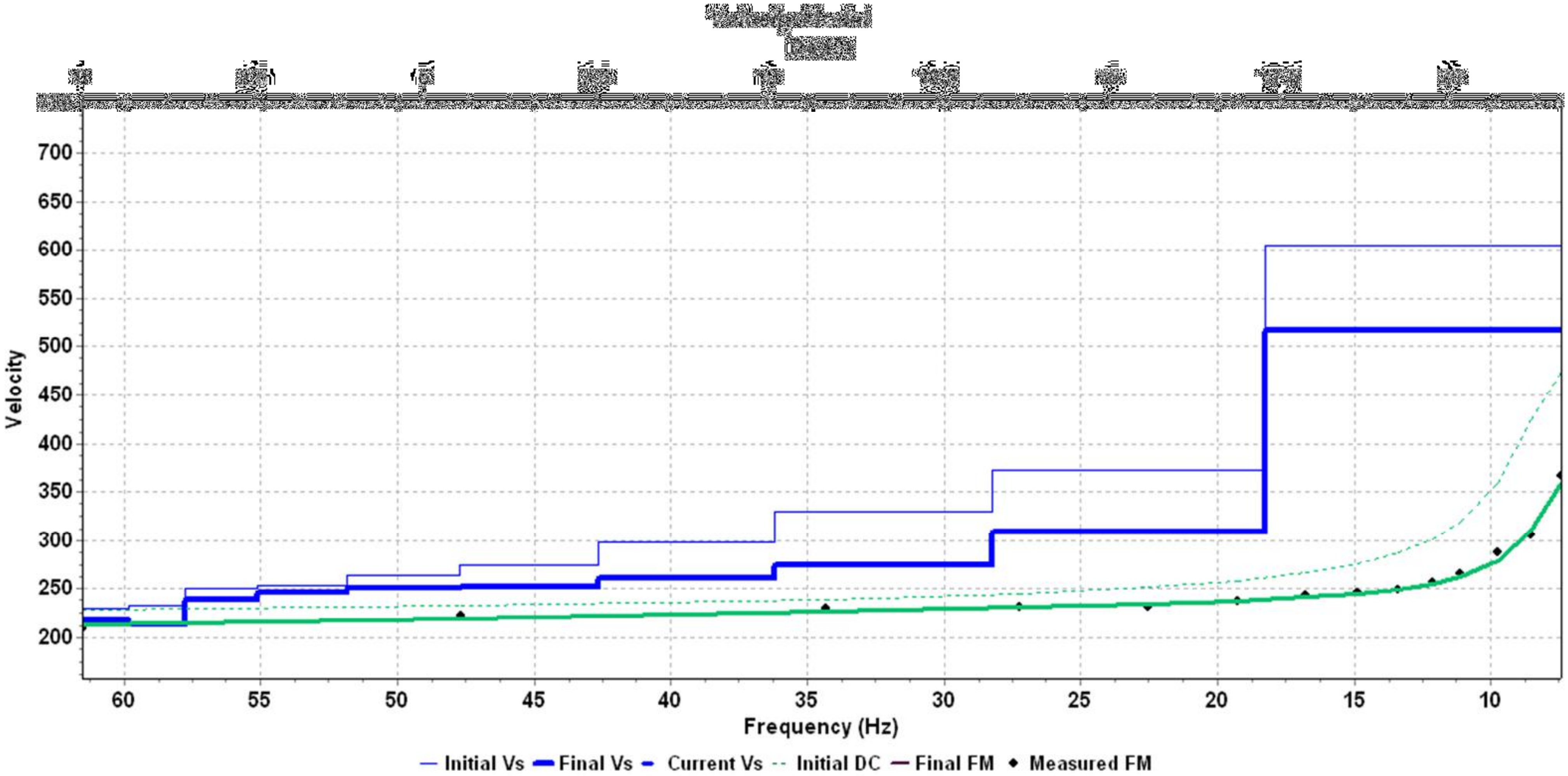
MM-1 Velocity Model



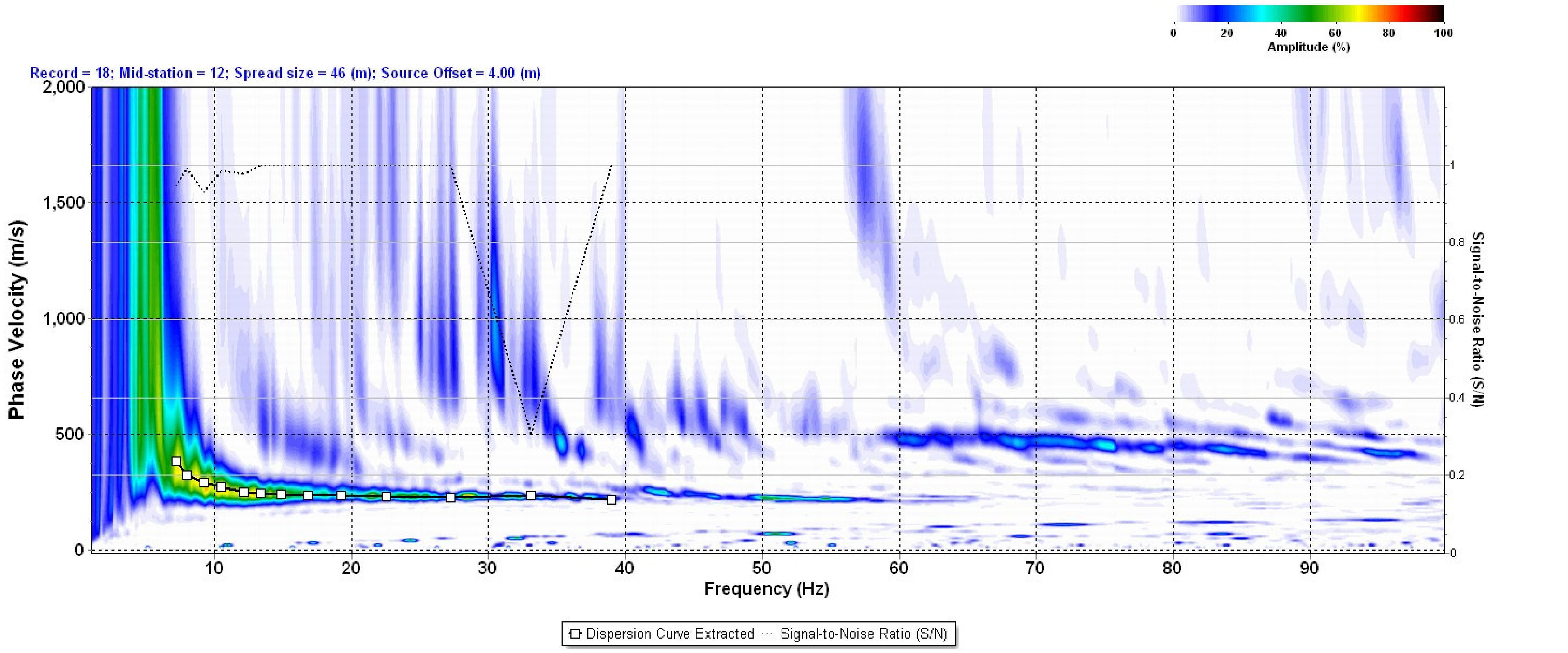
MM-2 Overtone Image



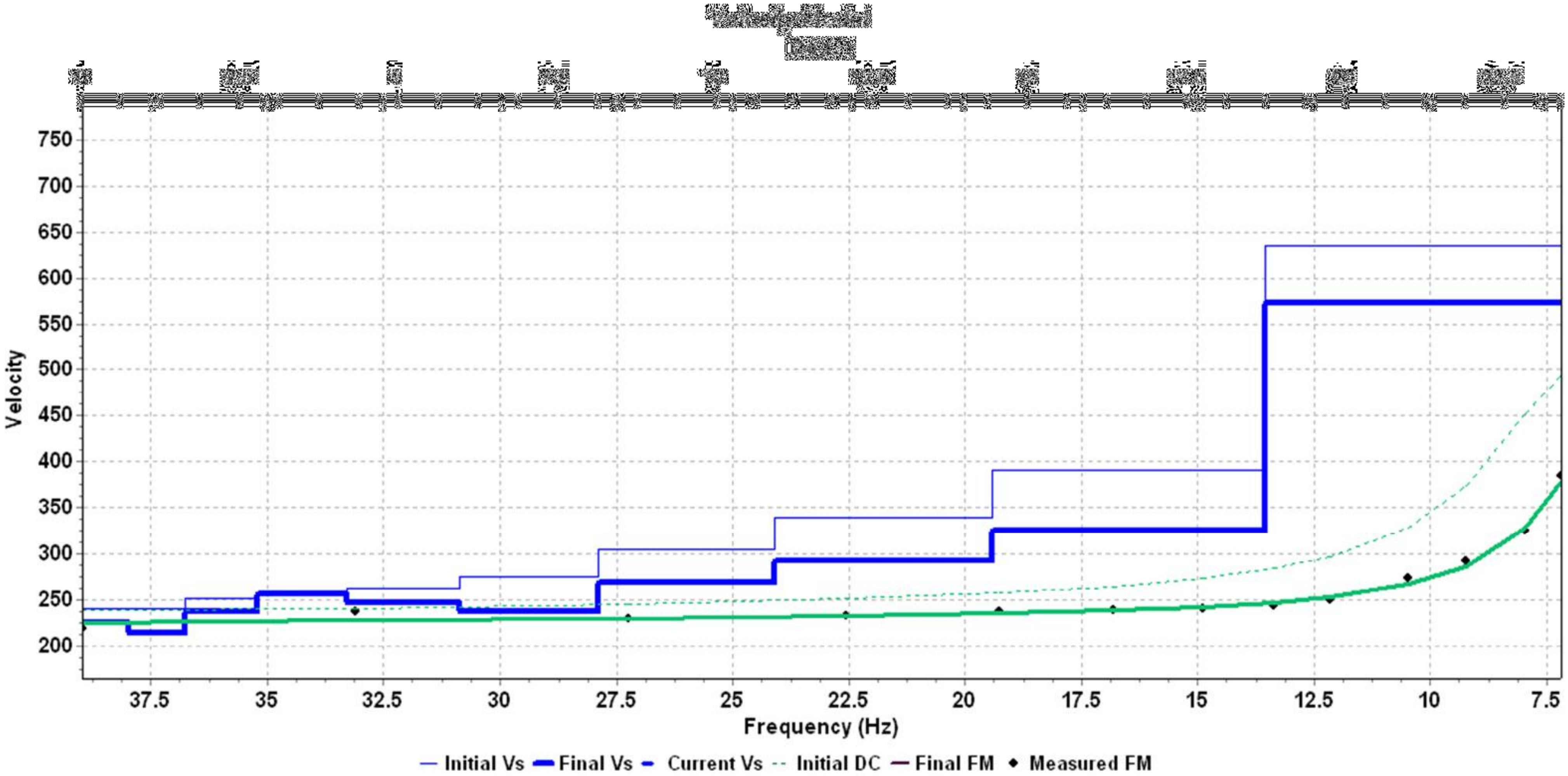
MM-2 Velocity Model



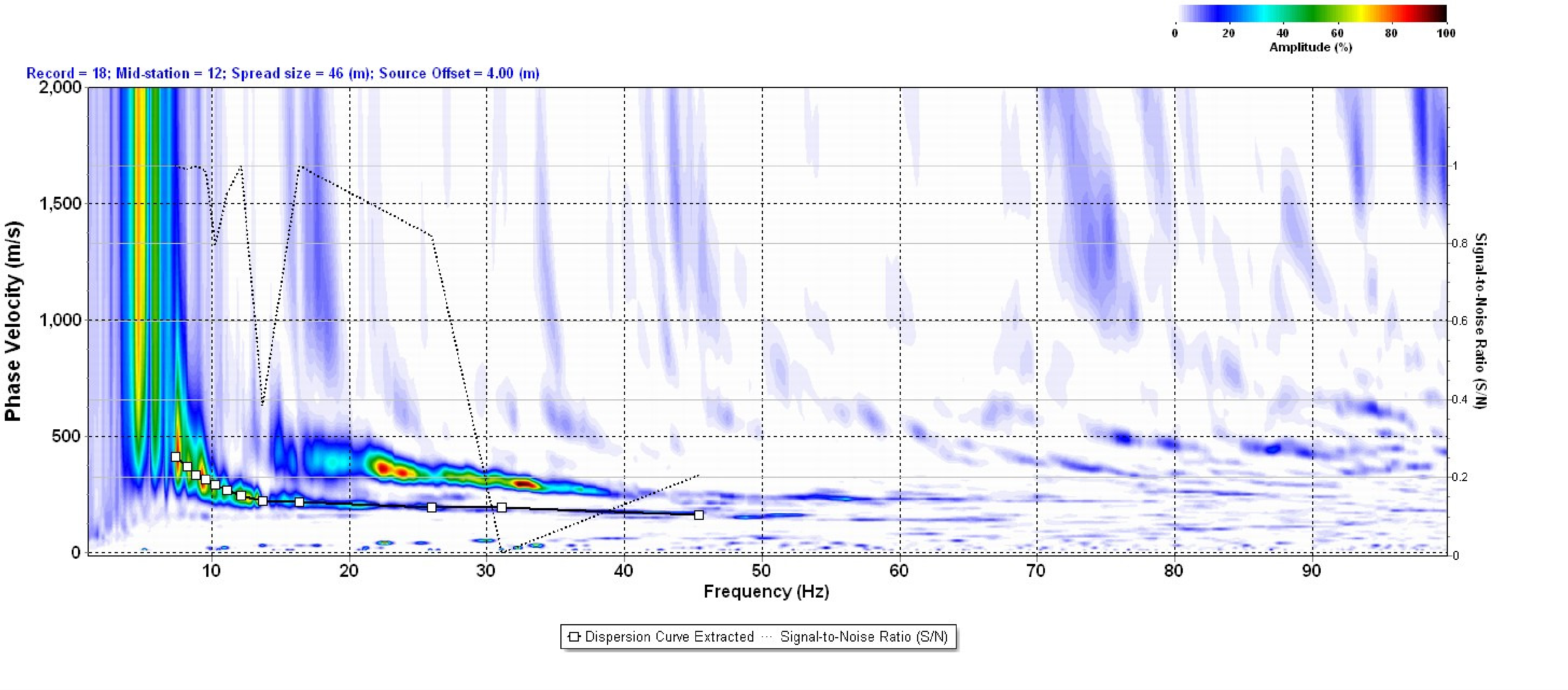
MM-3 Overtone Image



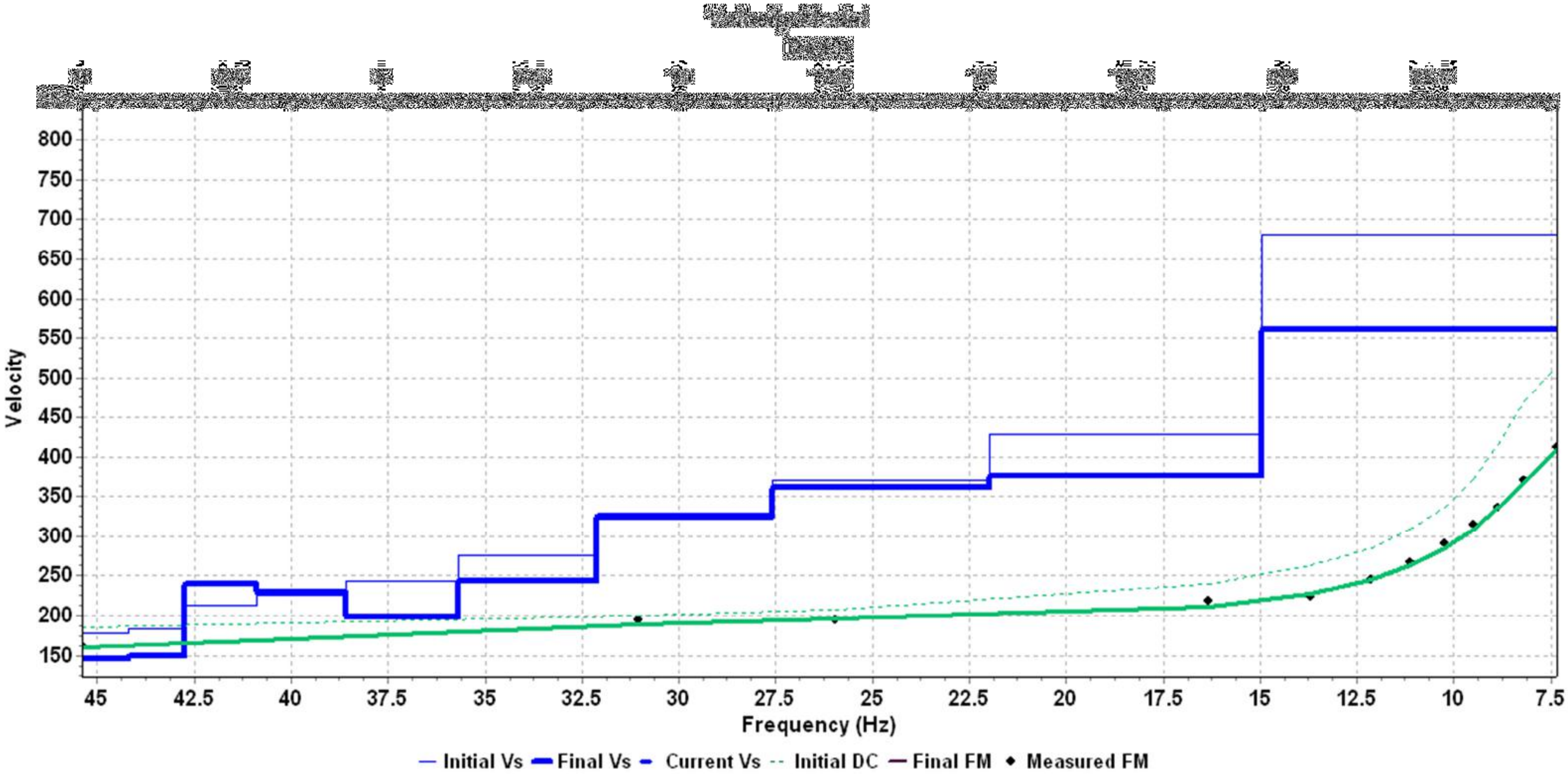
MM-3 Velocity Model



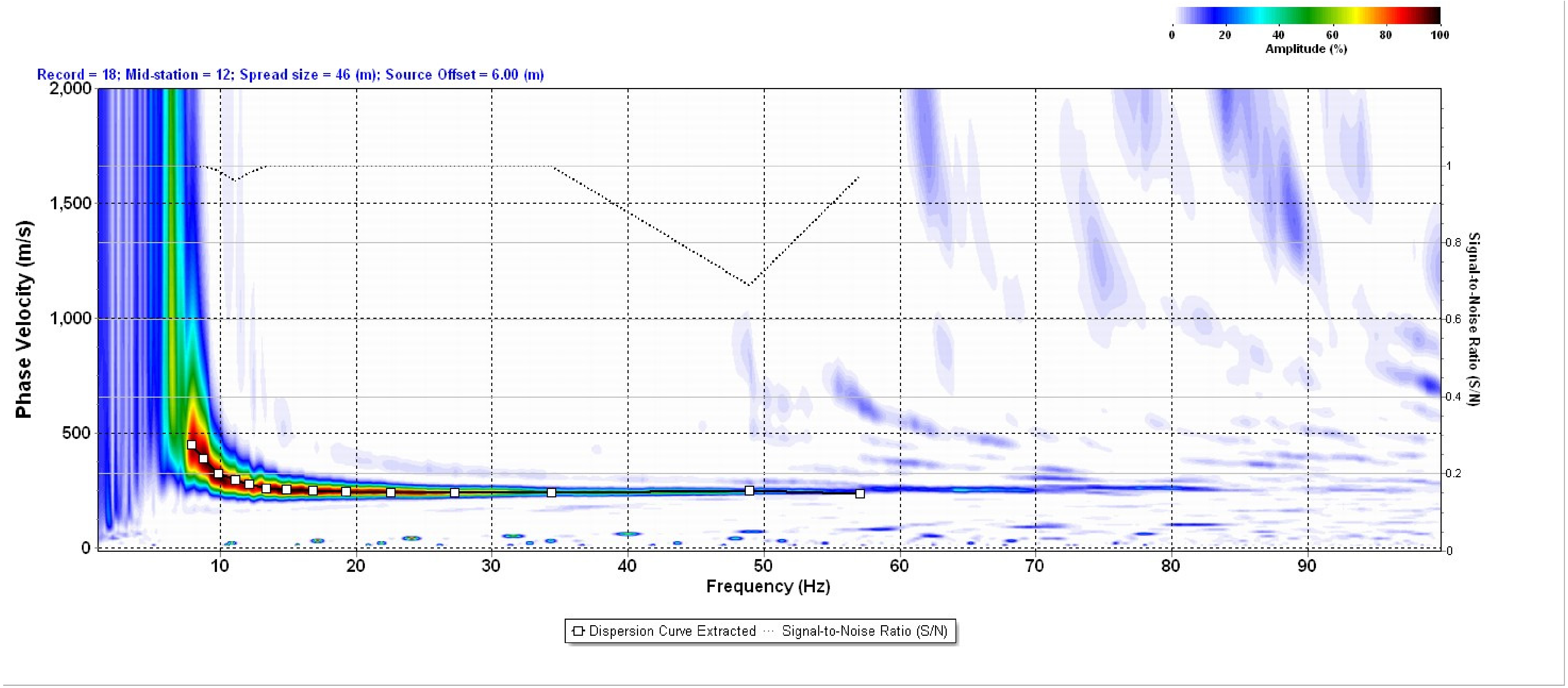
MM-4 Overtone Image



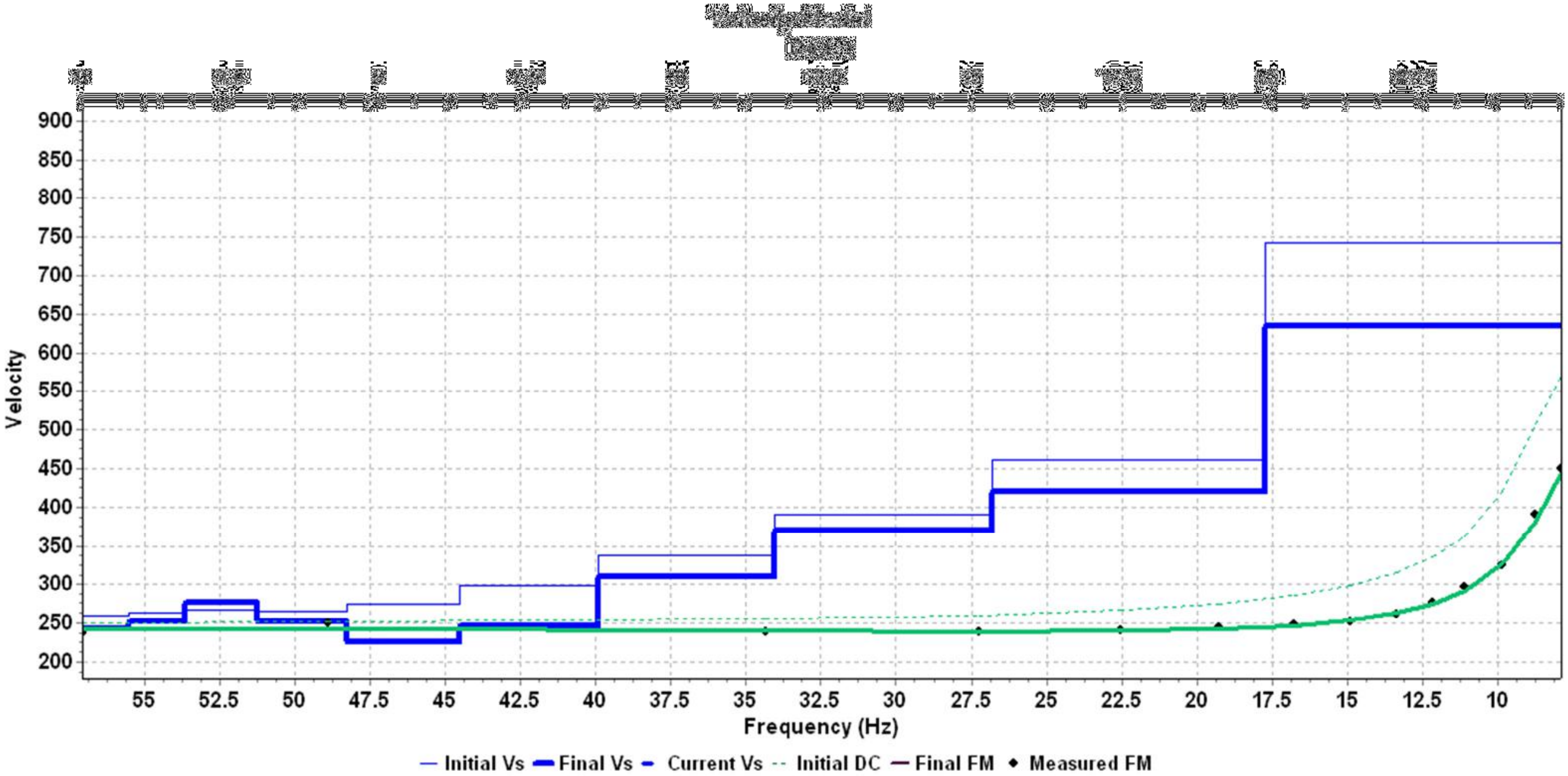
MM-4 Velocity Model



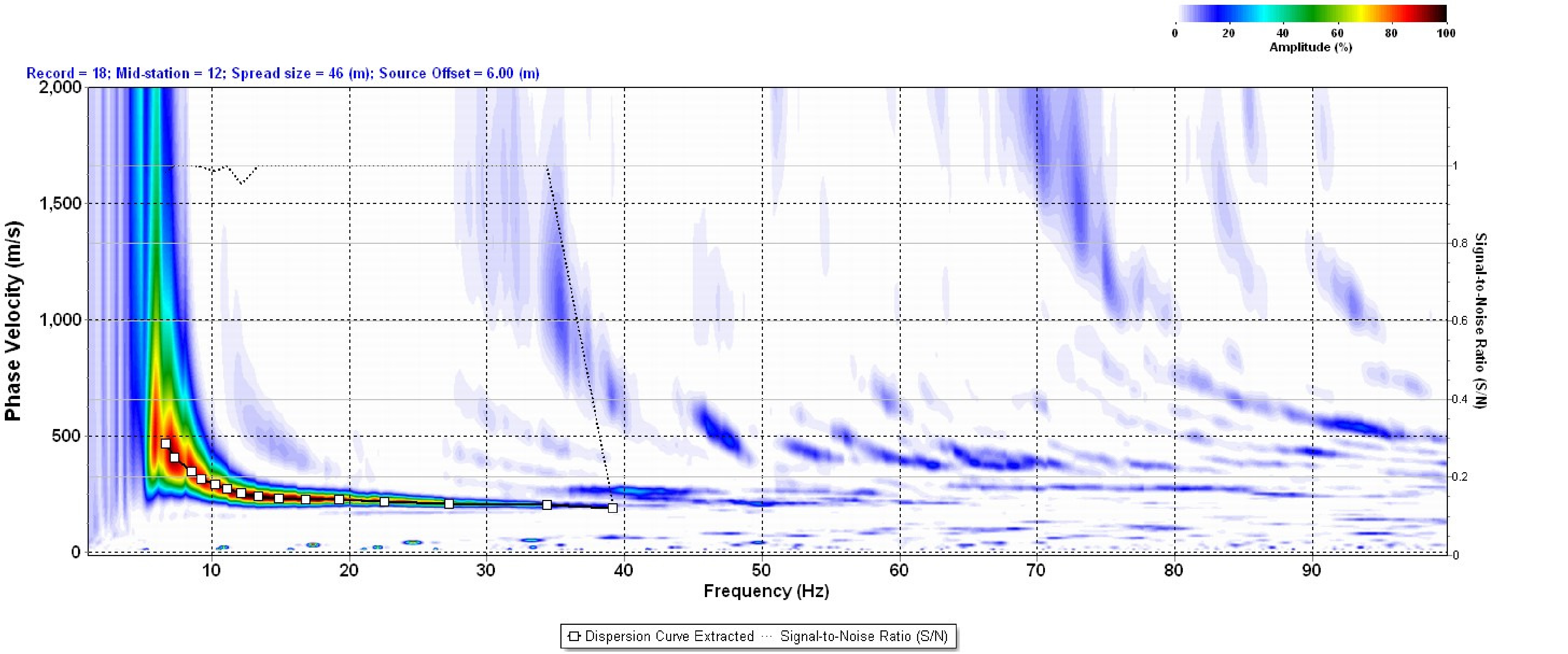
MM-5 Overtone Image



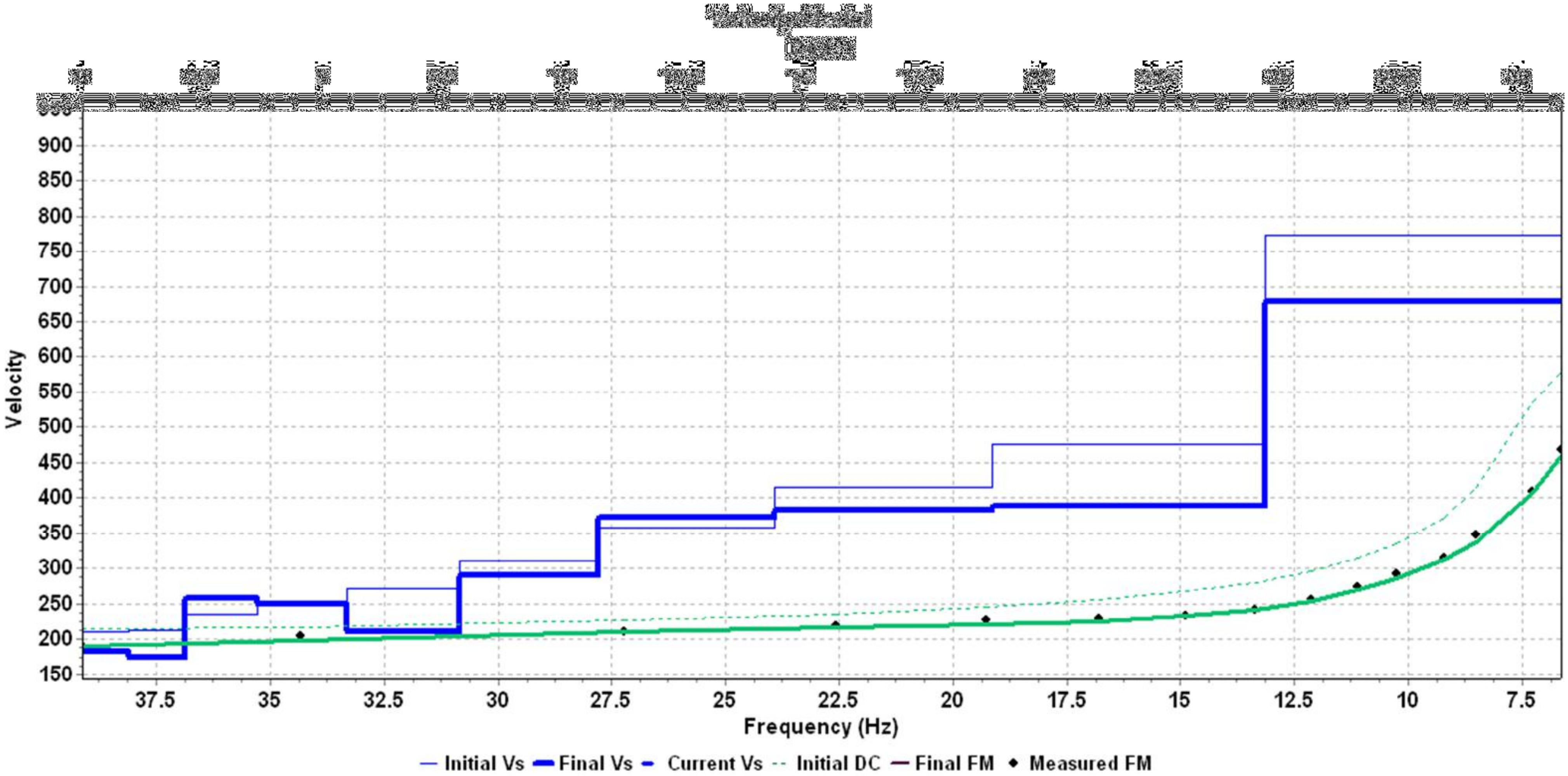
MM-5 Velocity Model



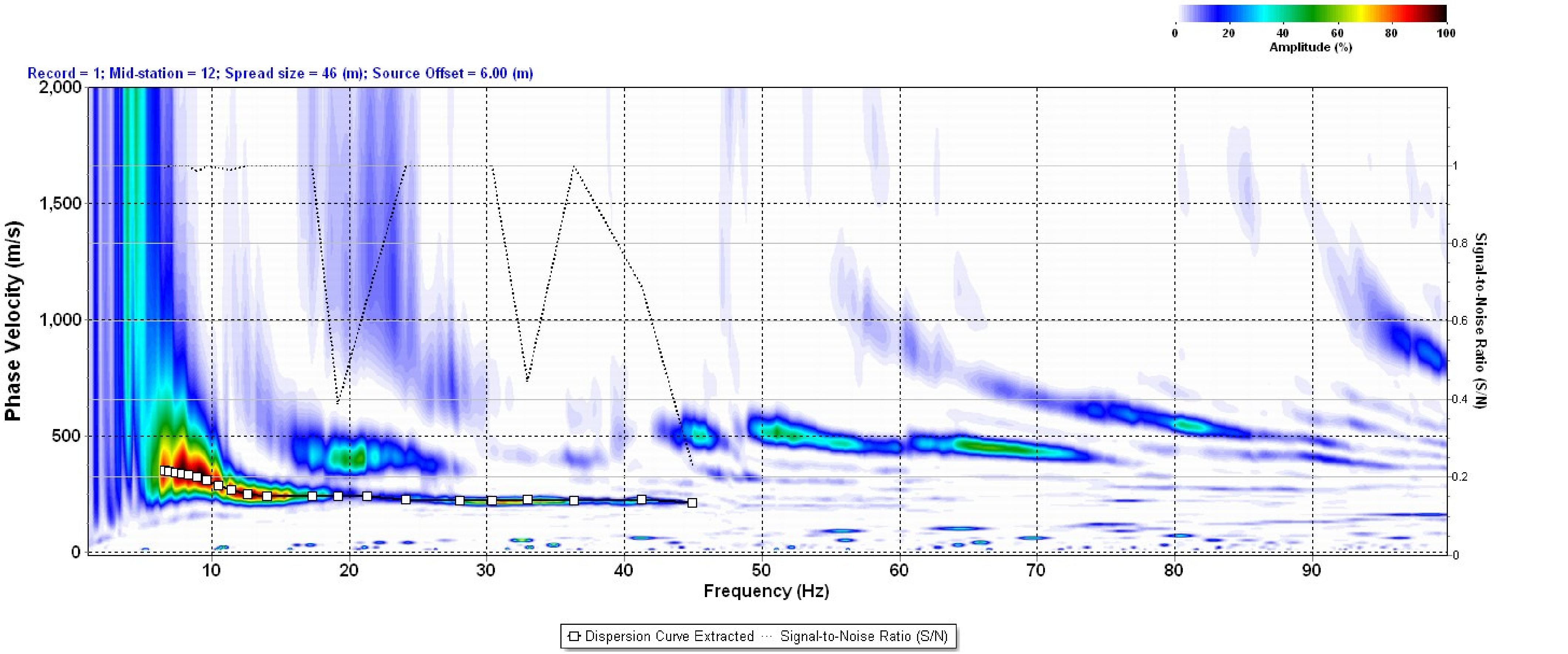
MM-6 Overtone Image



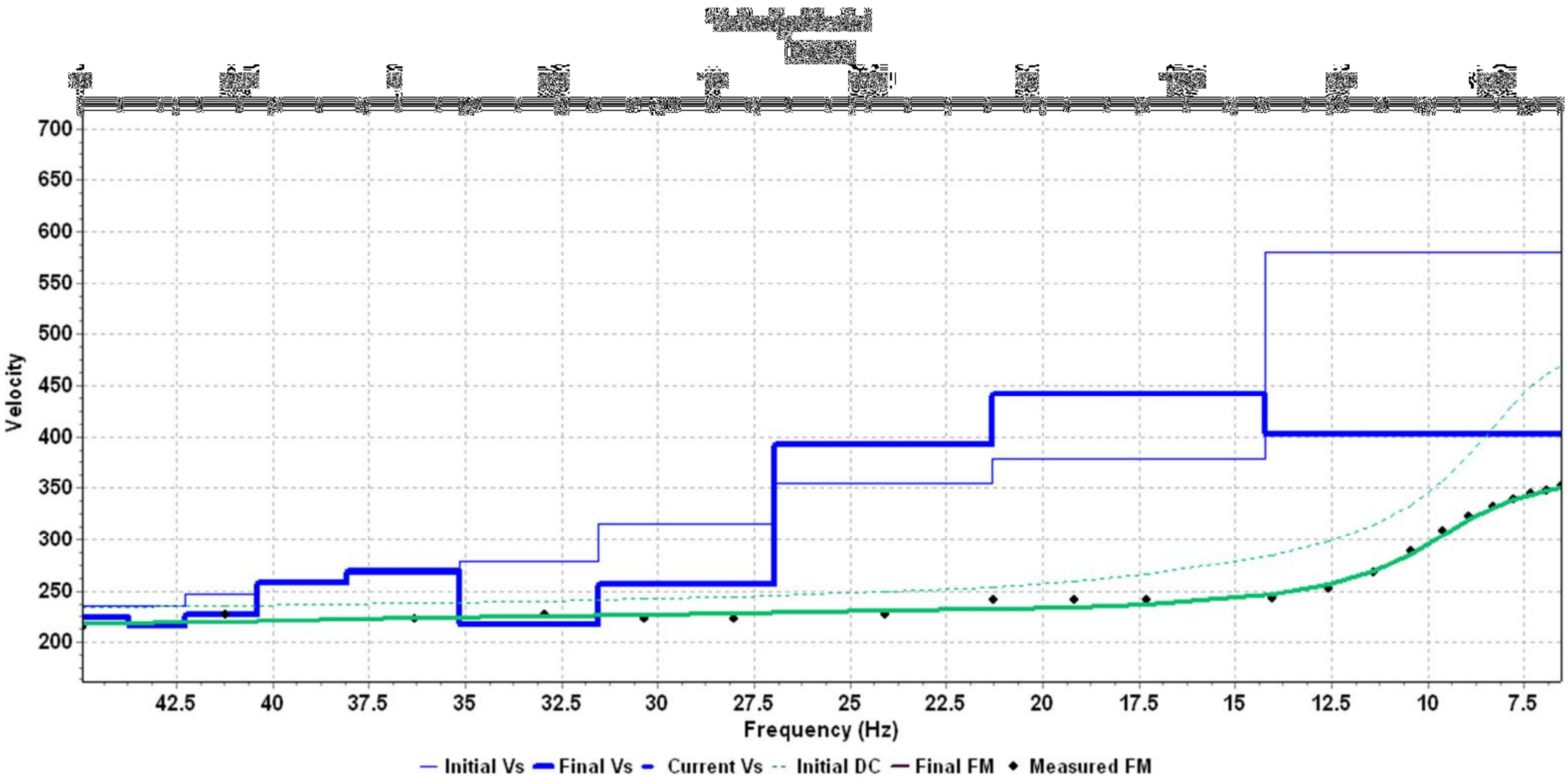
MM-6 Velocity Model



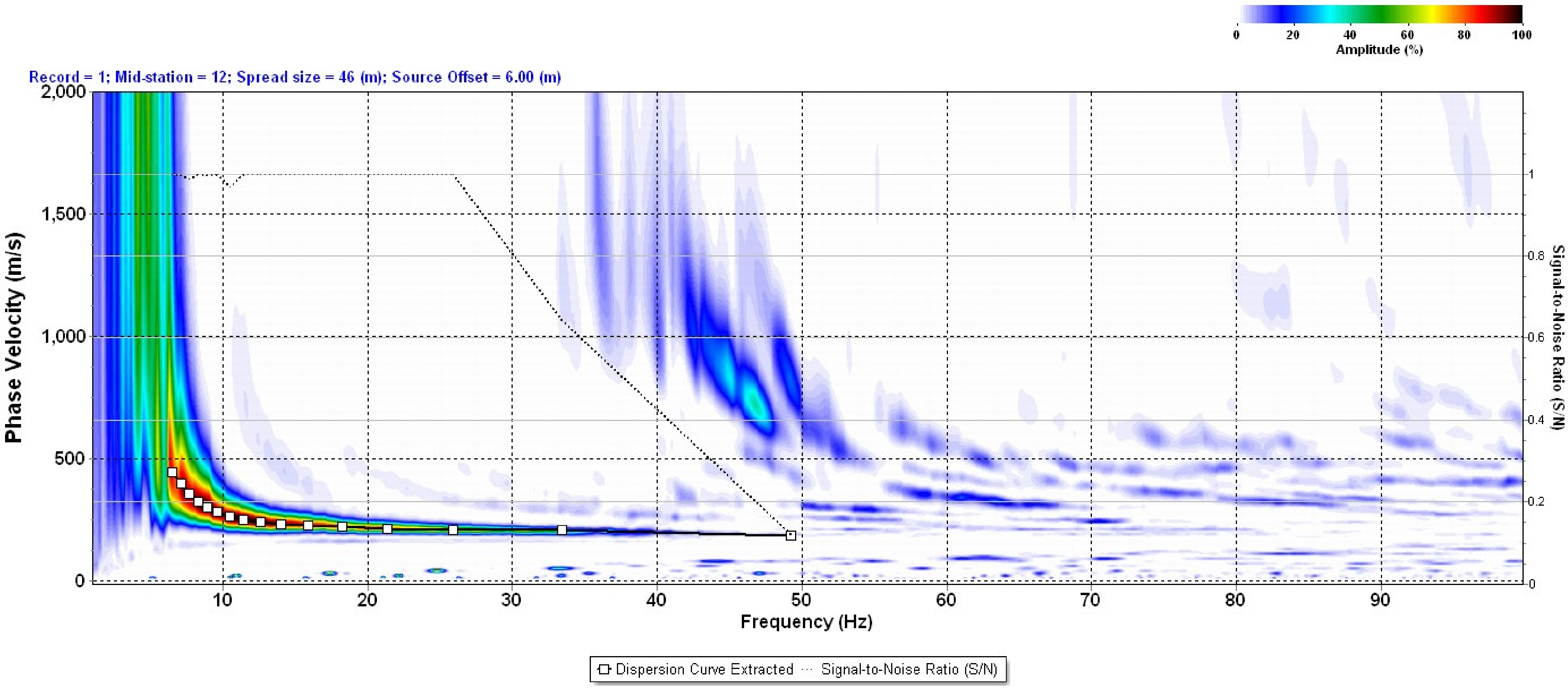
MI-1 Overtone Image



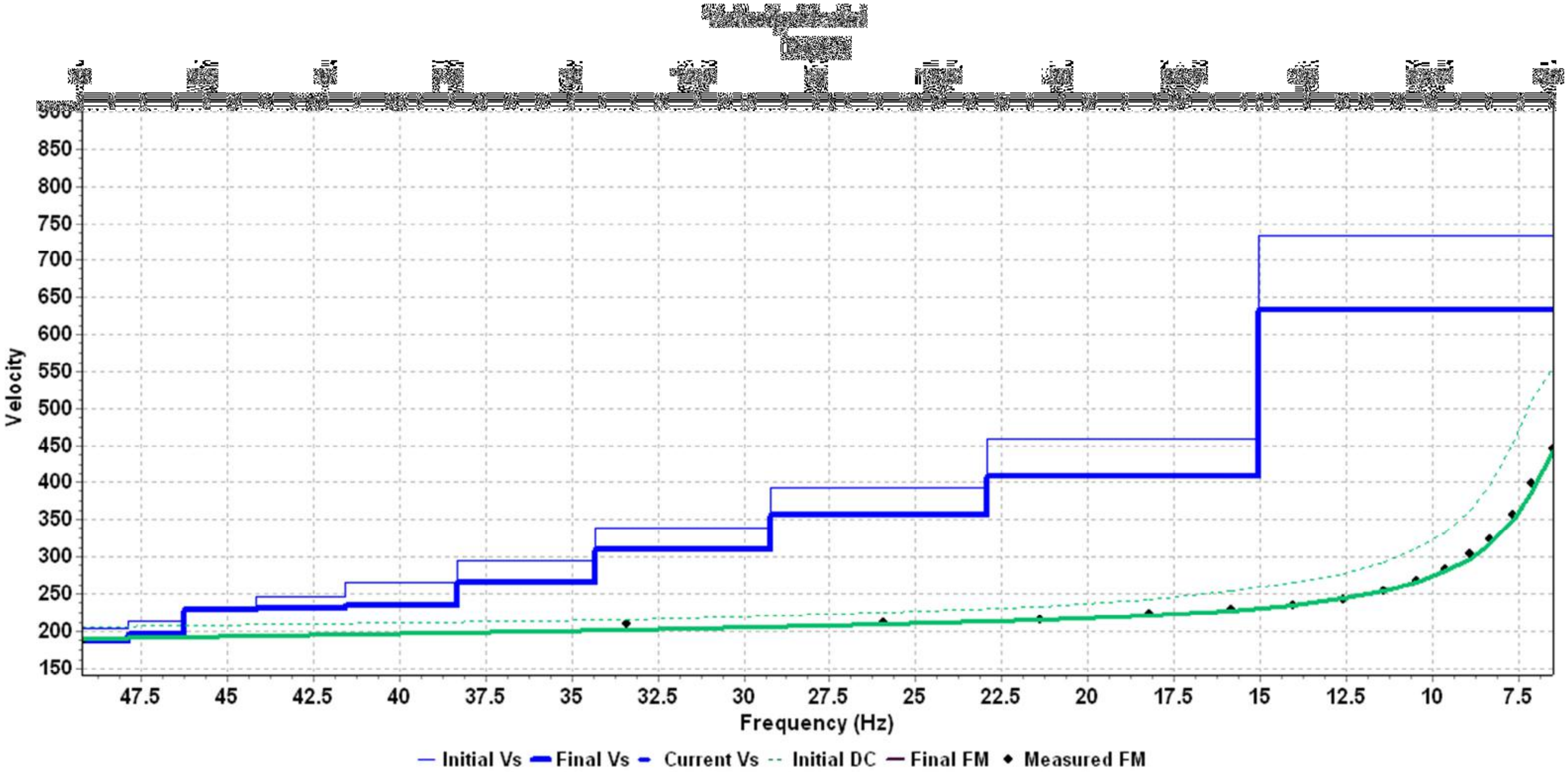
MI-1 Velocity Model



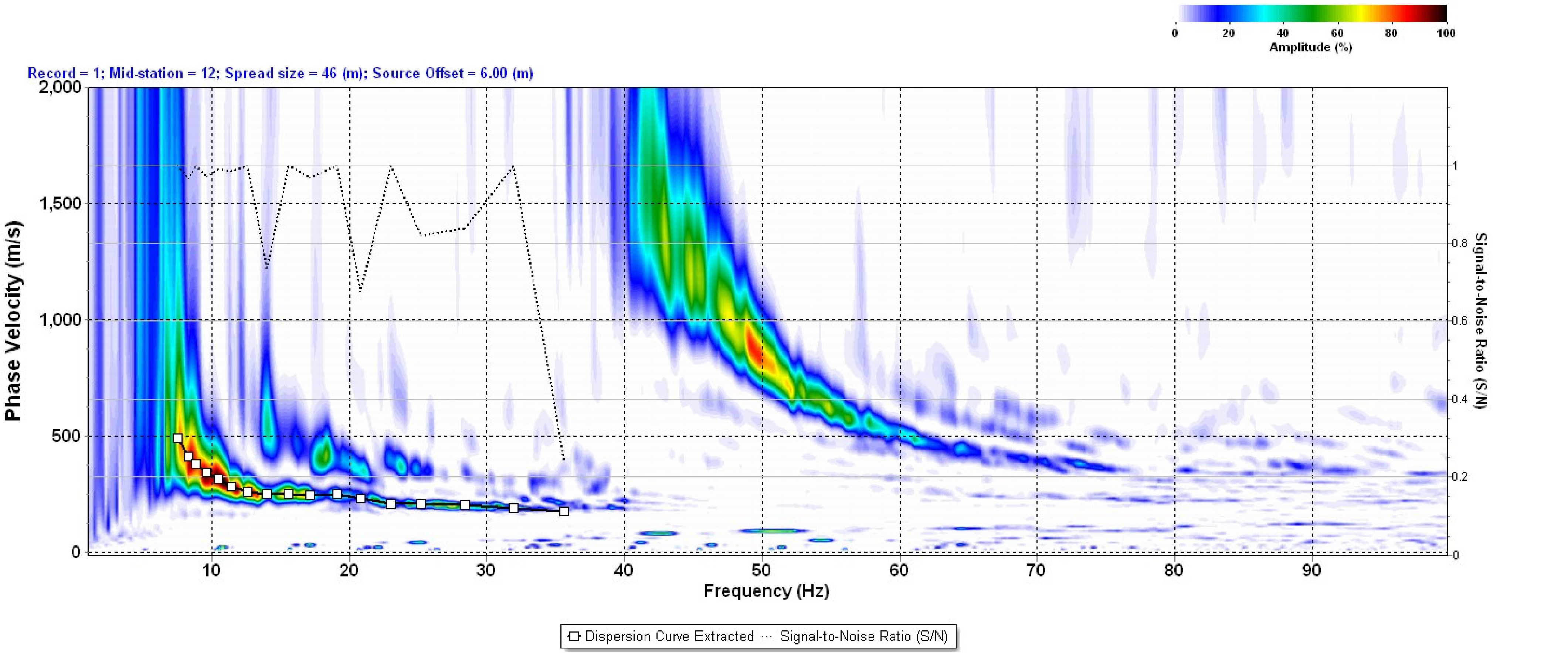
MI-2 Overtone Image



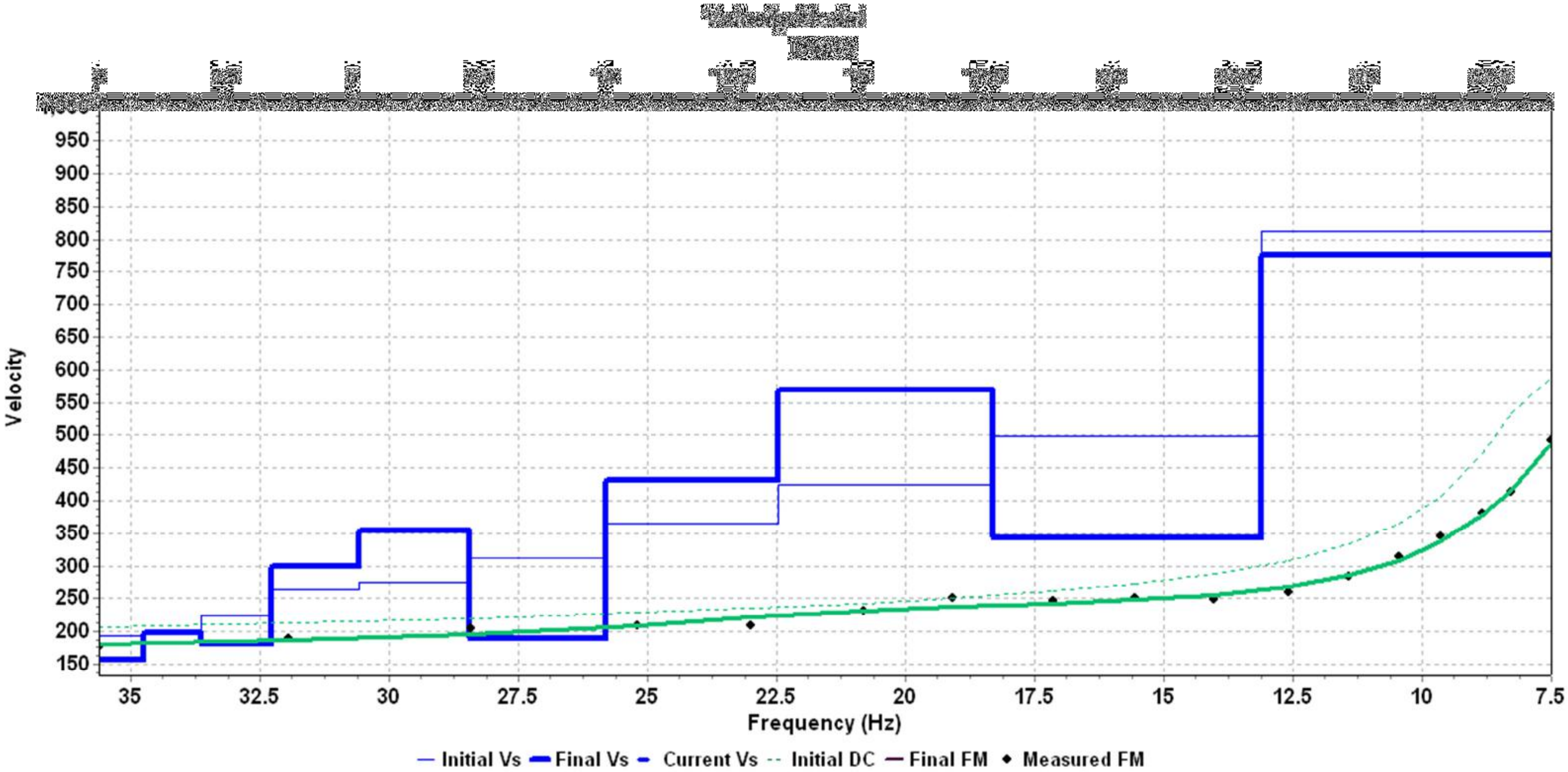
MI-2 Velocity Model



MI-3 Overtone Image



MI-3 Velocity Model



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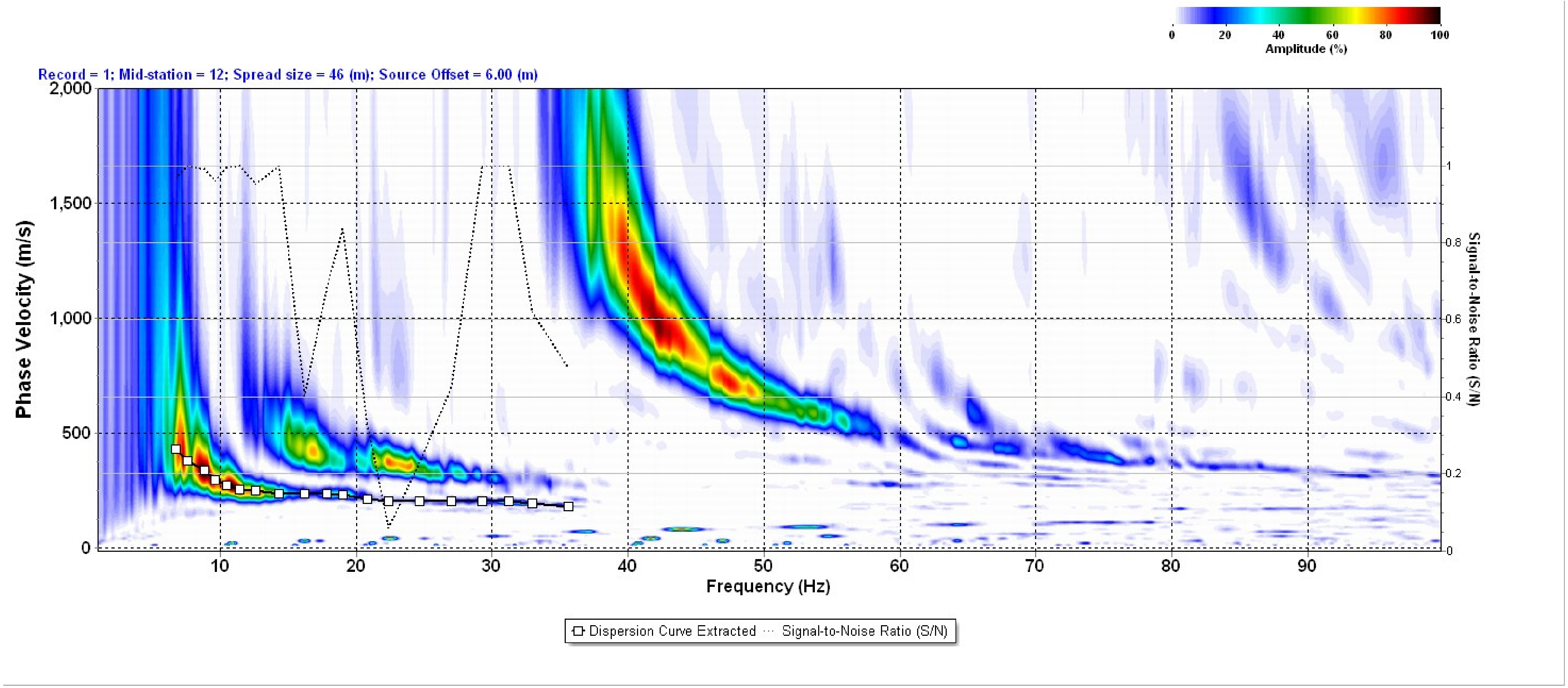

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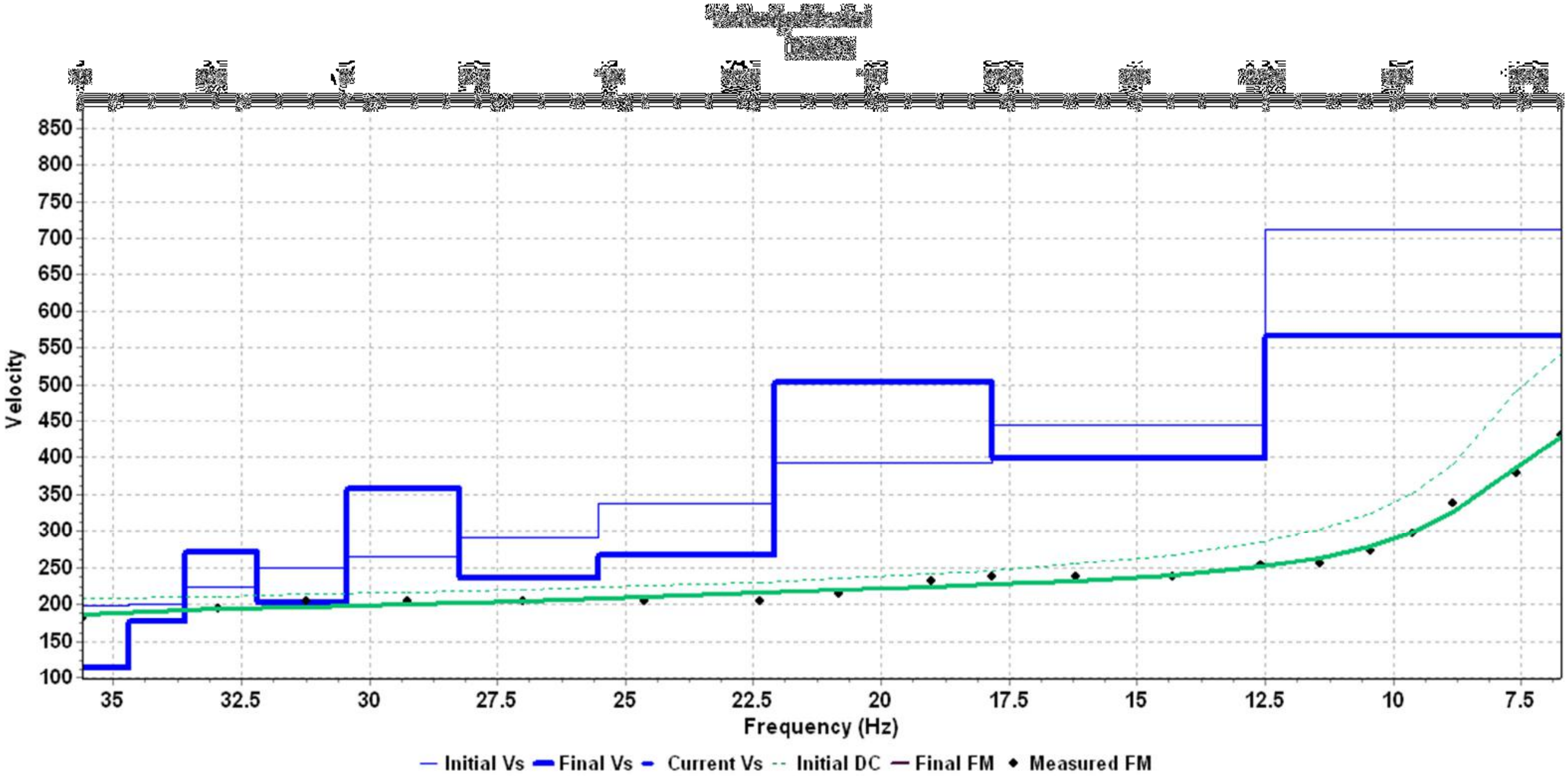

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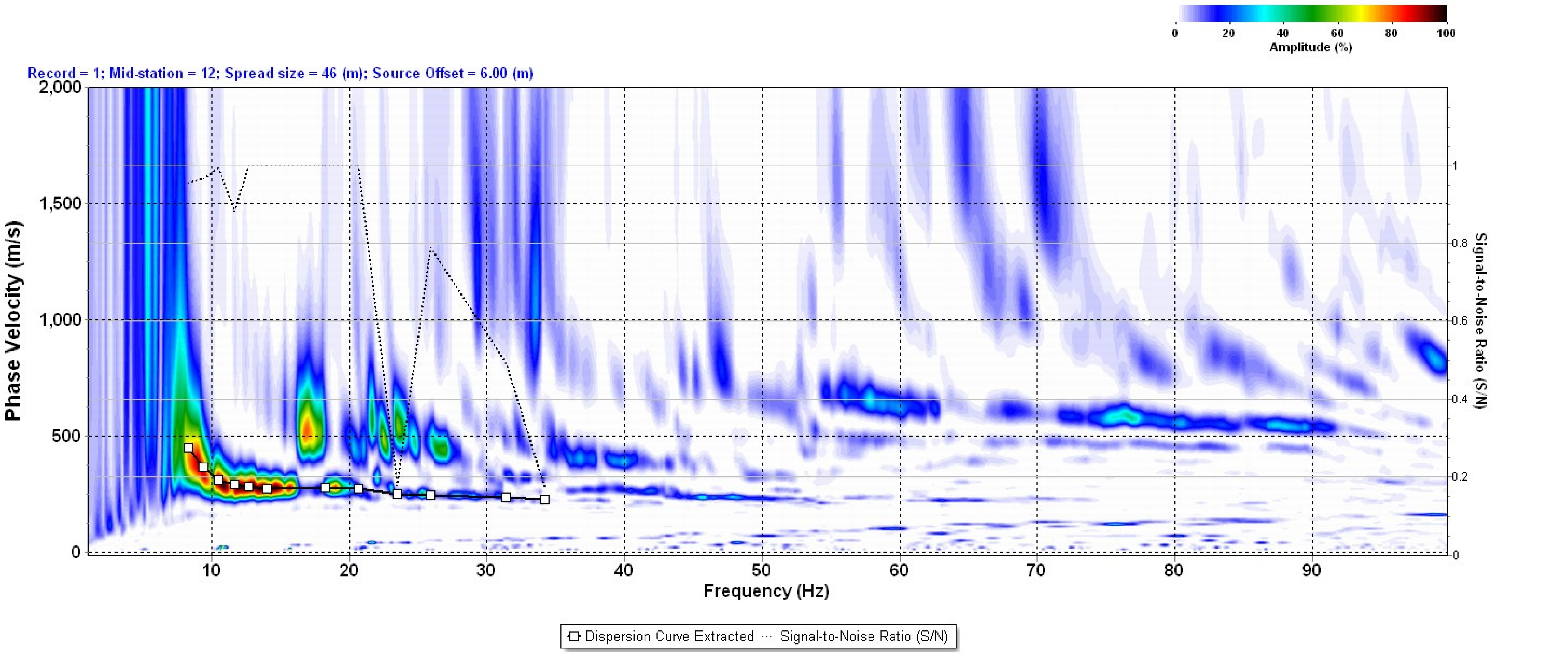

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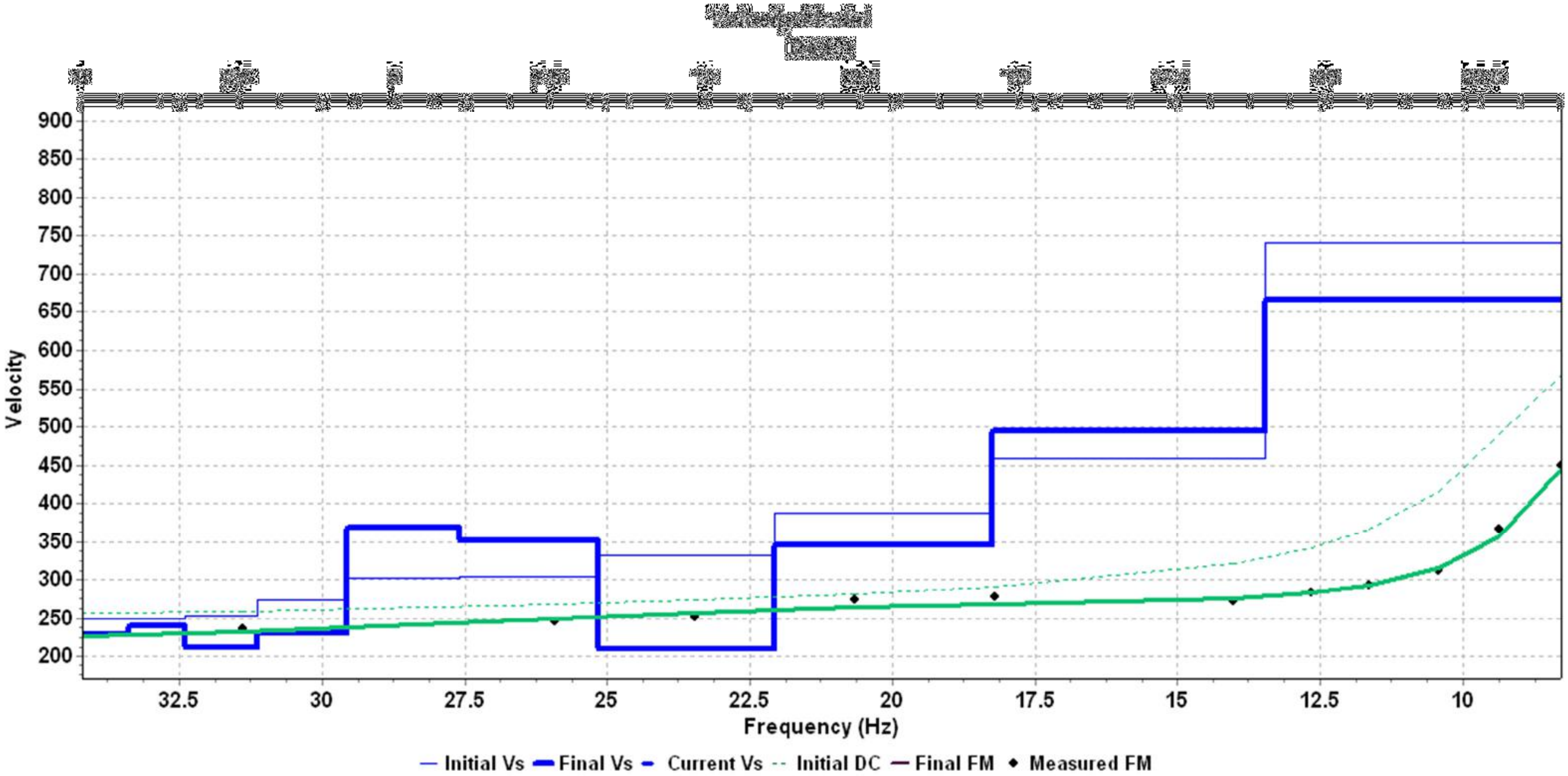

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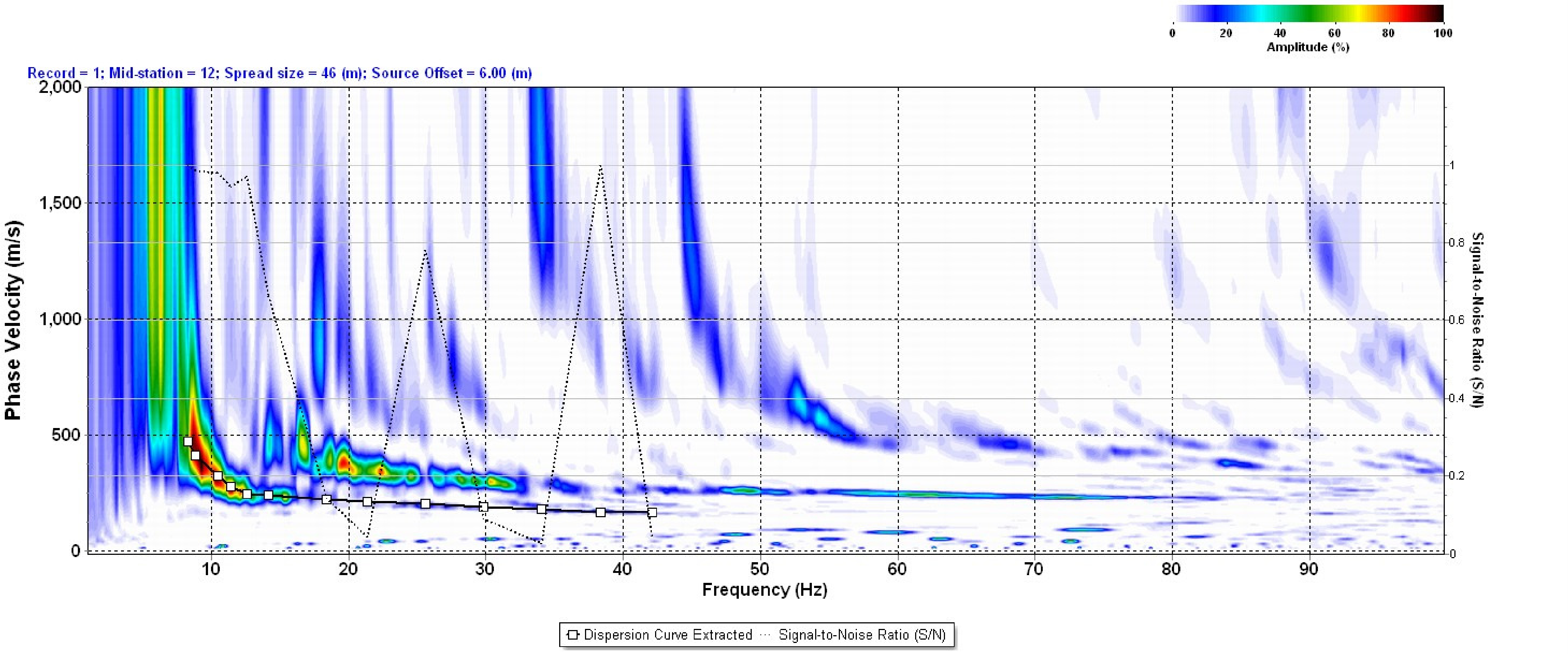

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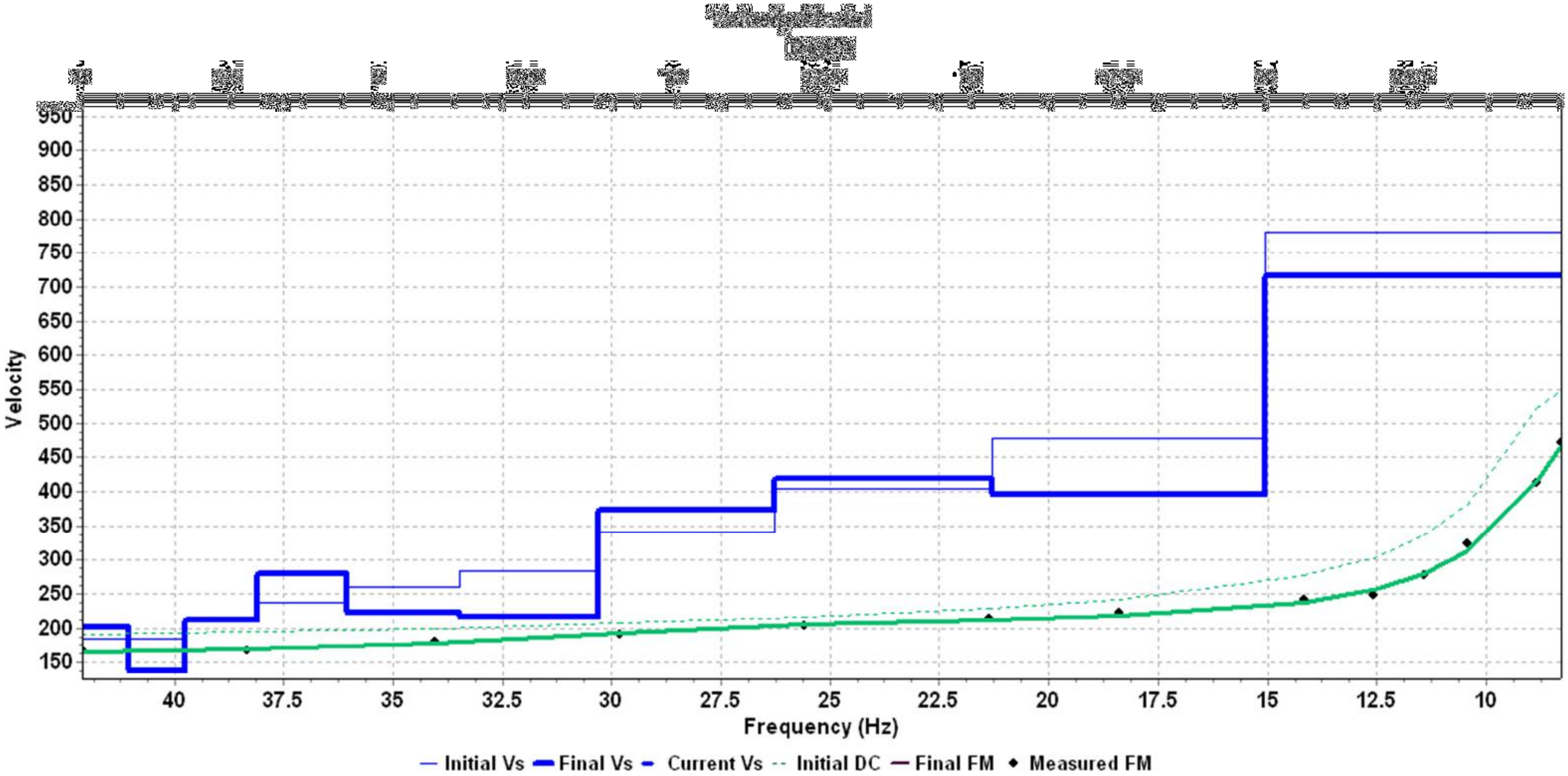

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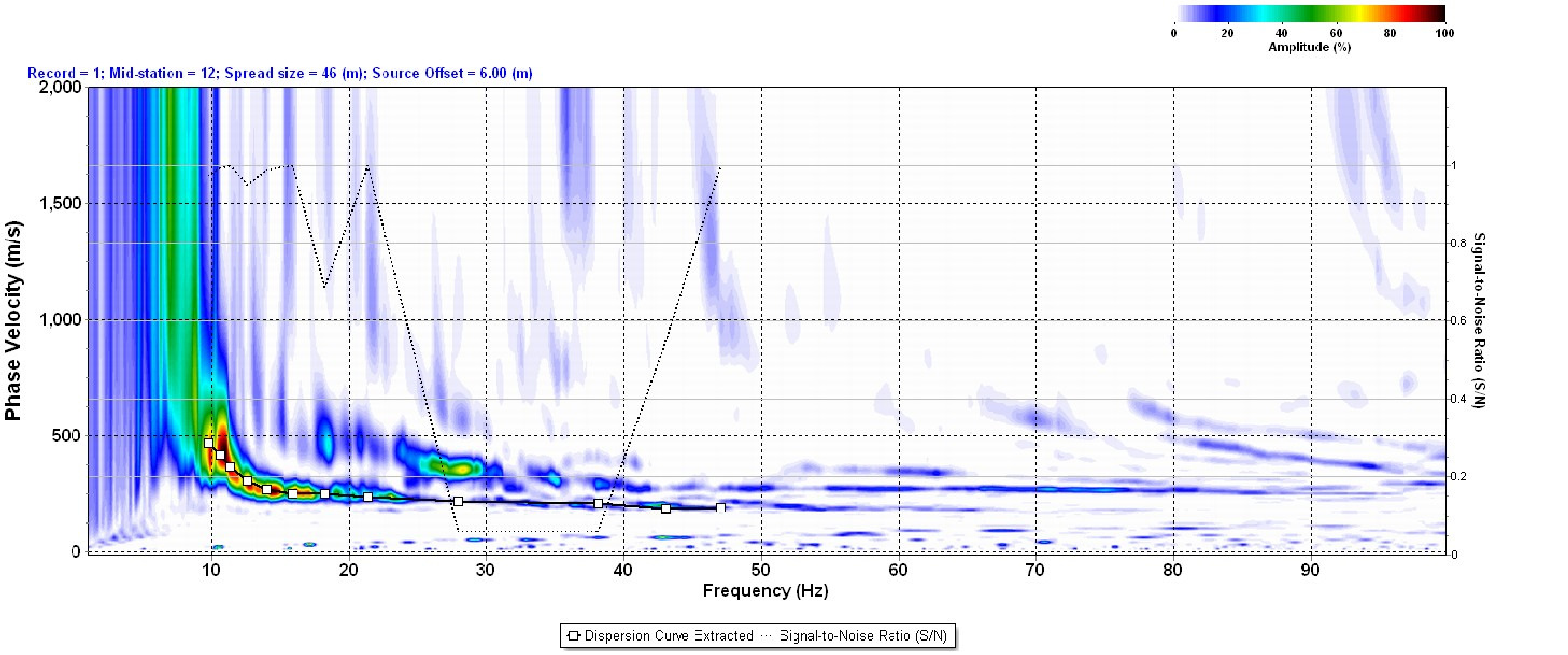

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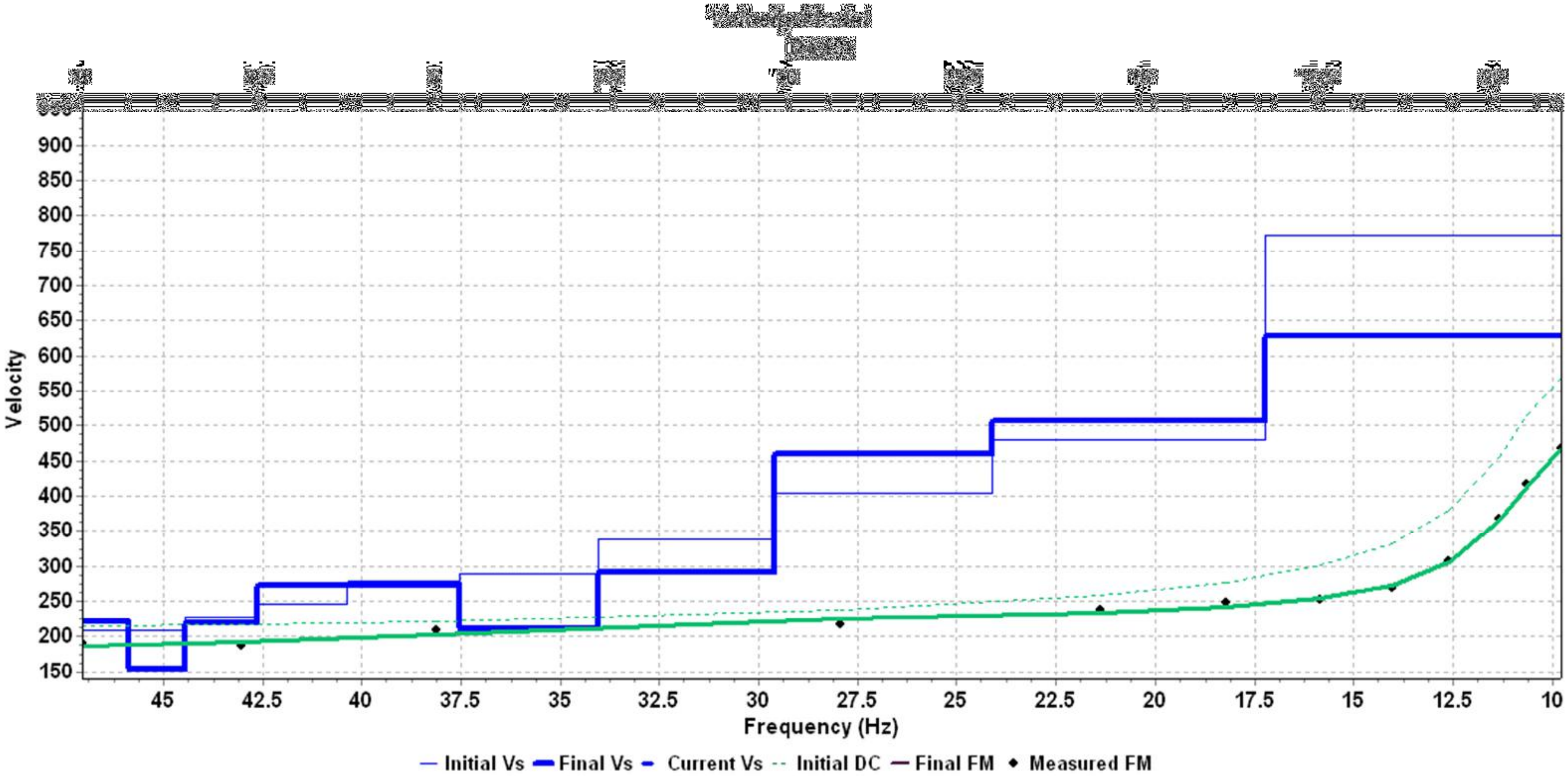

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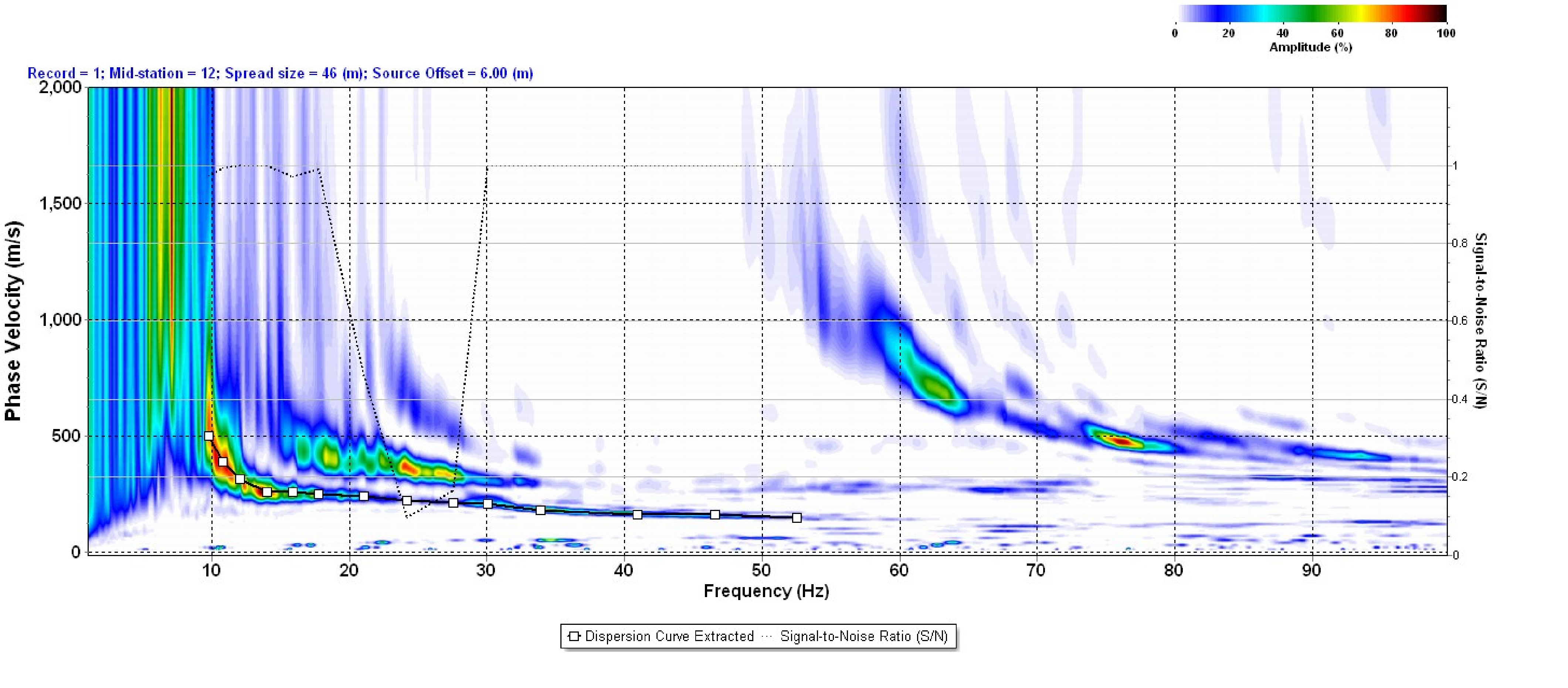

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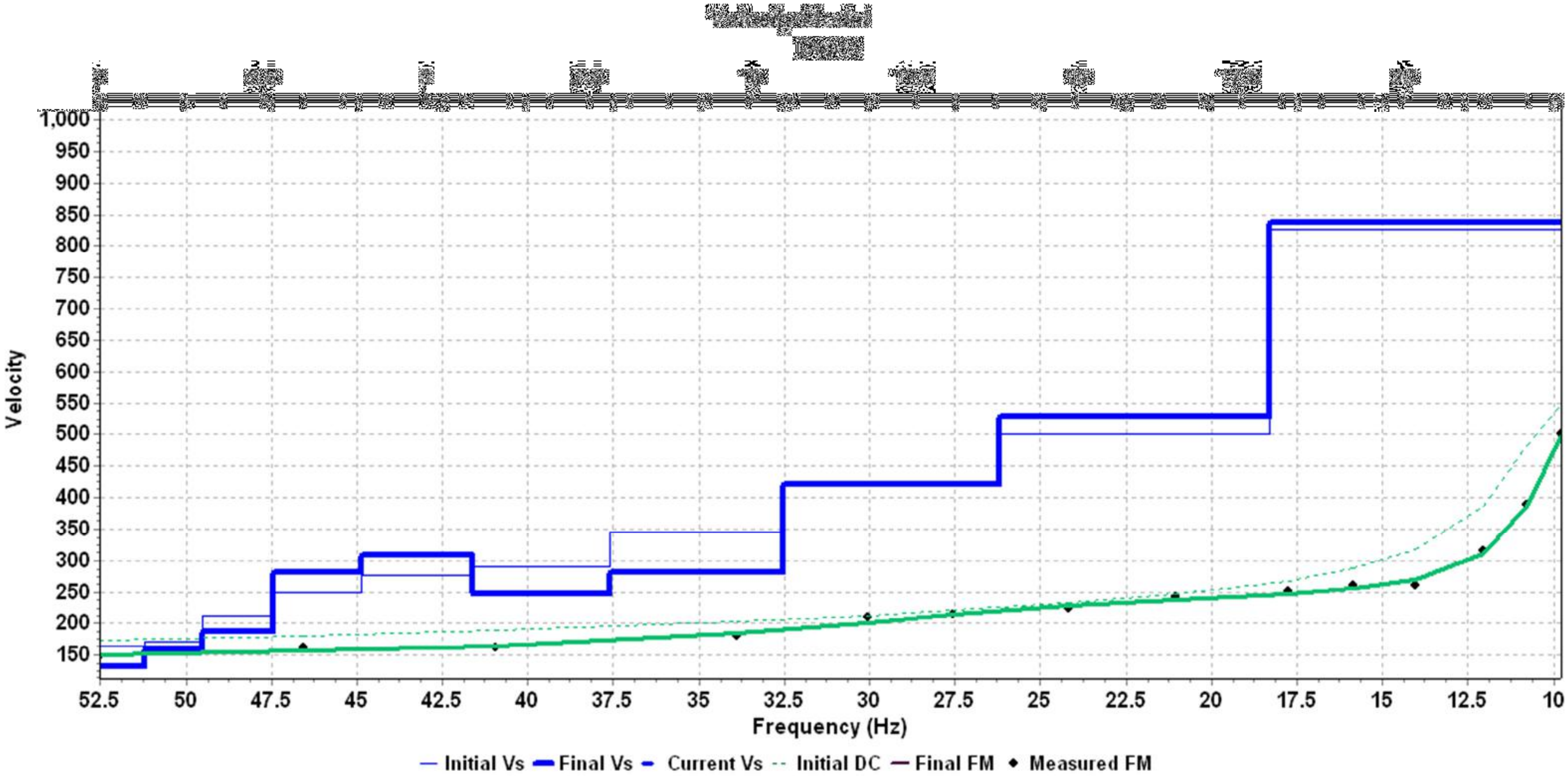

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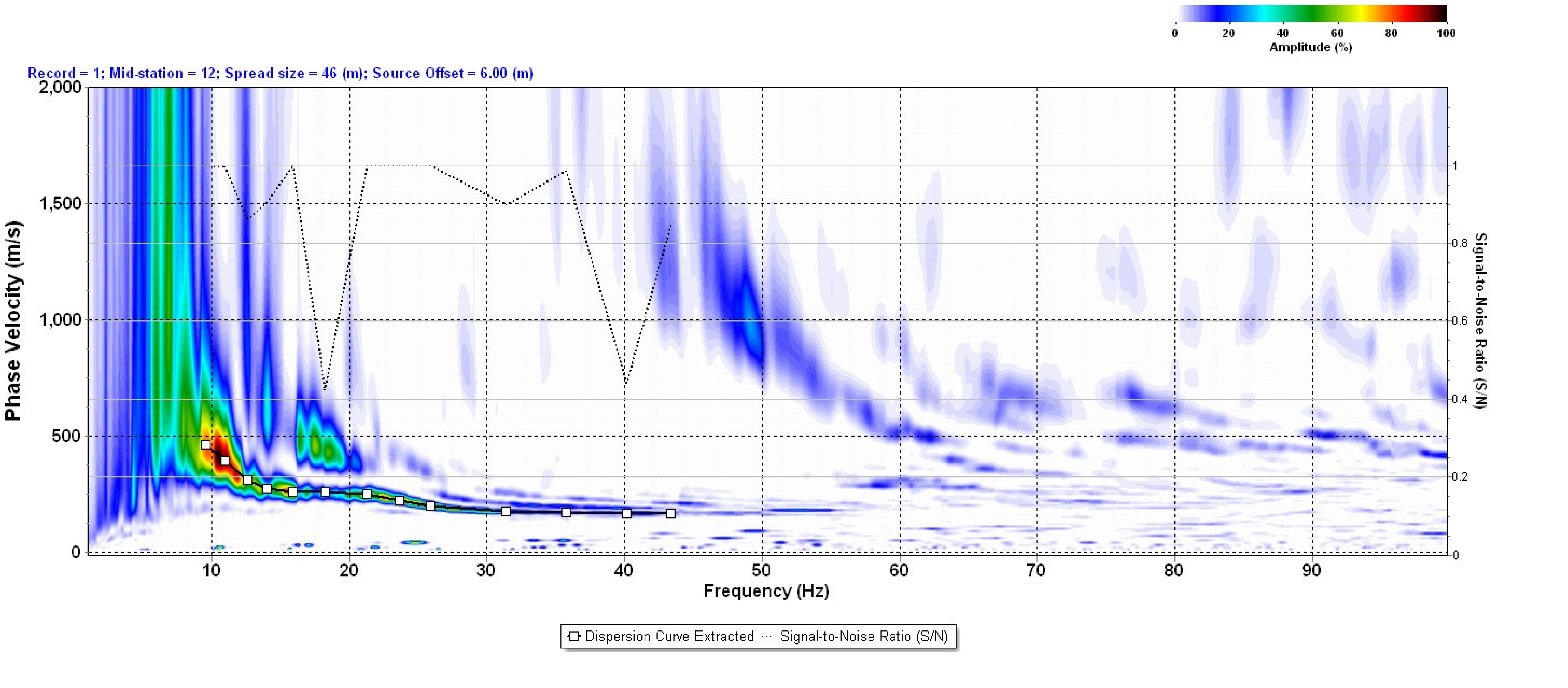

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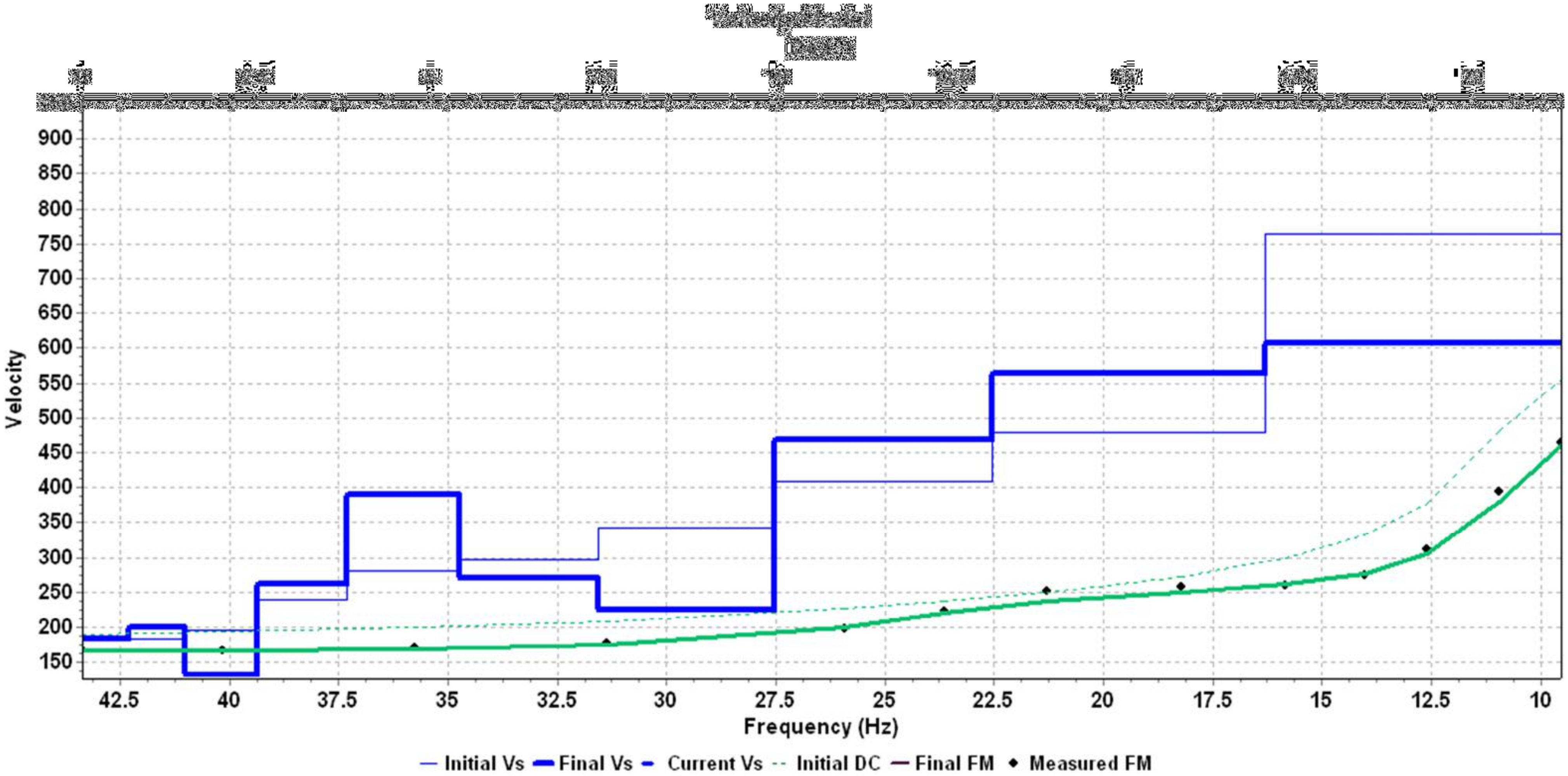

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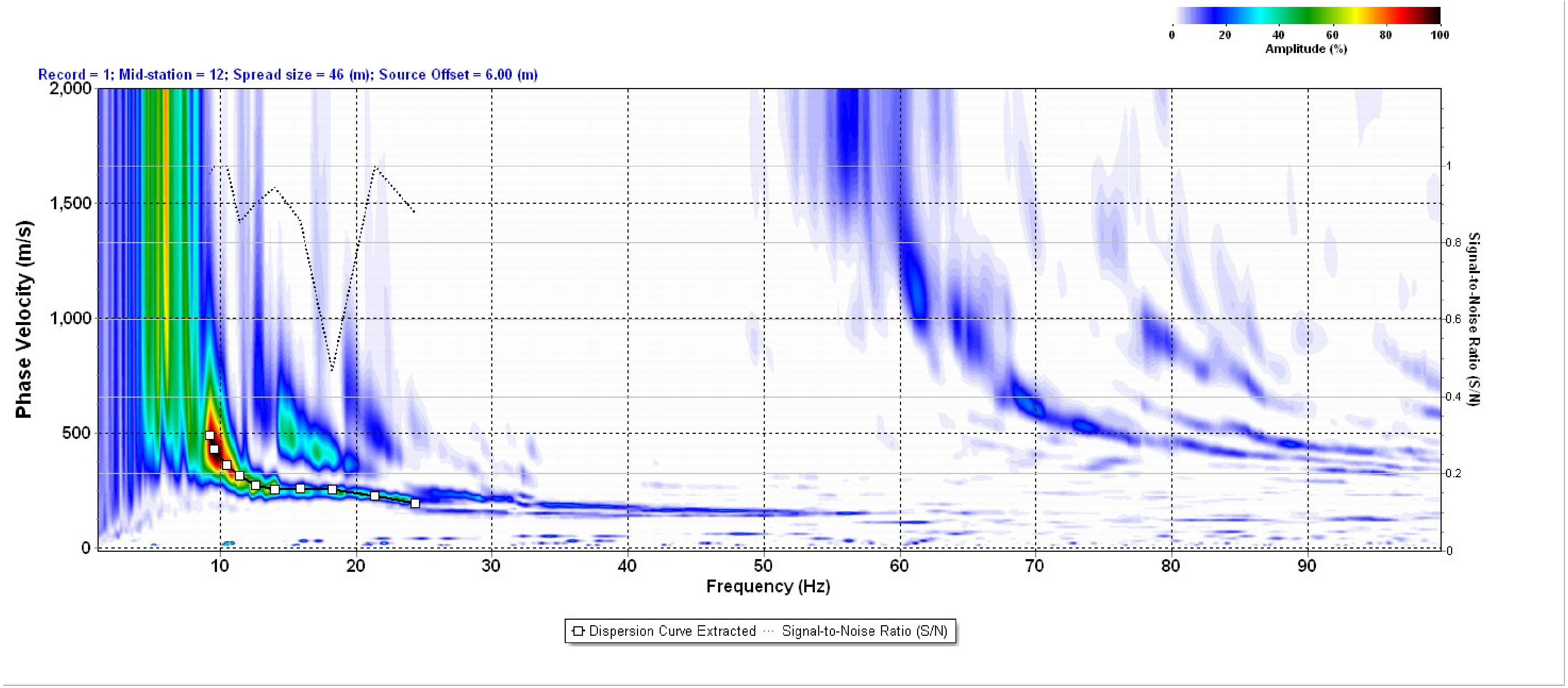

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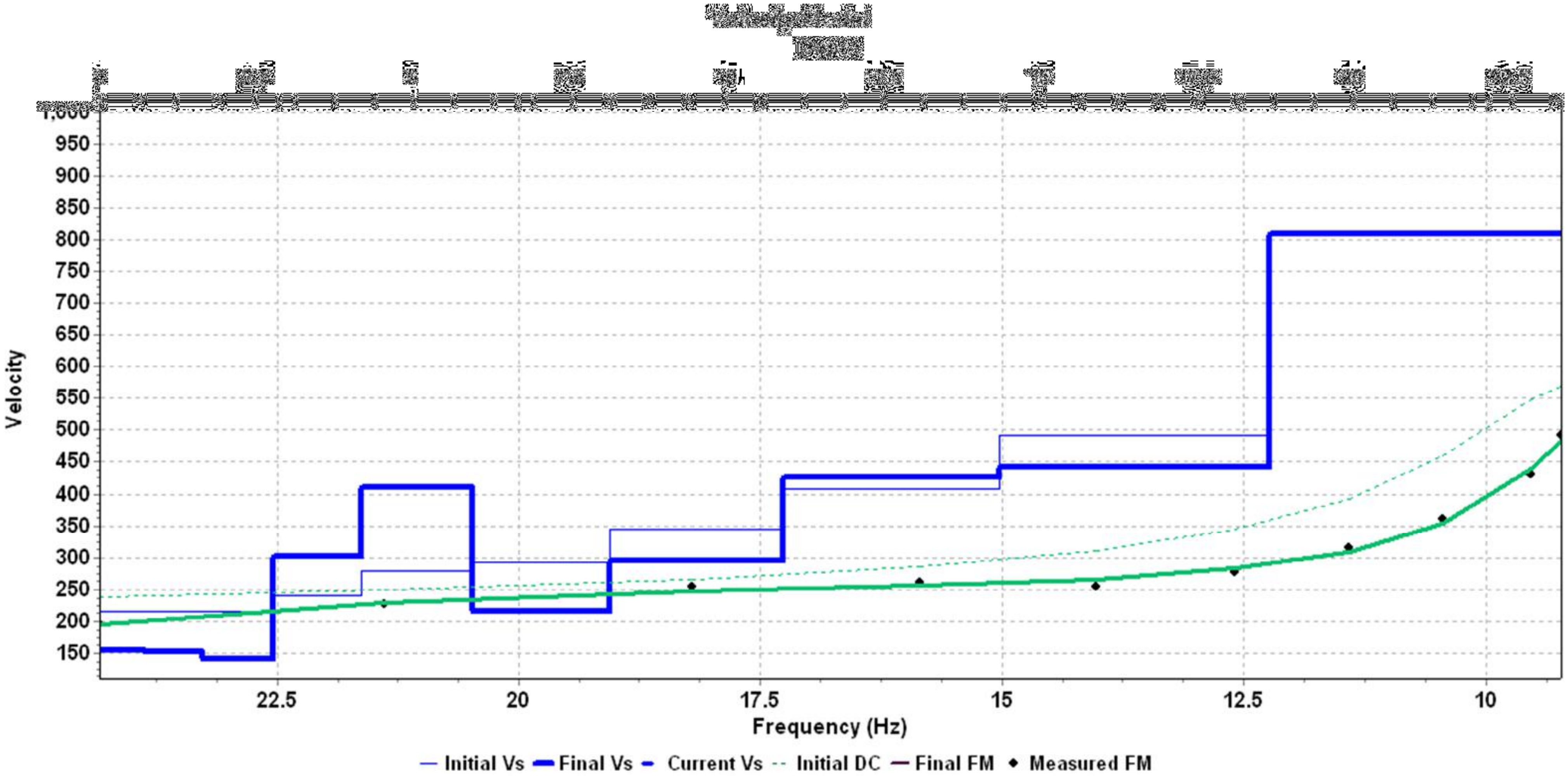

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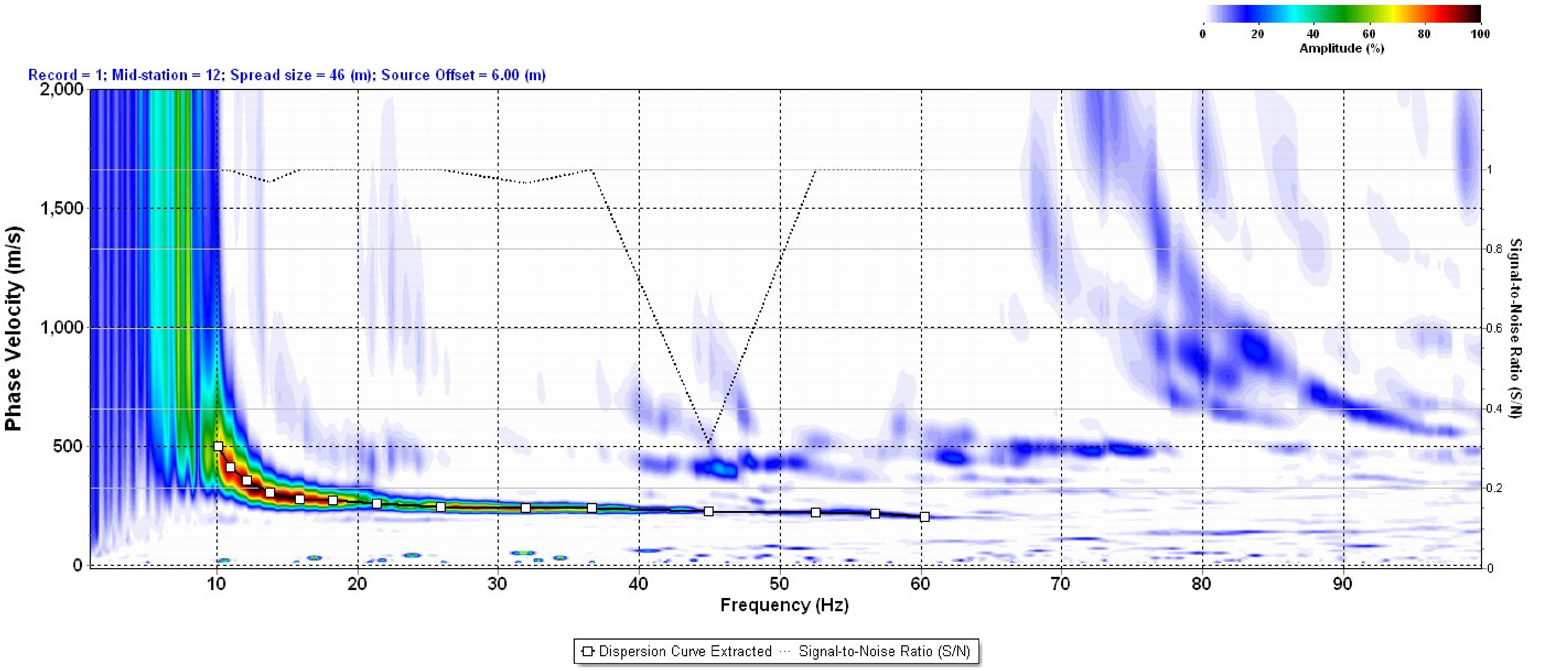

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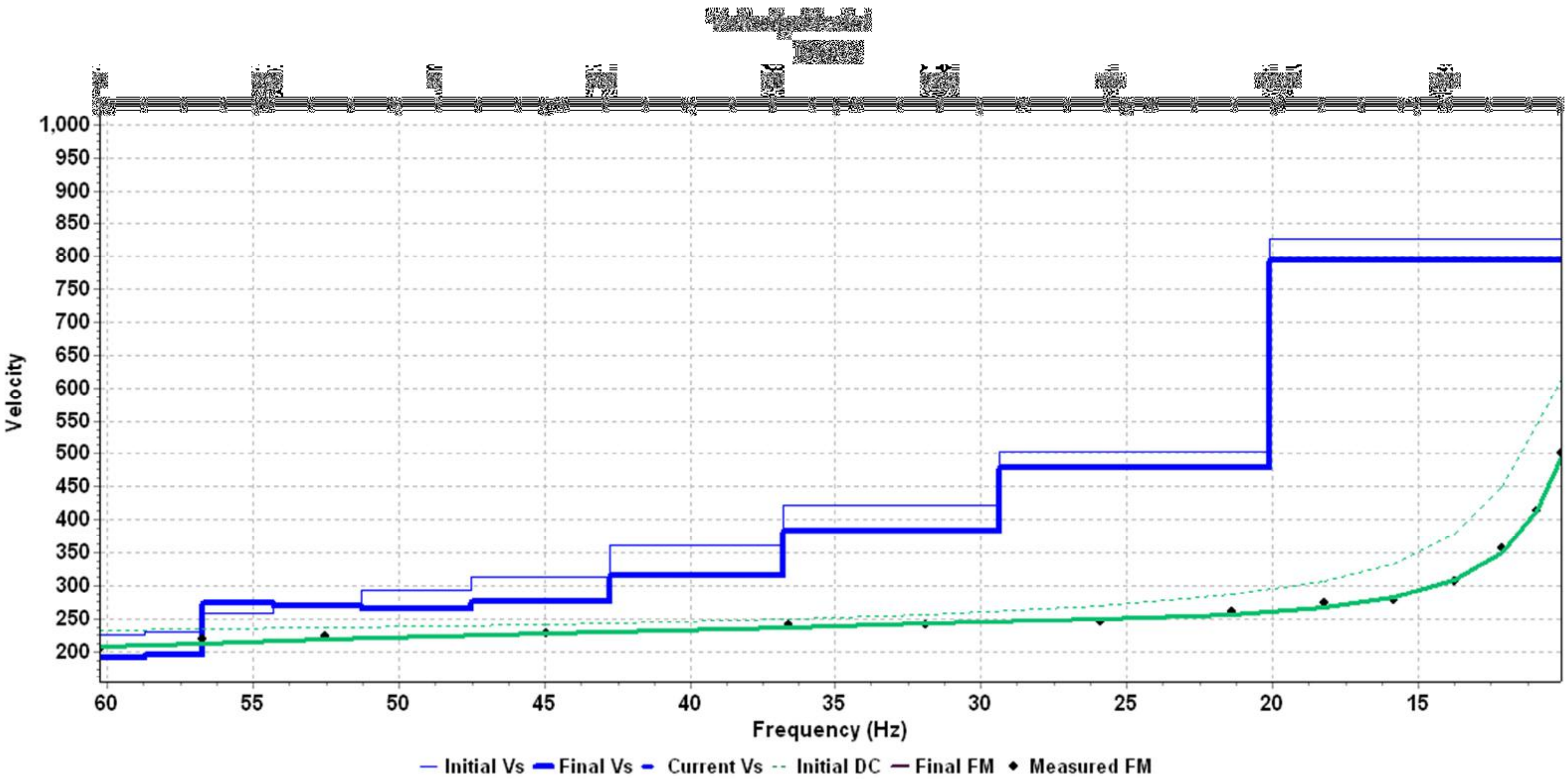
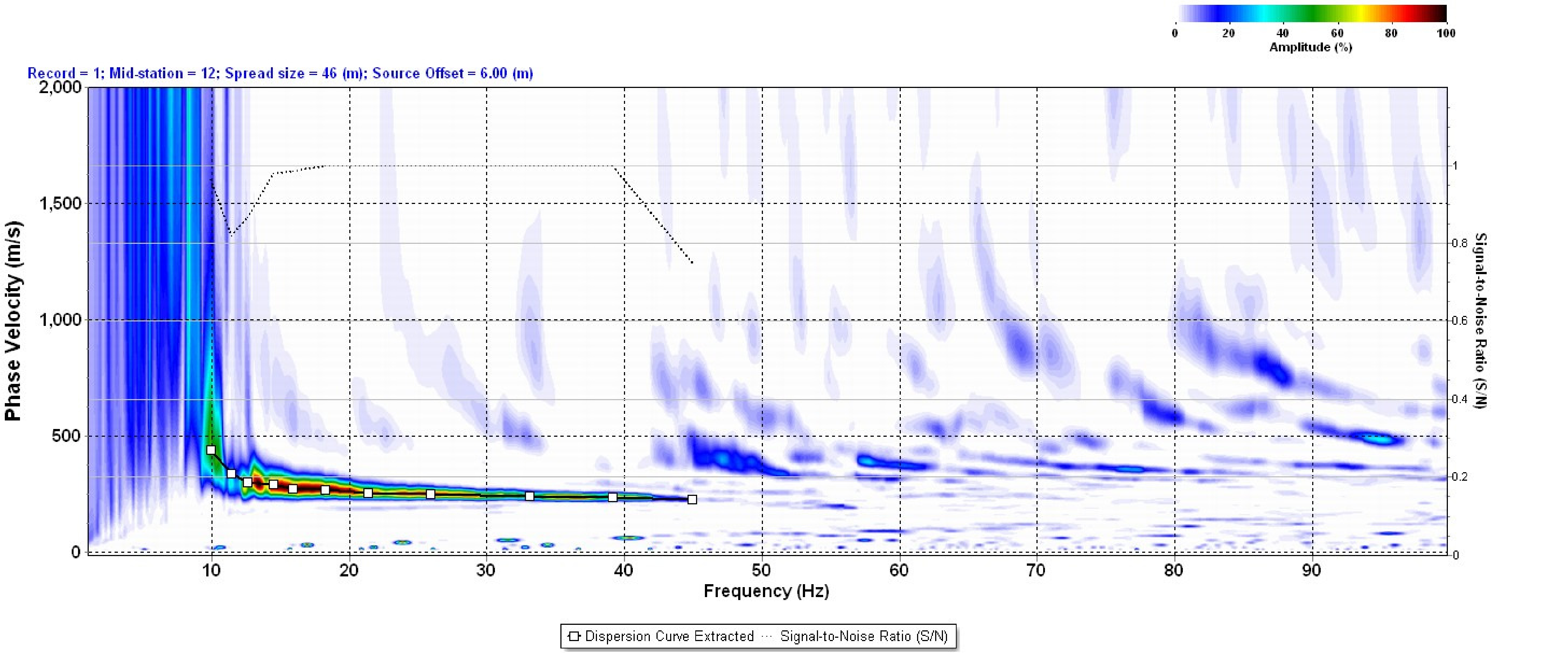


MI-12 Overtone Image



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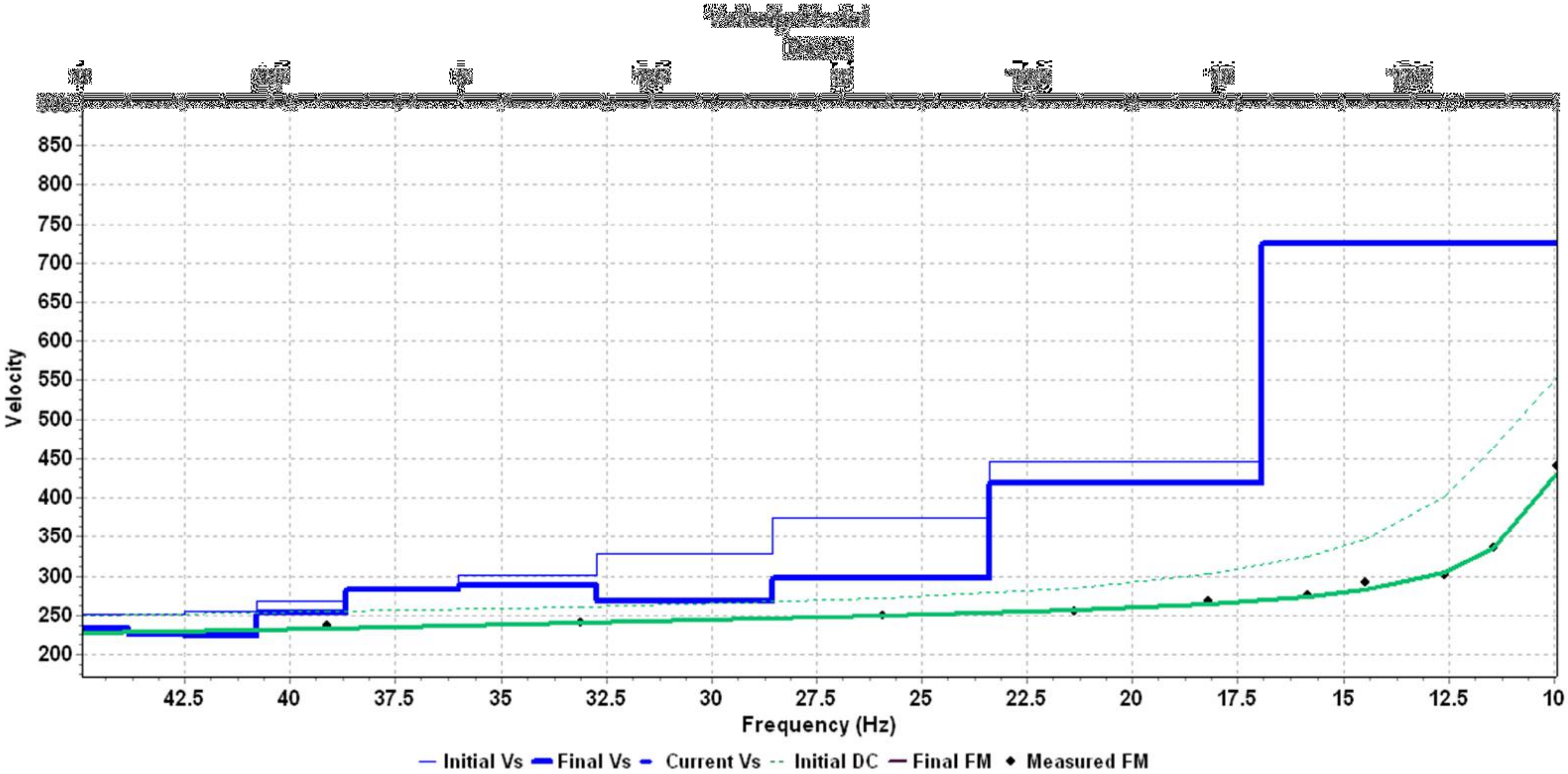

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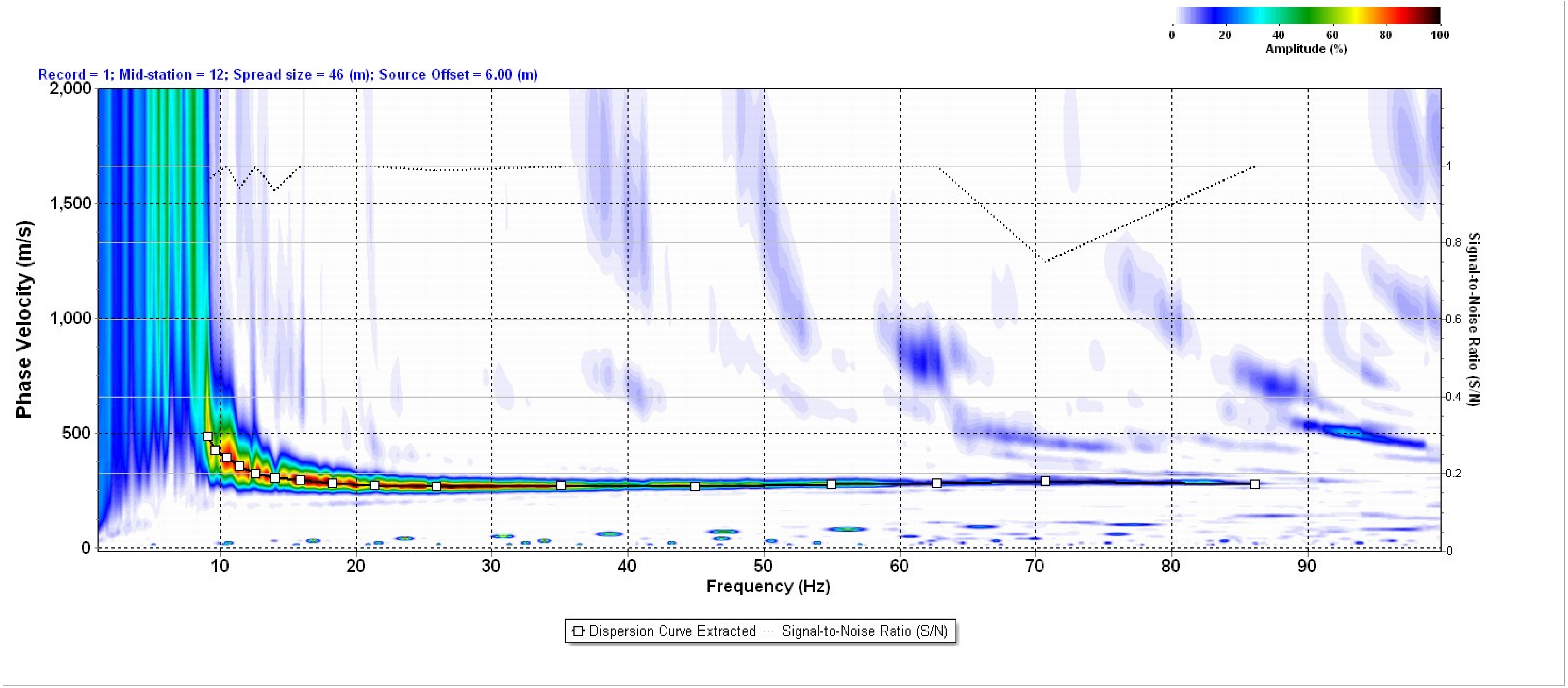

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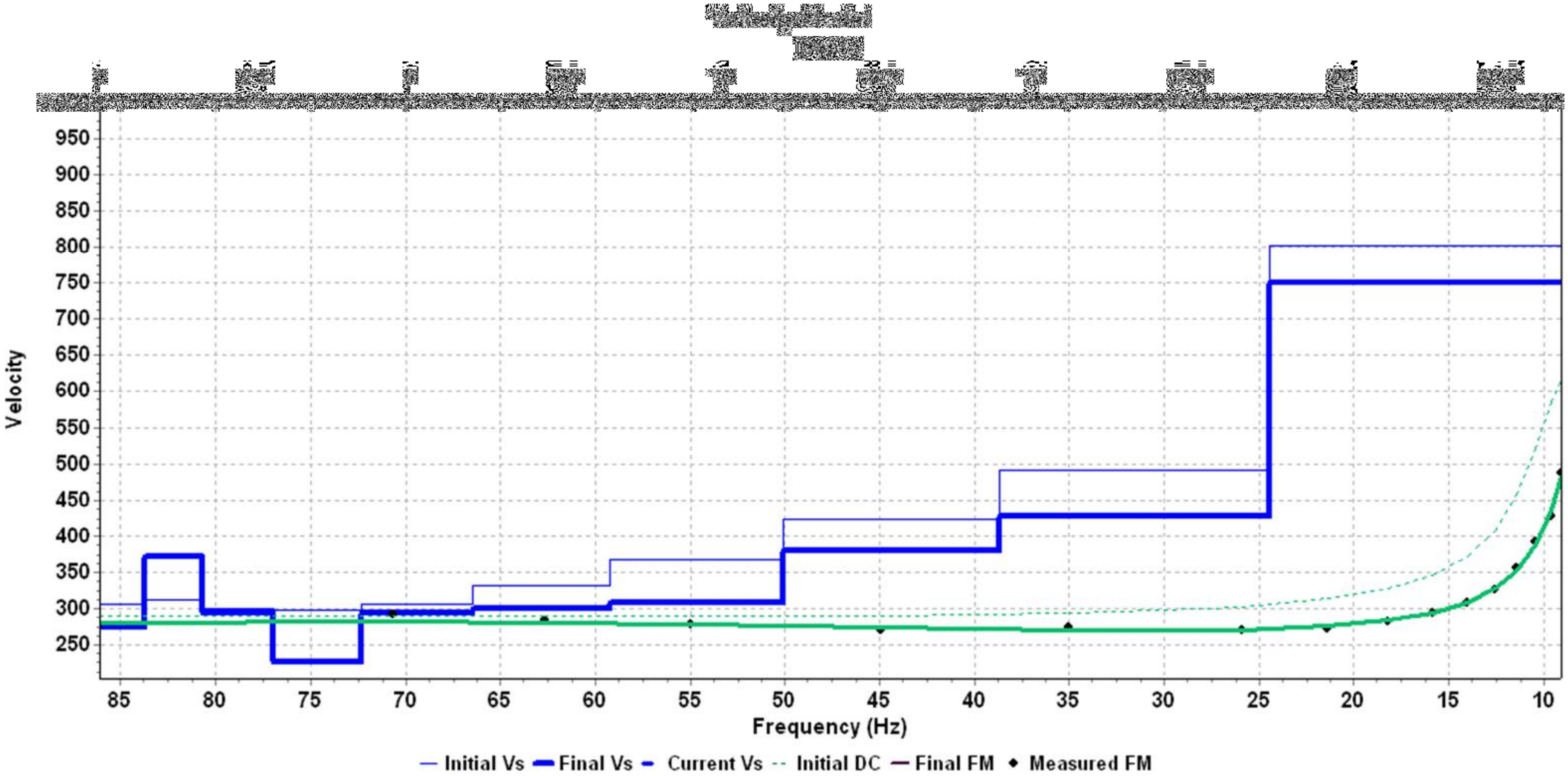

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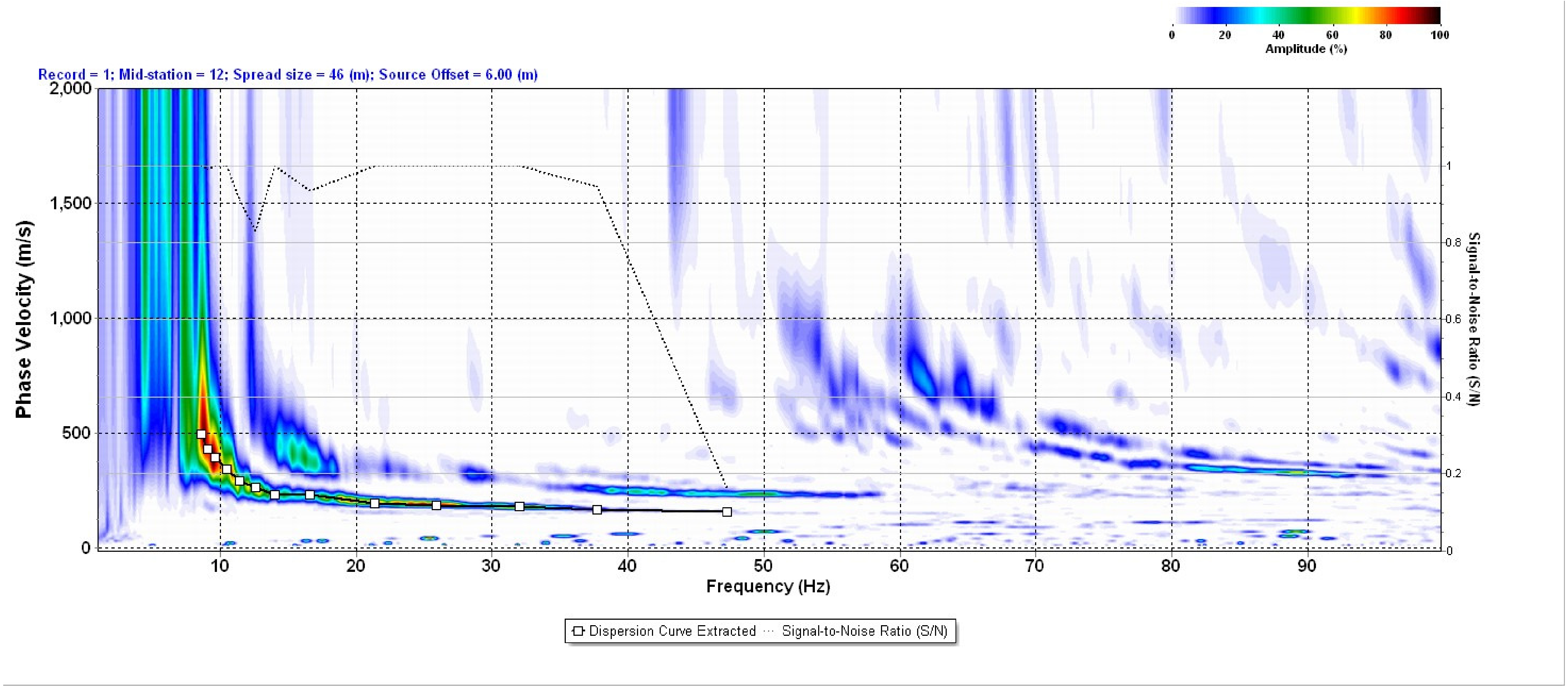

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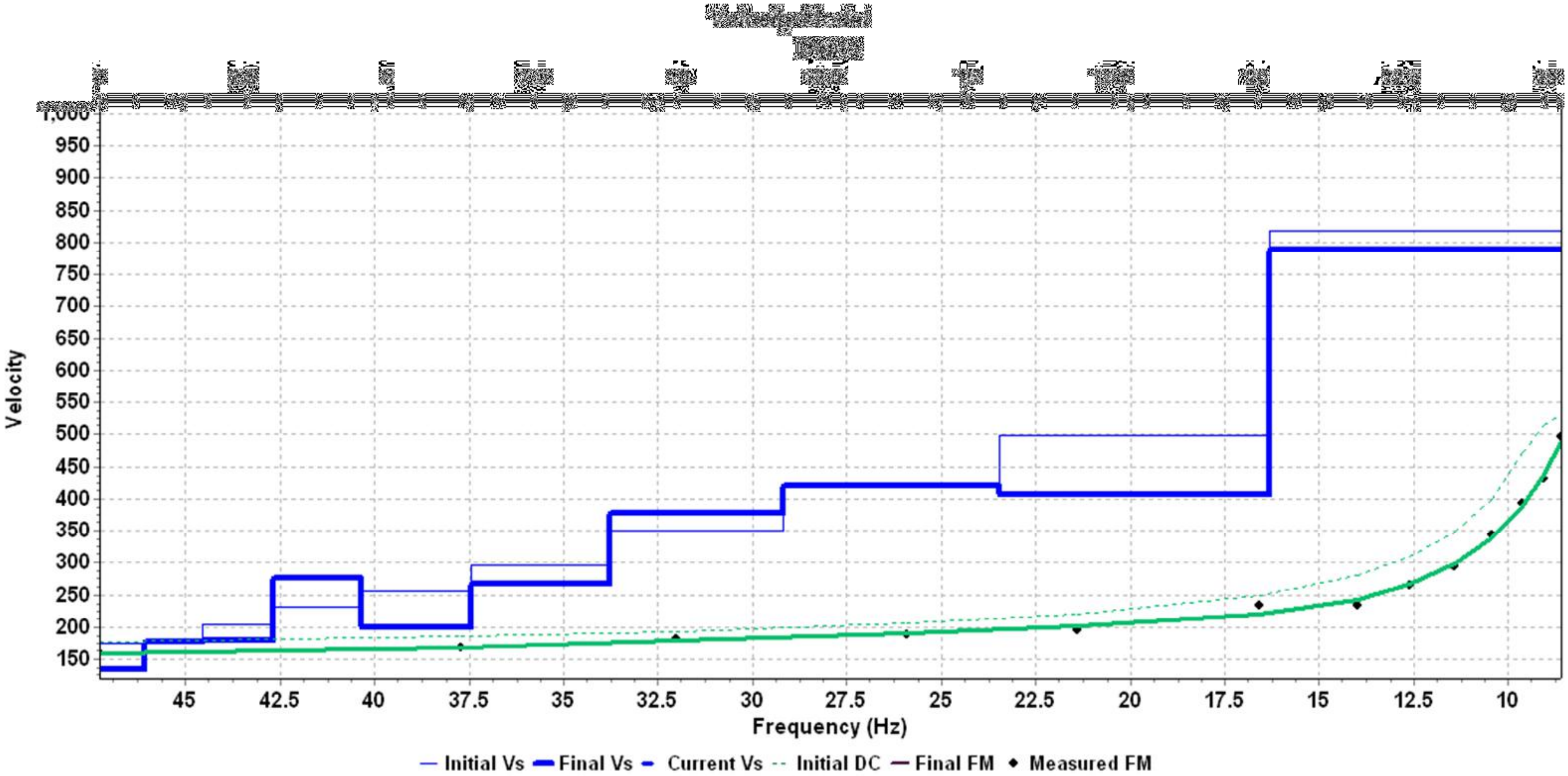

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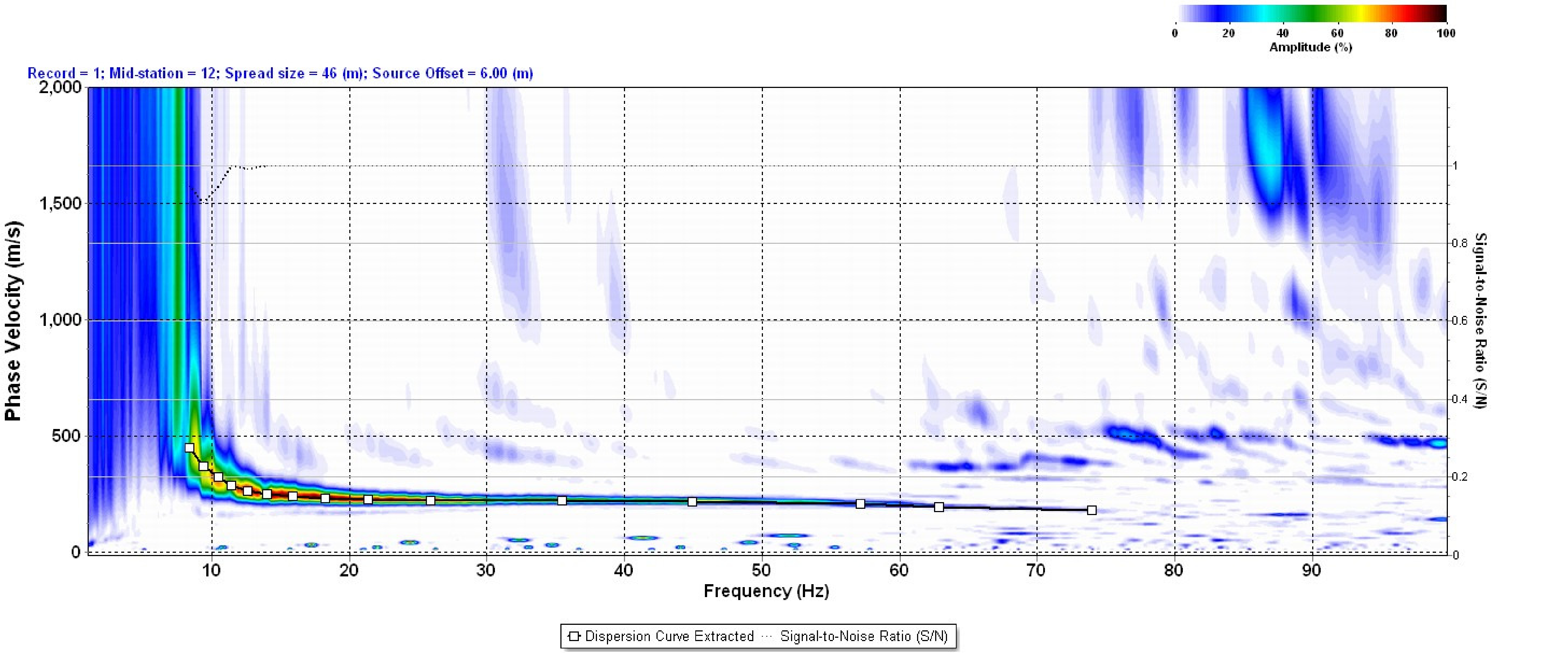

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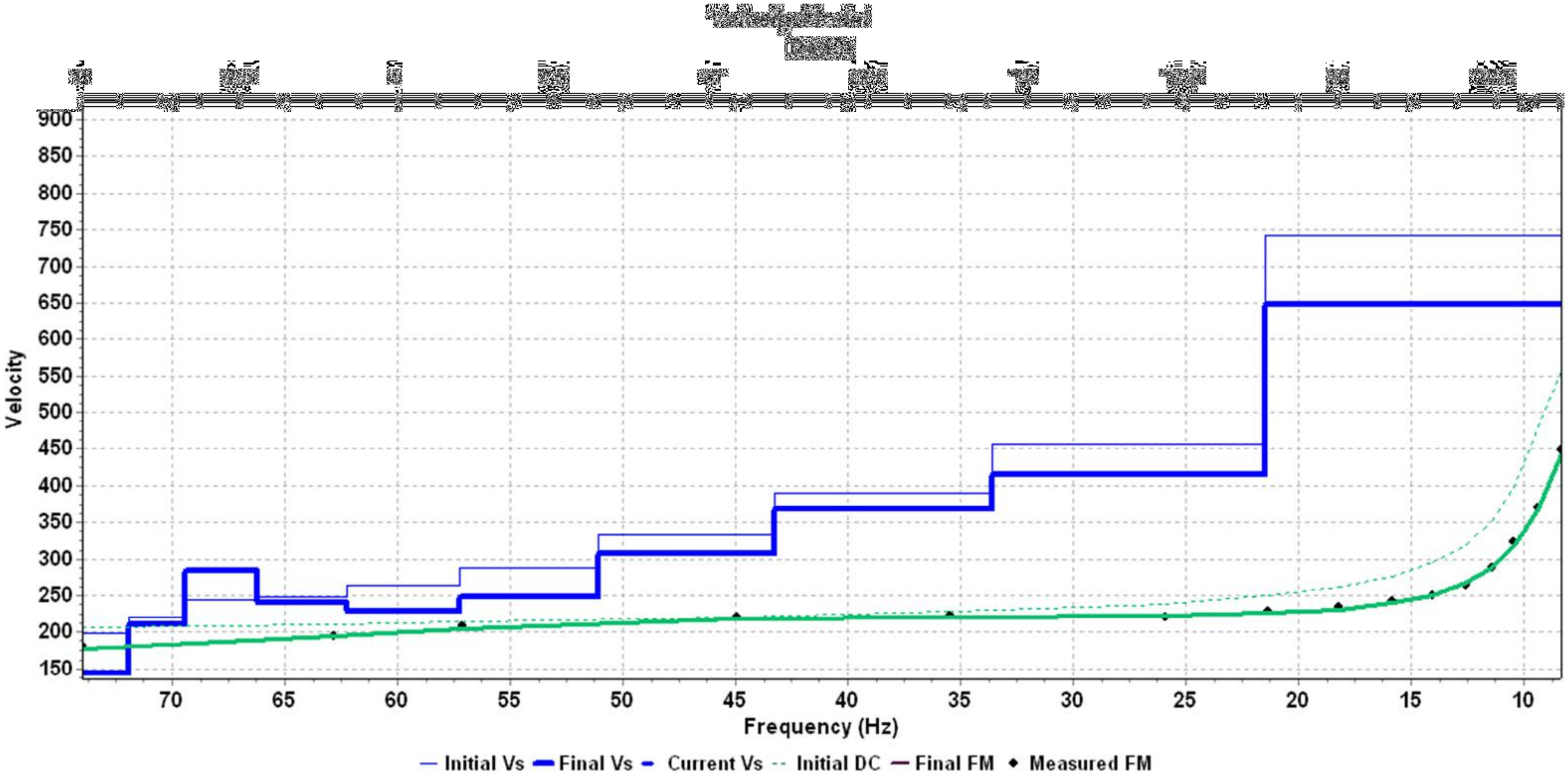

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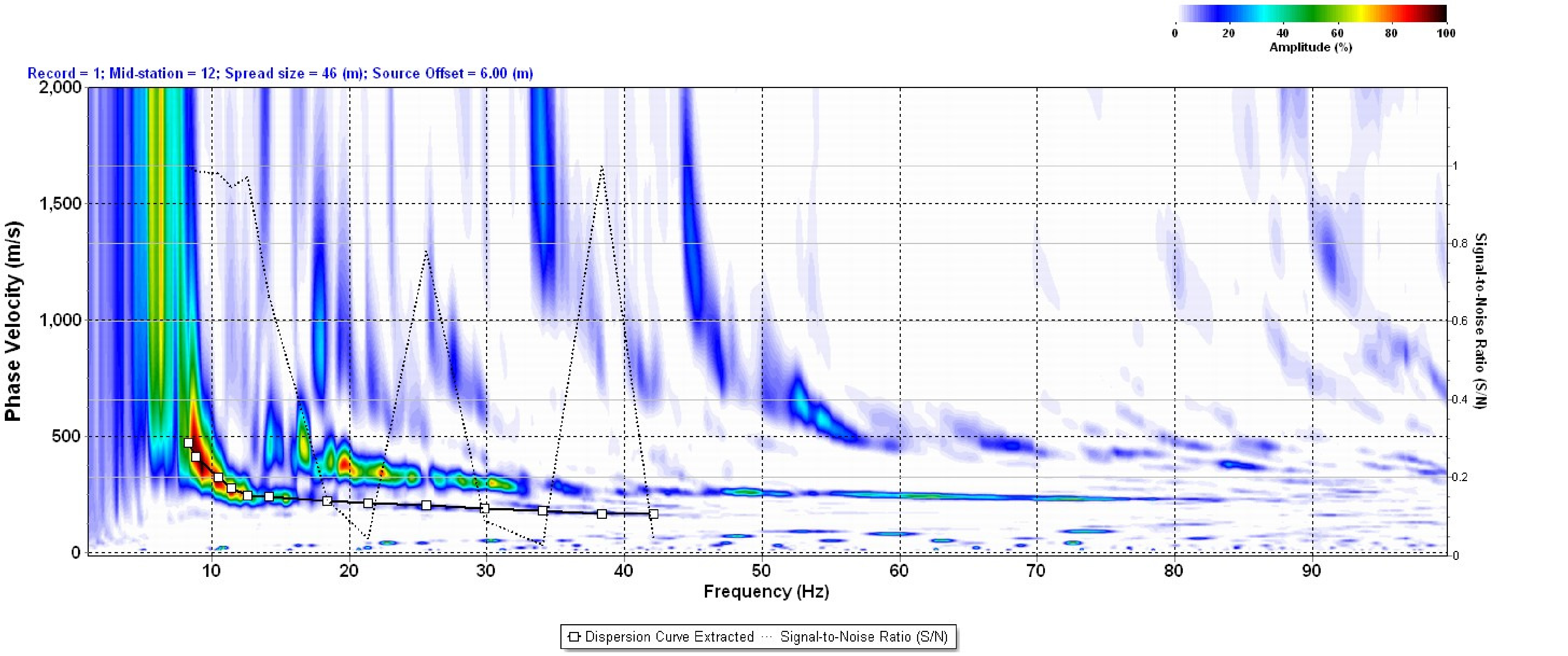

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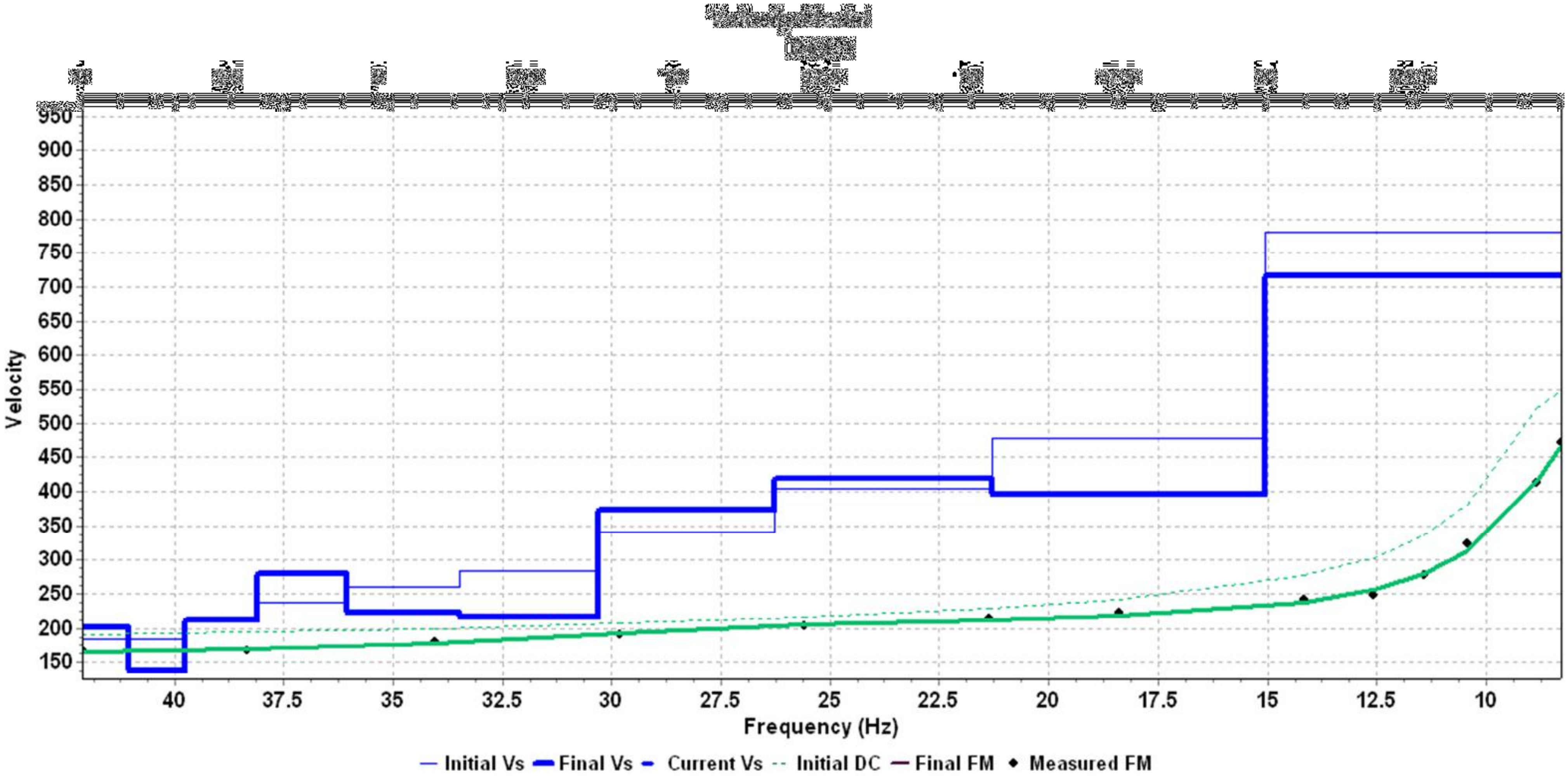

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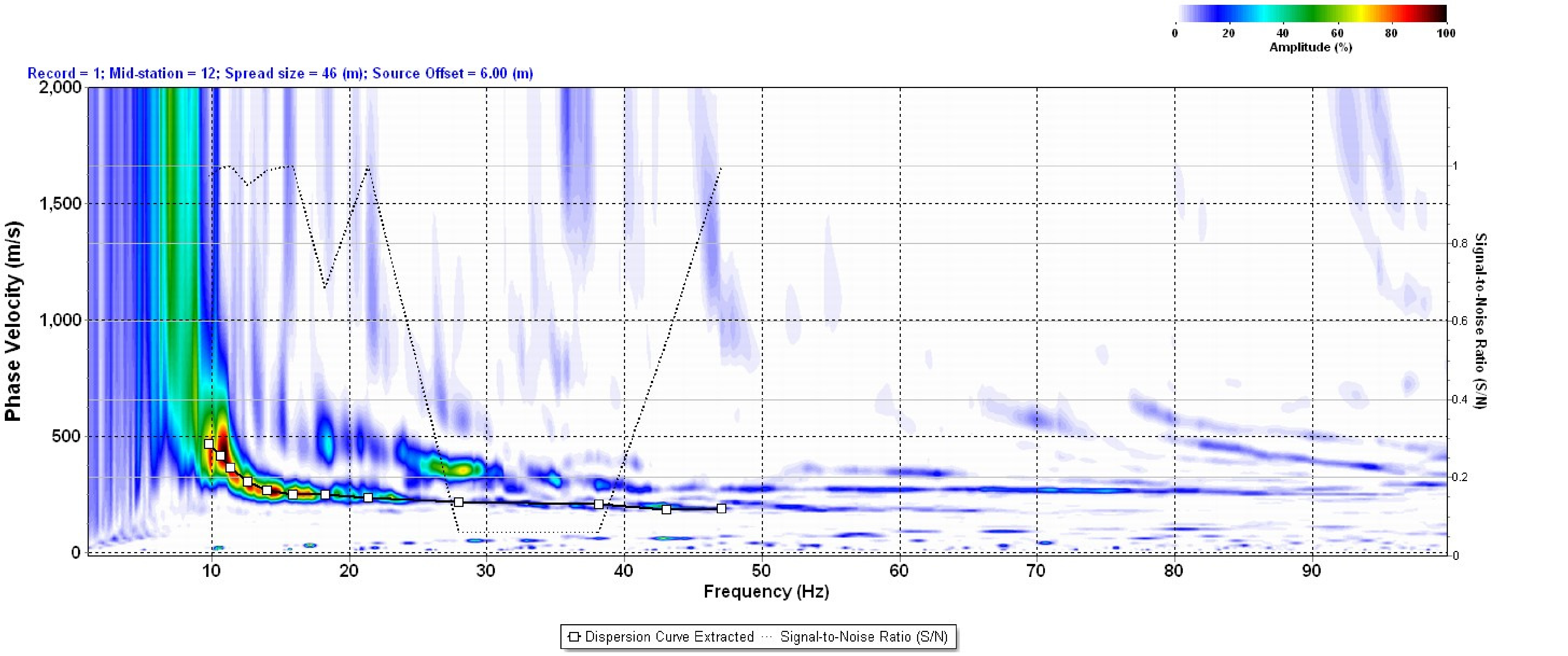

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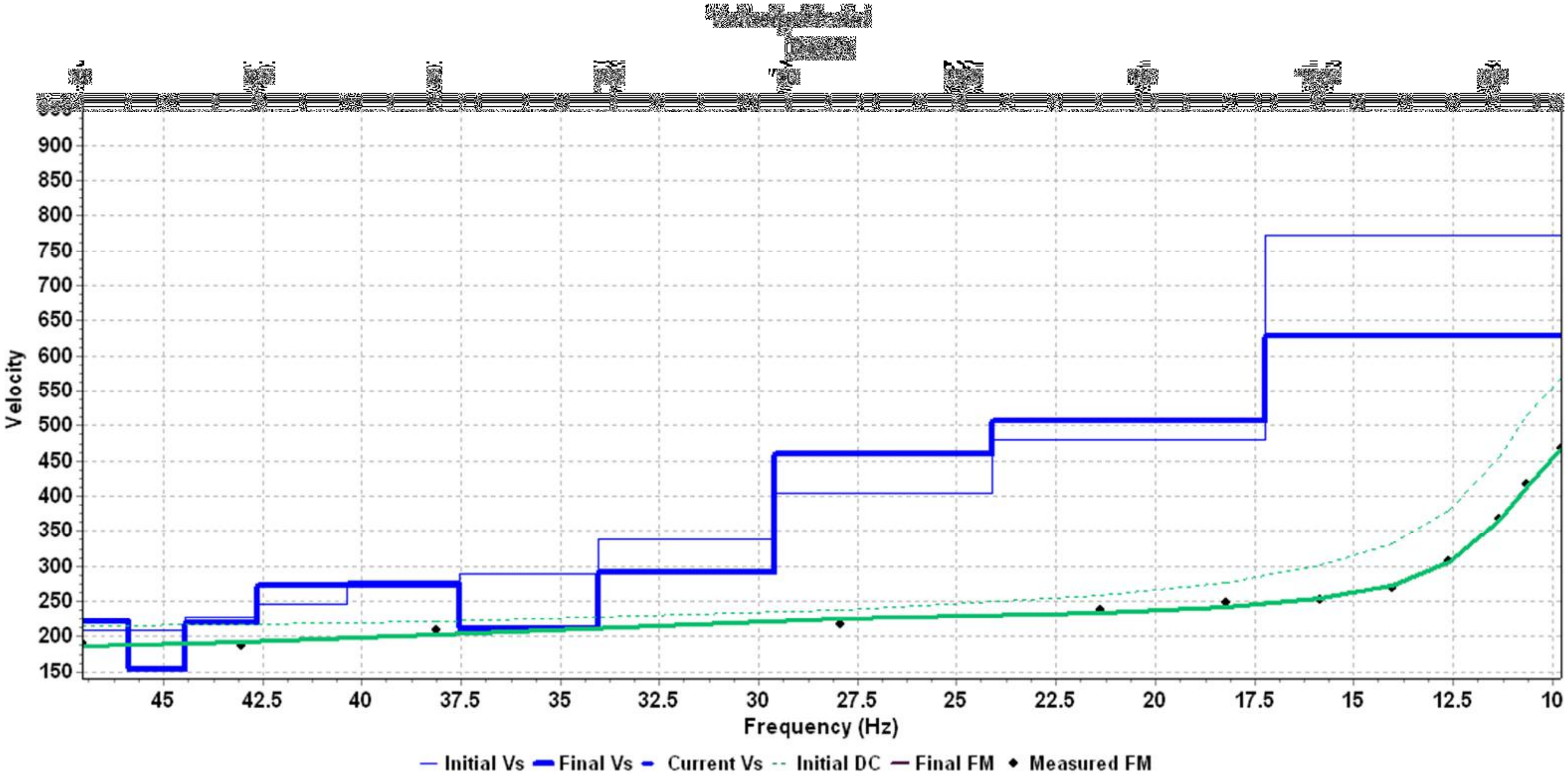

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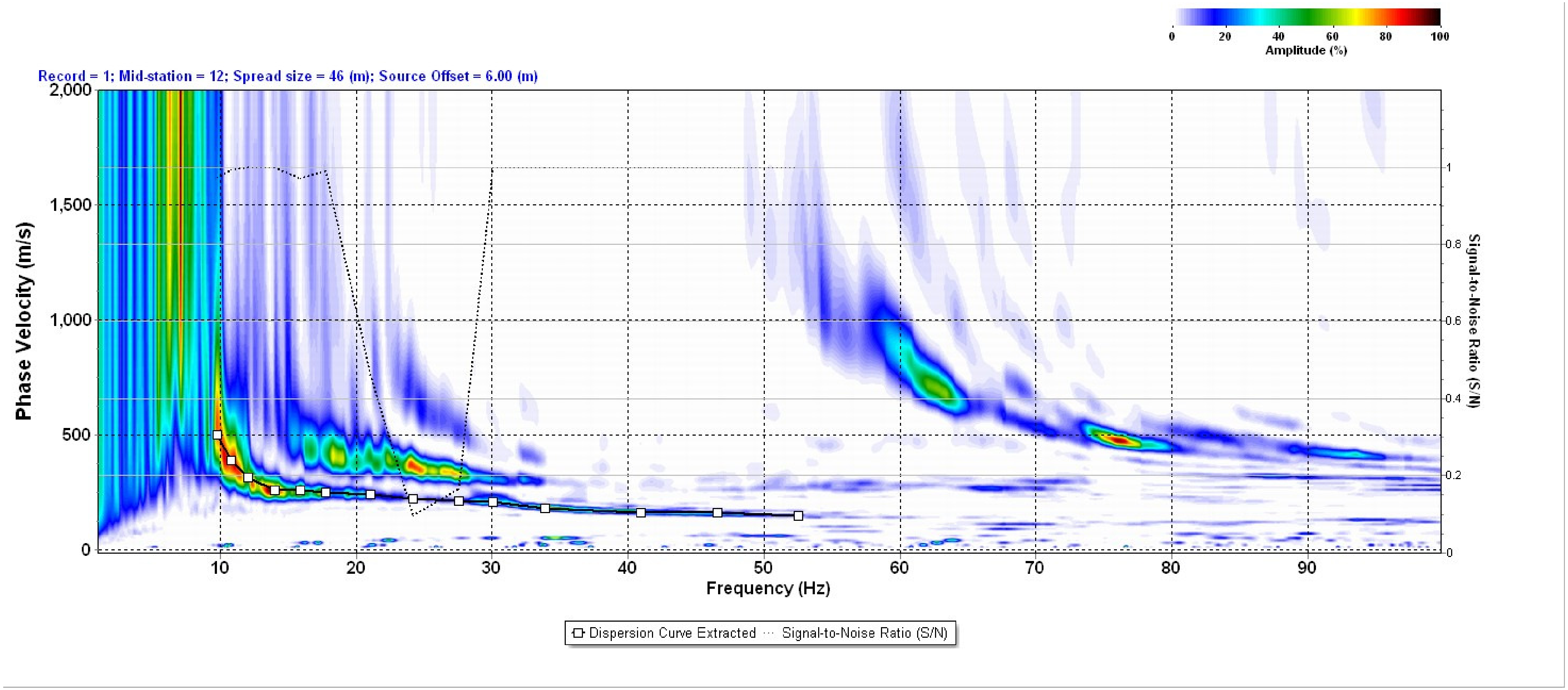

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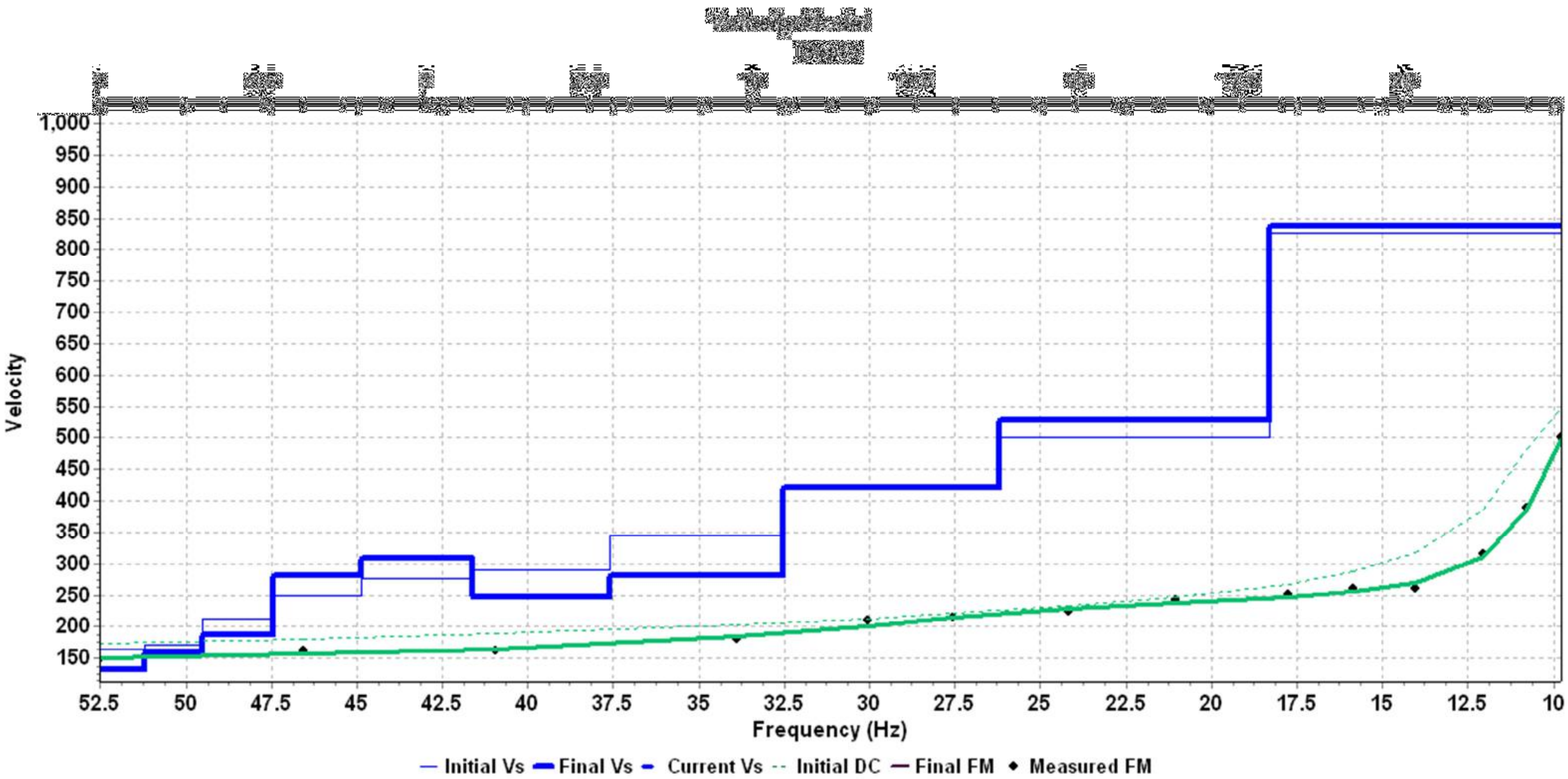

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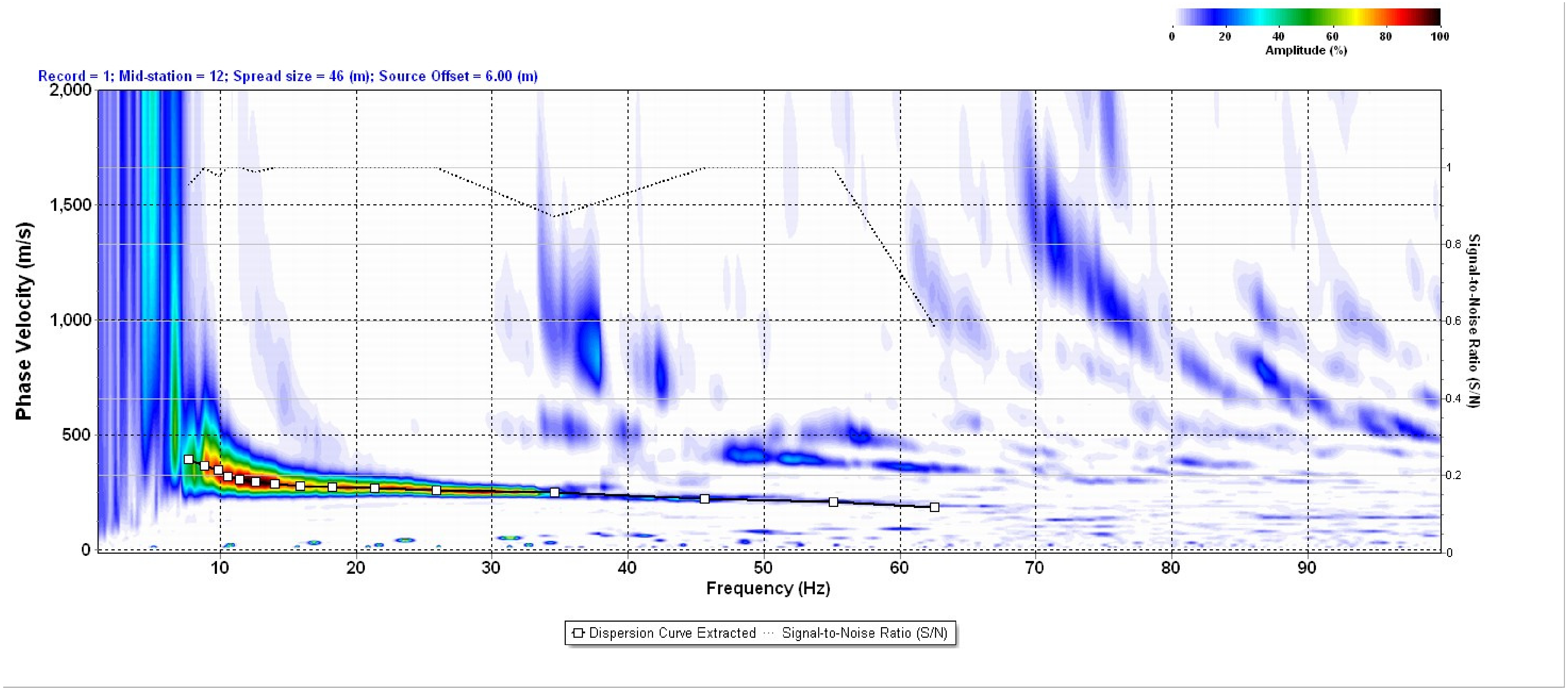

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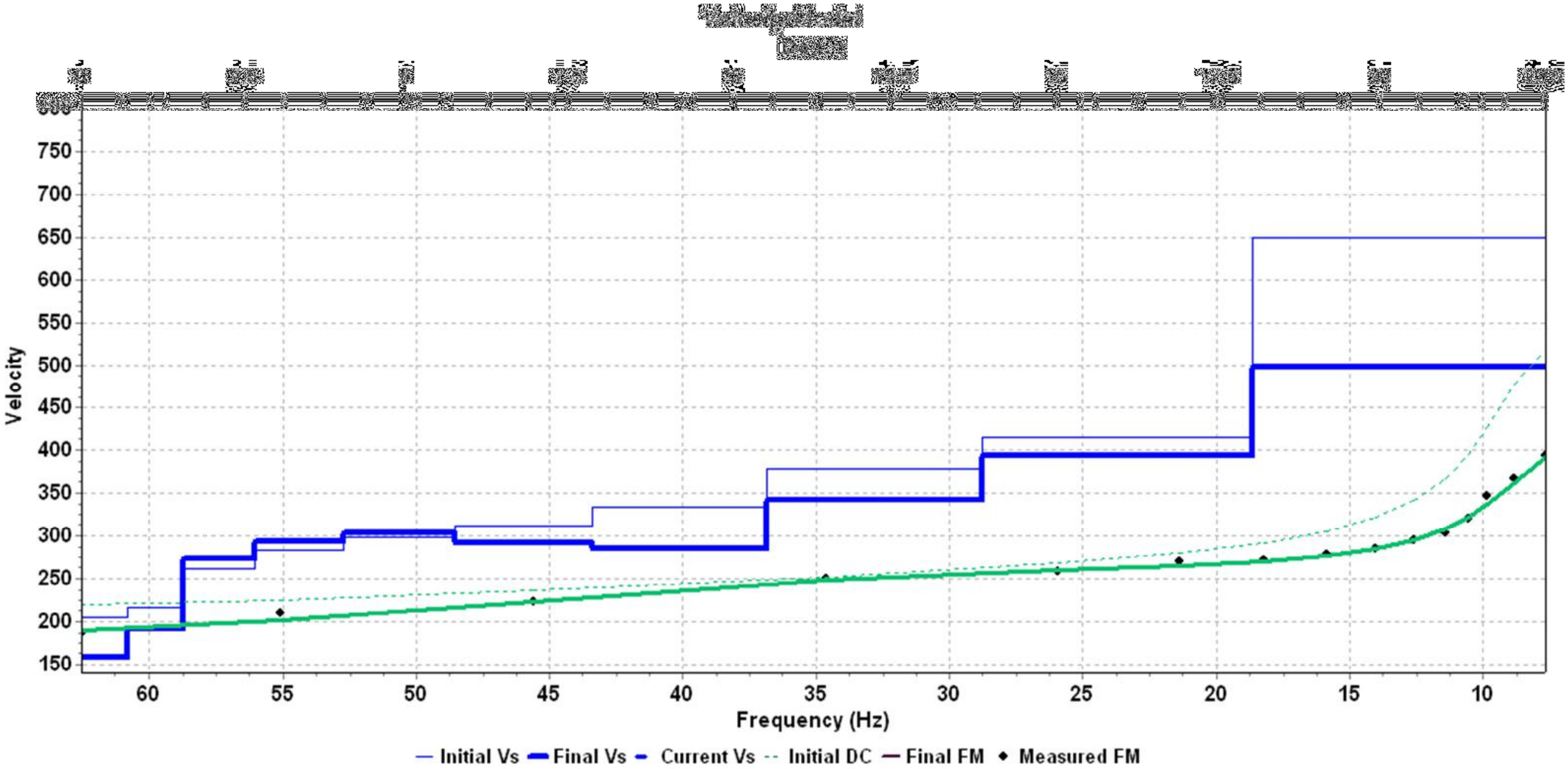

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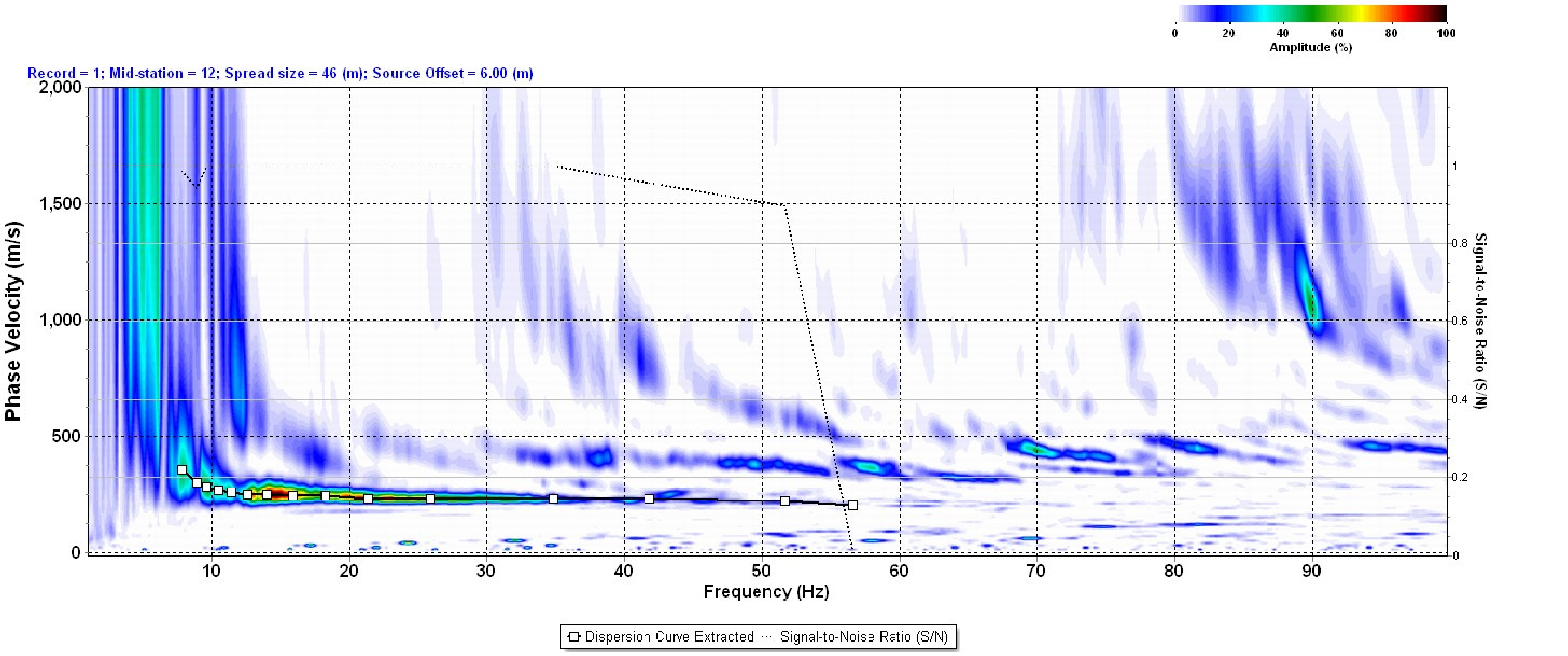

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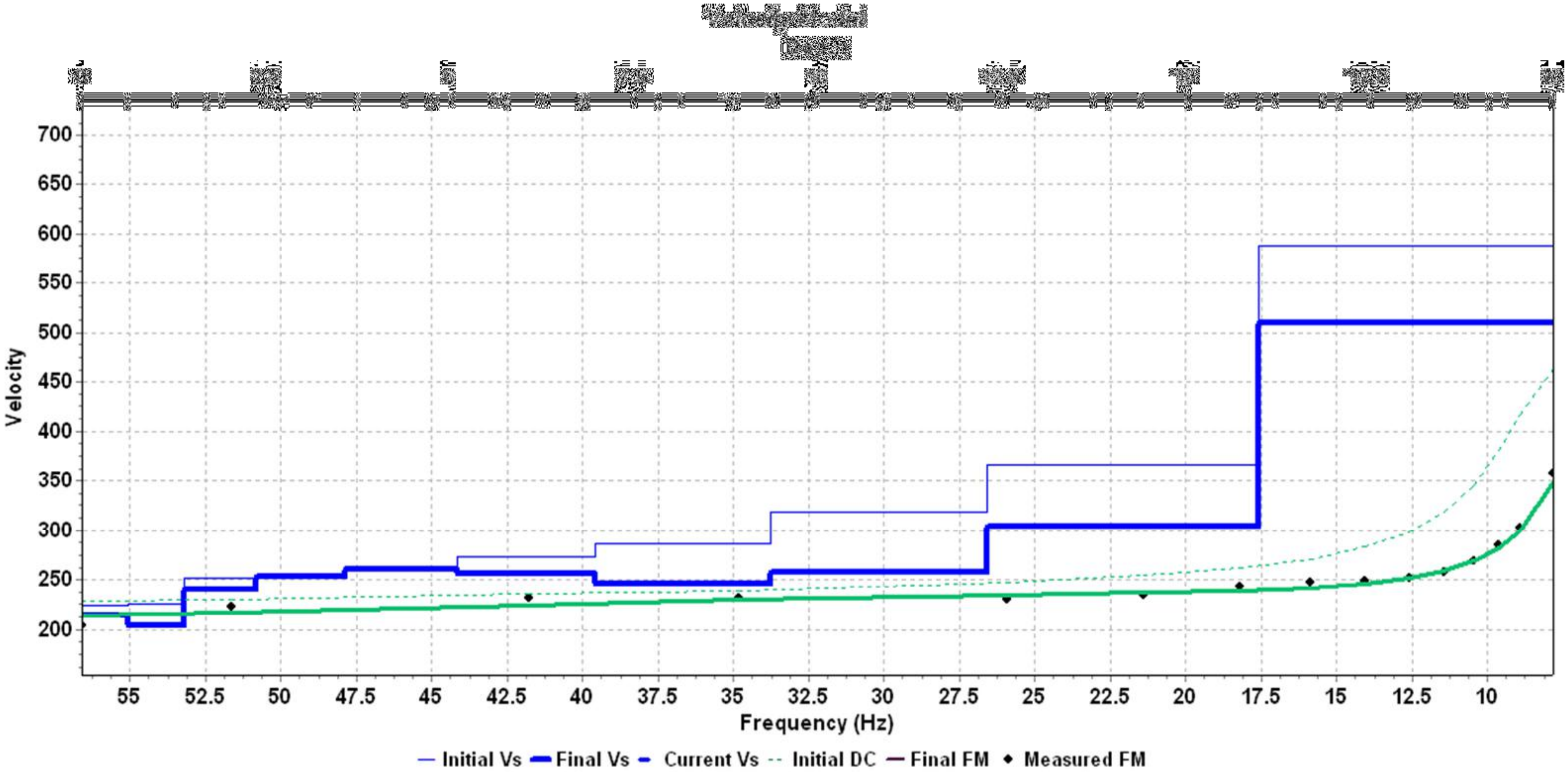

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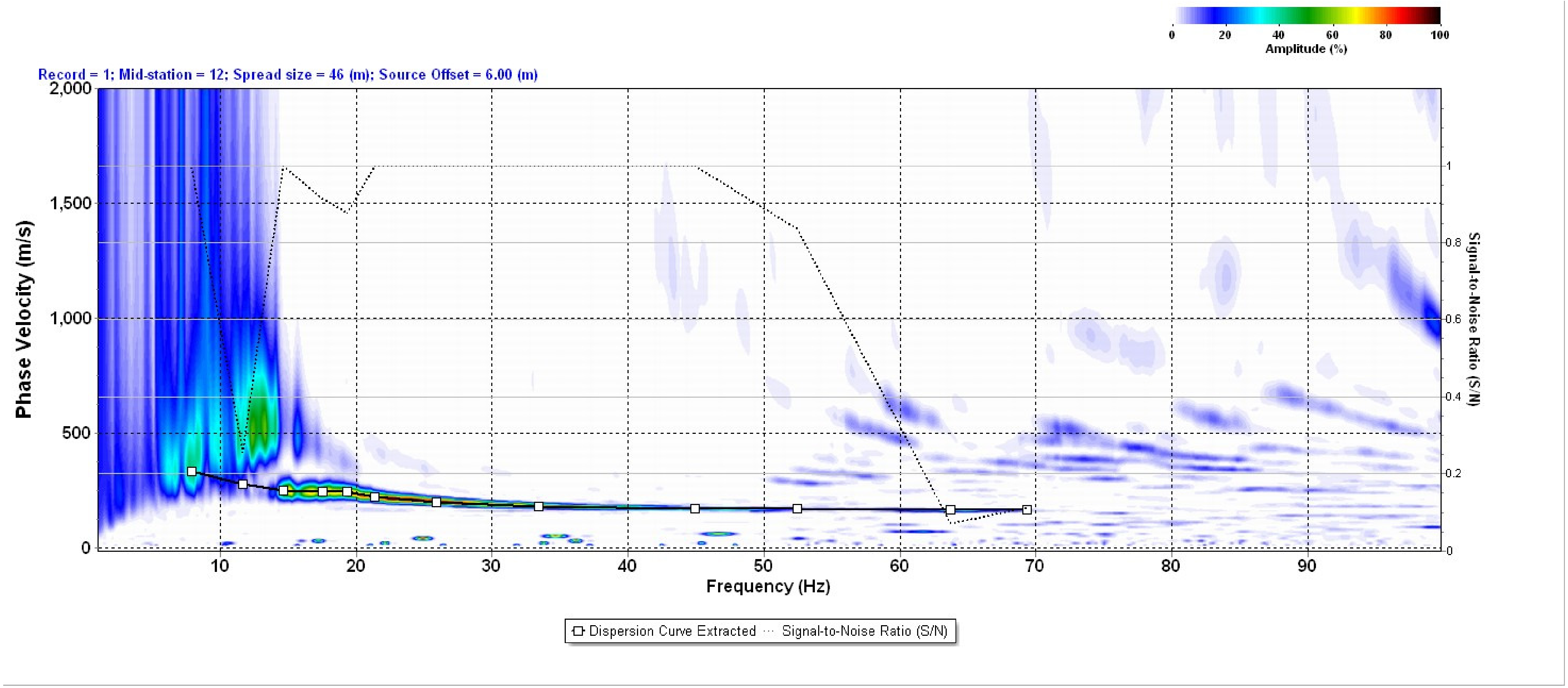

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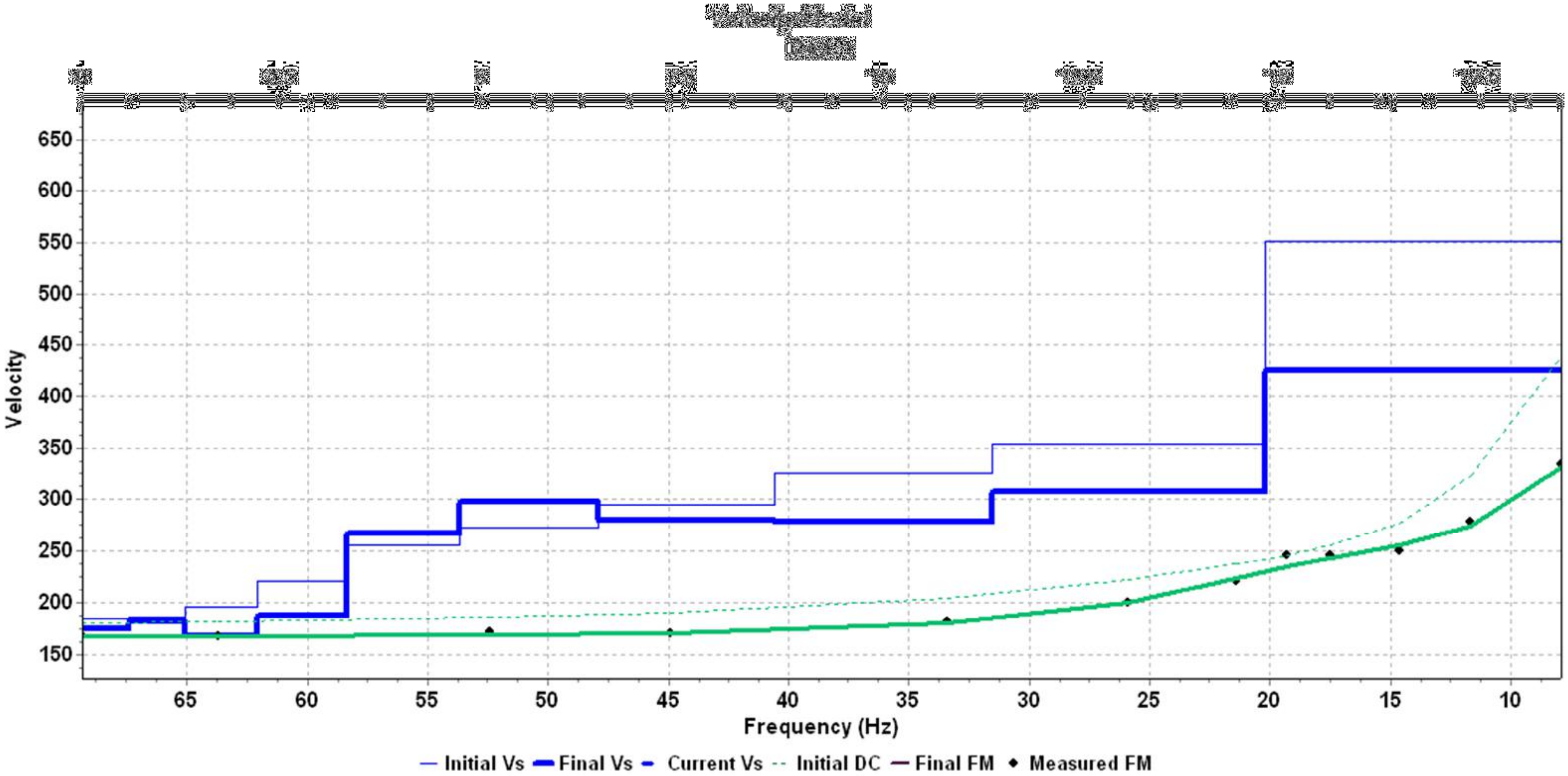

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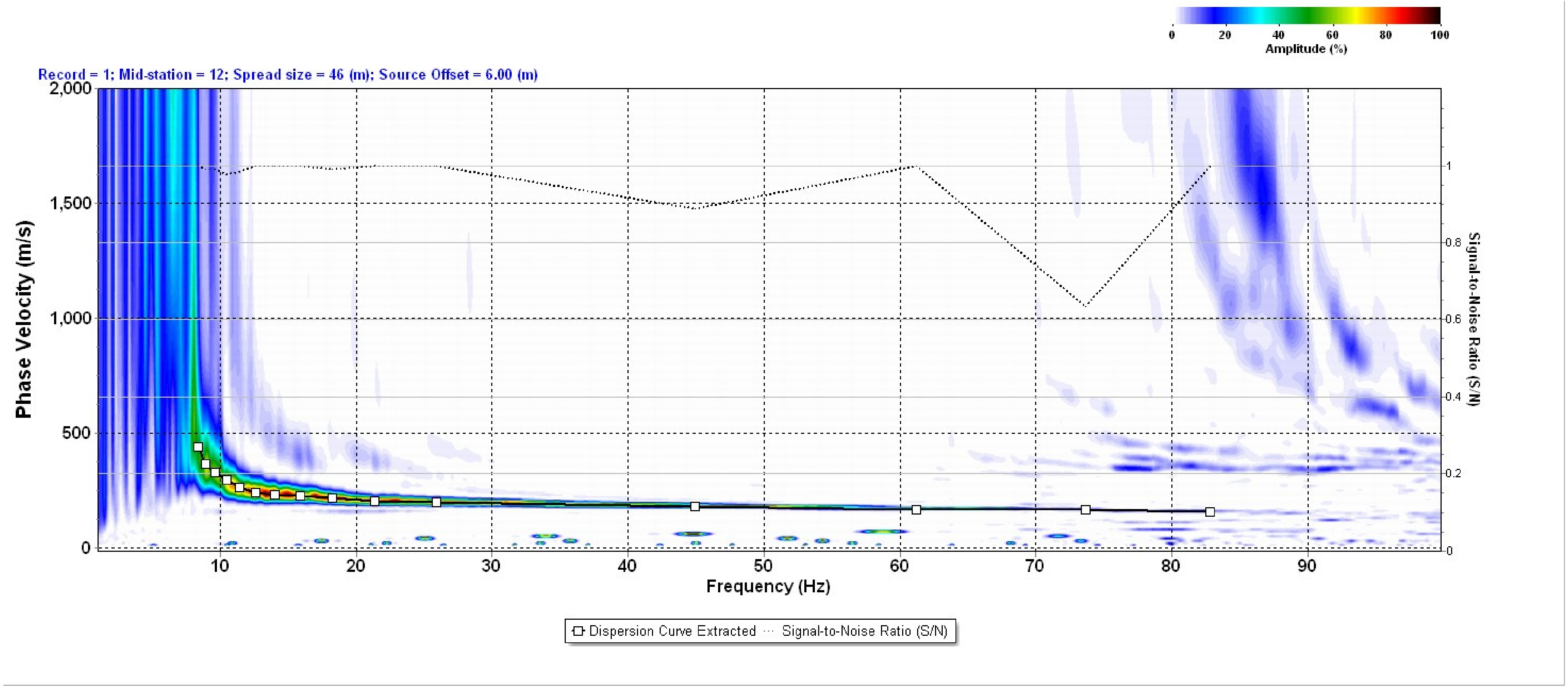

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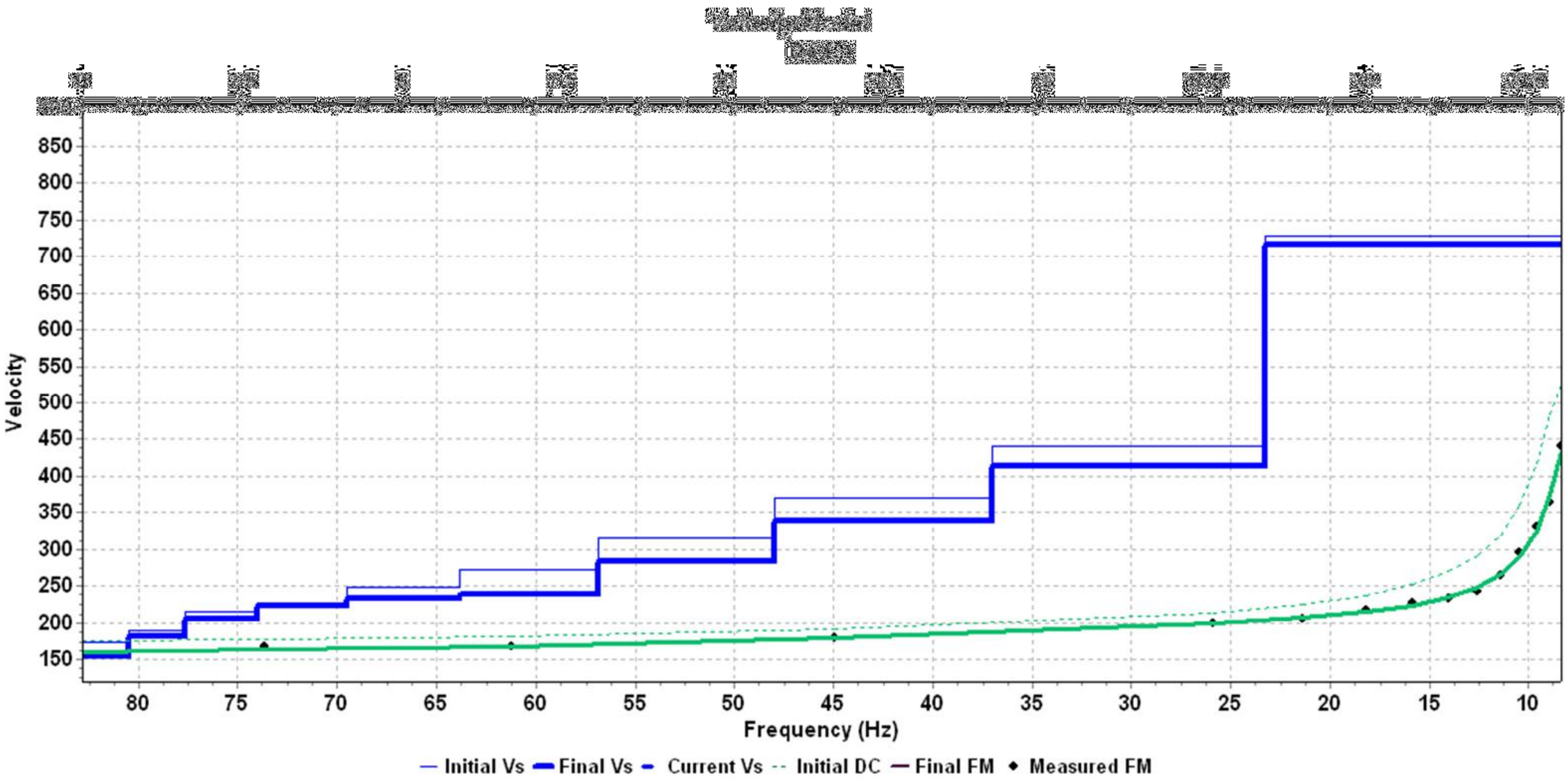

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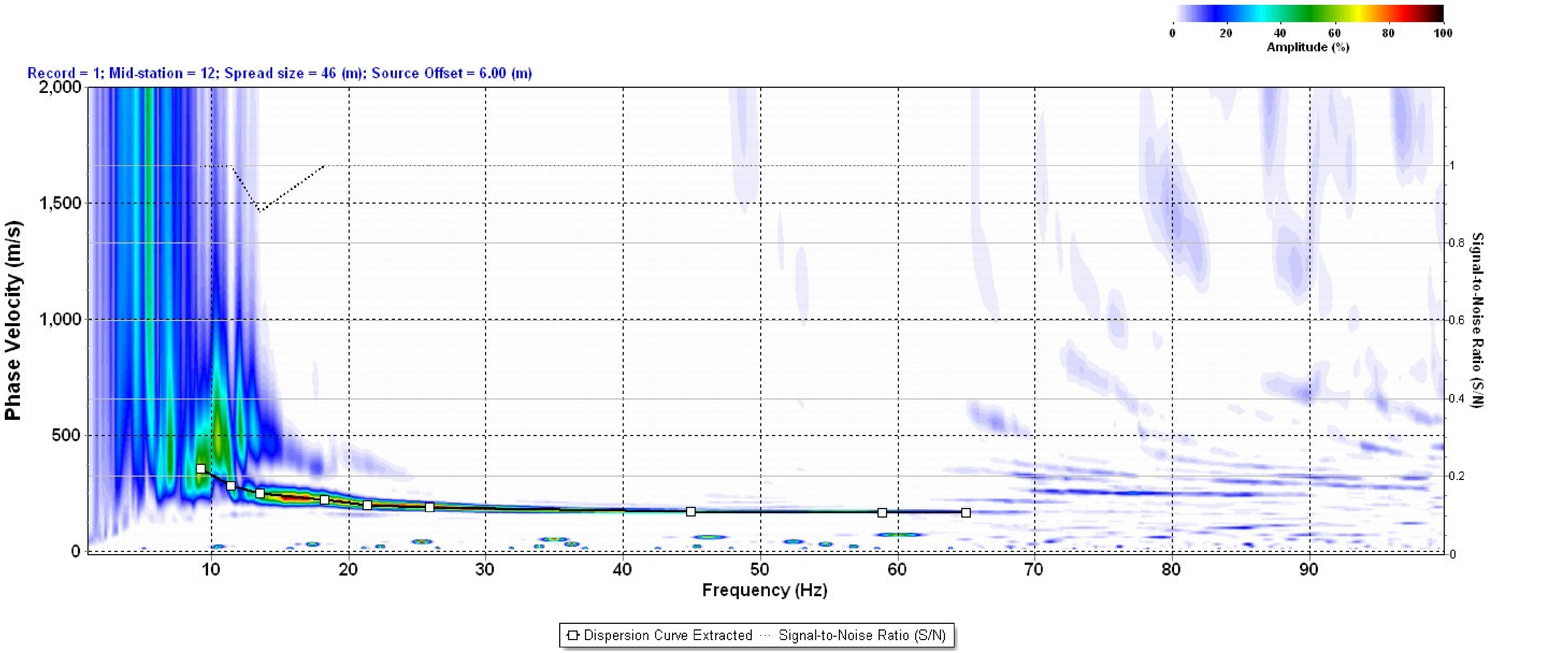

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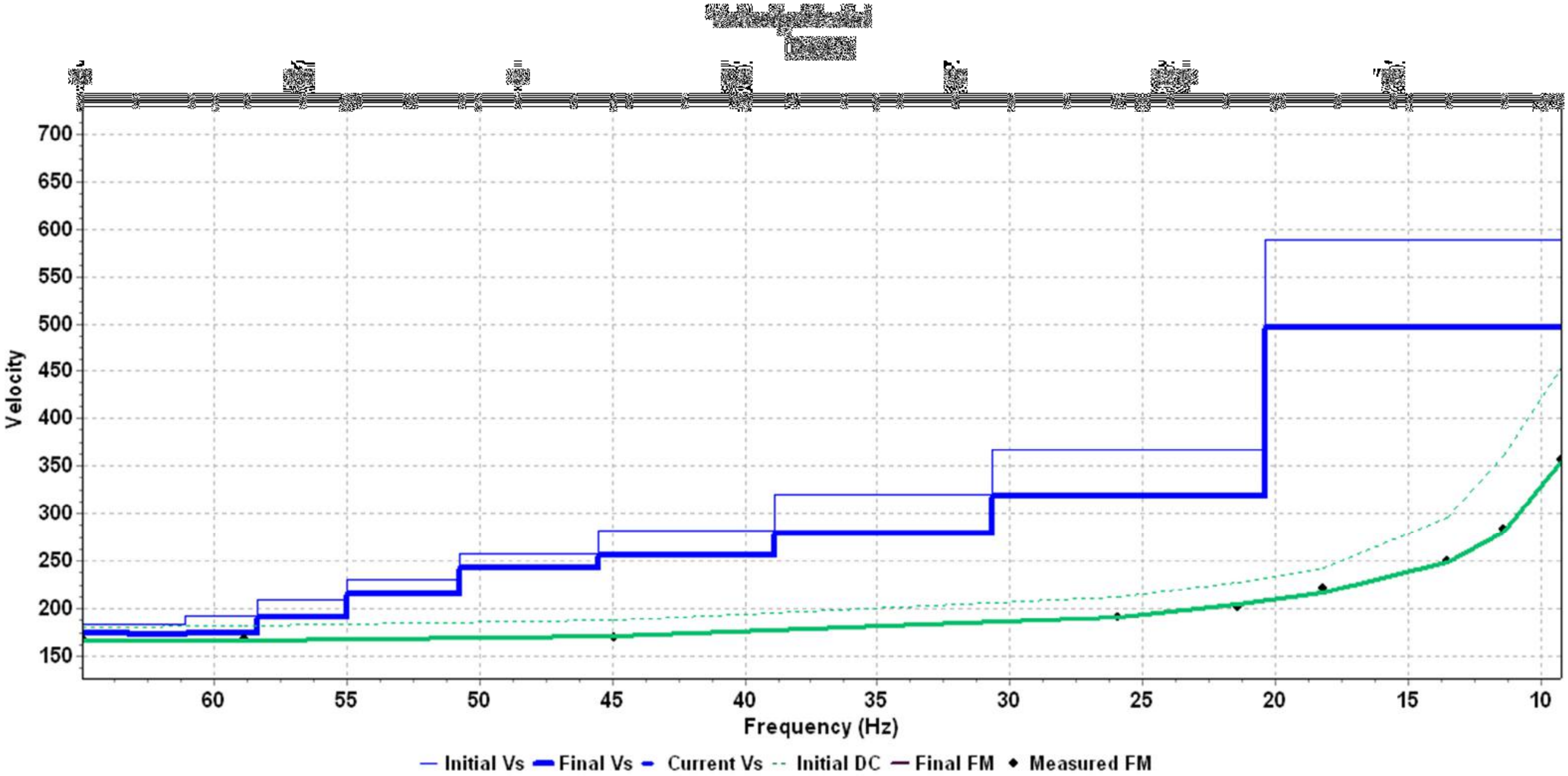
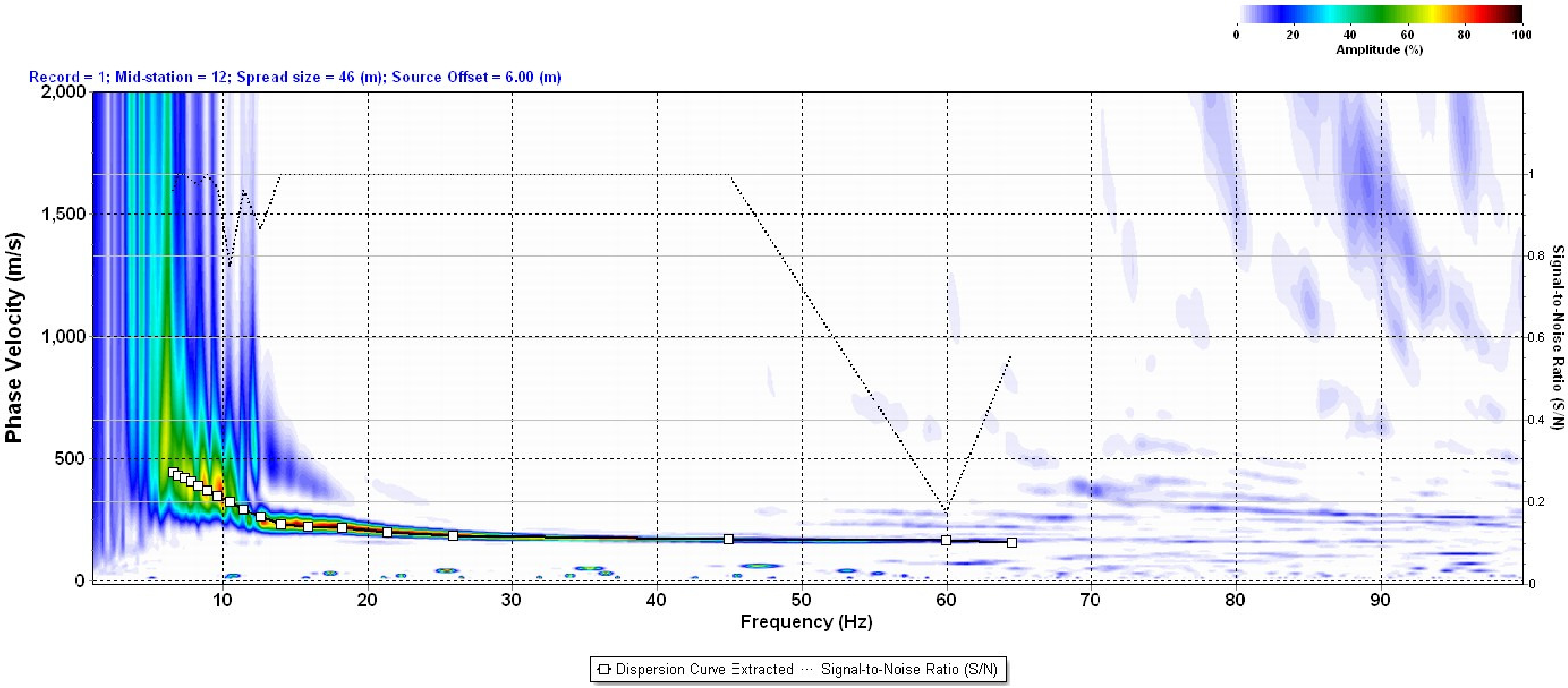


MI-24 Overtone Image



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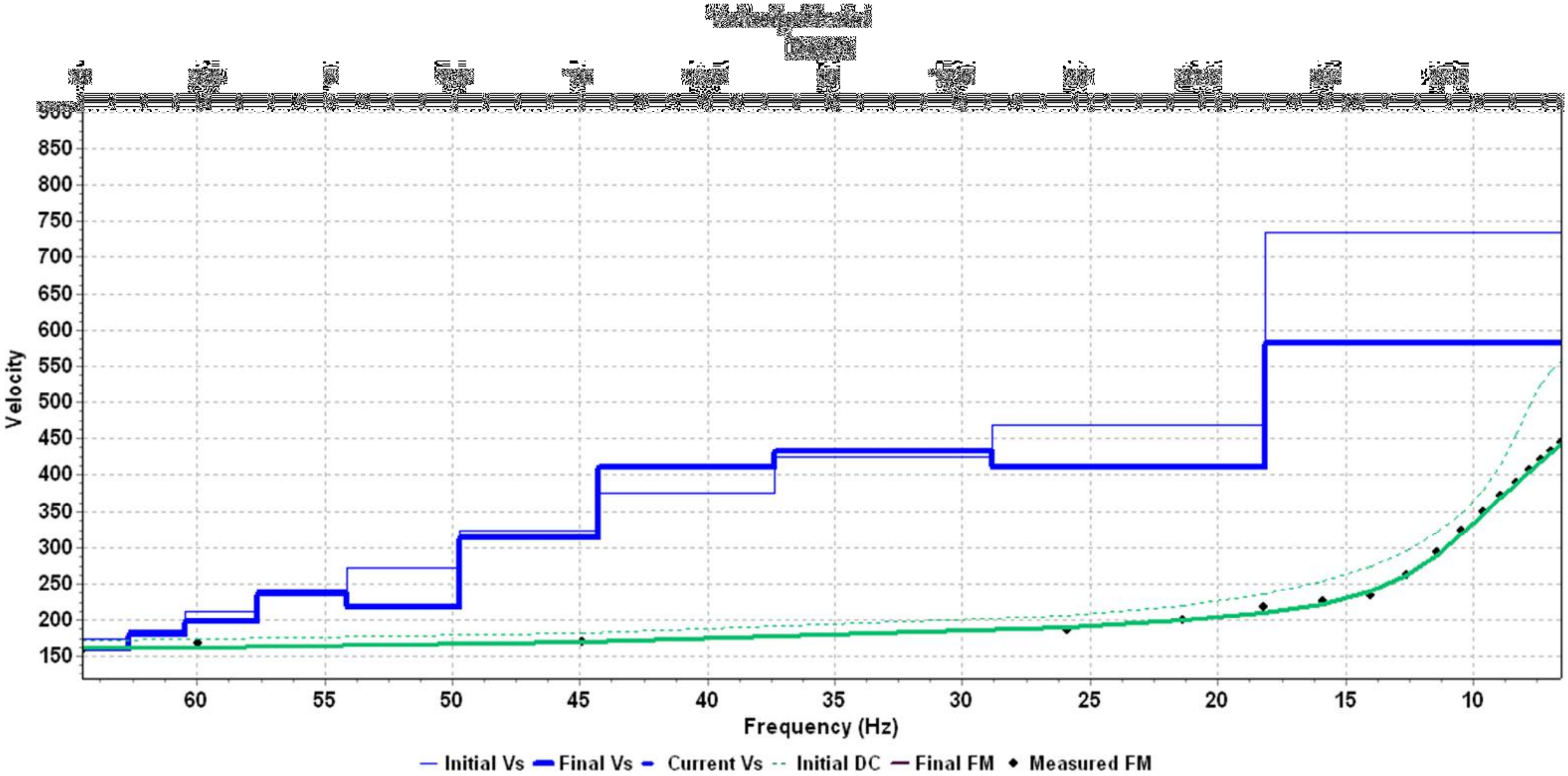

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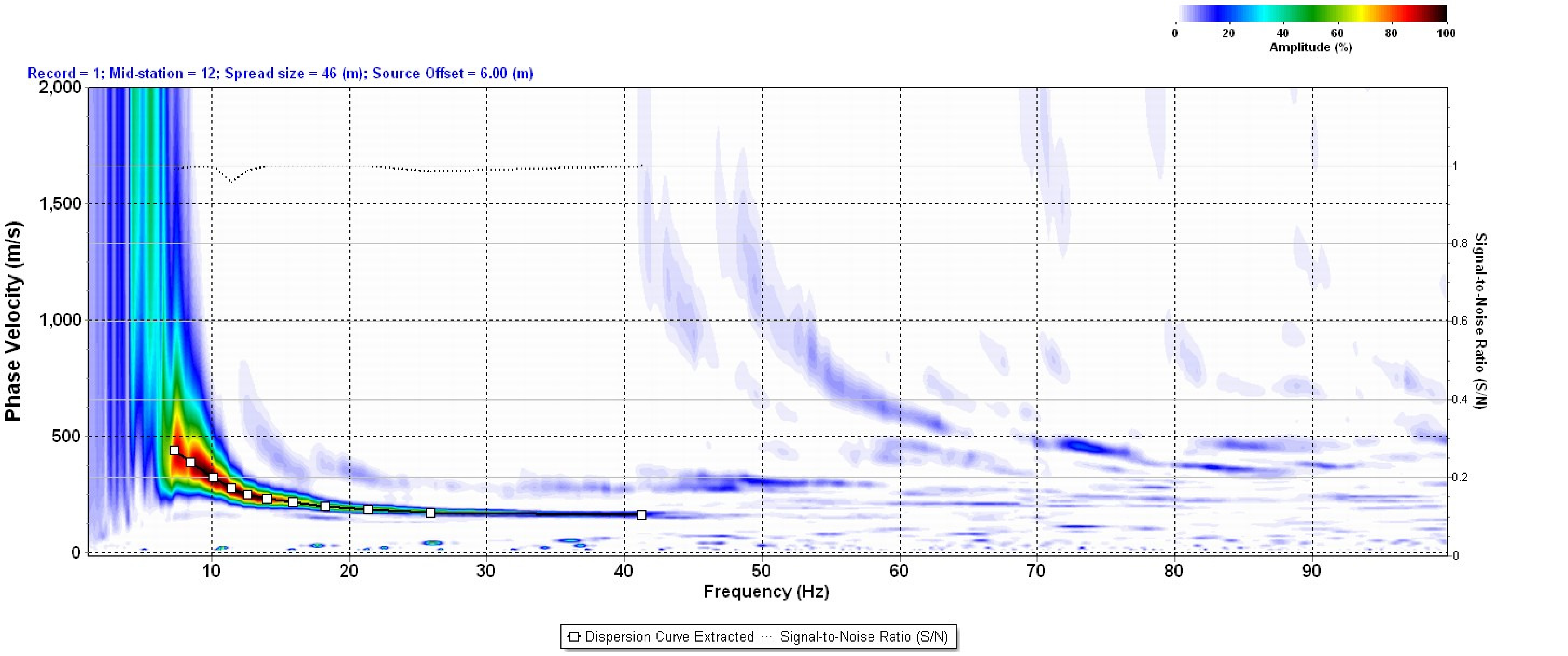

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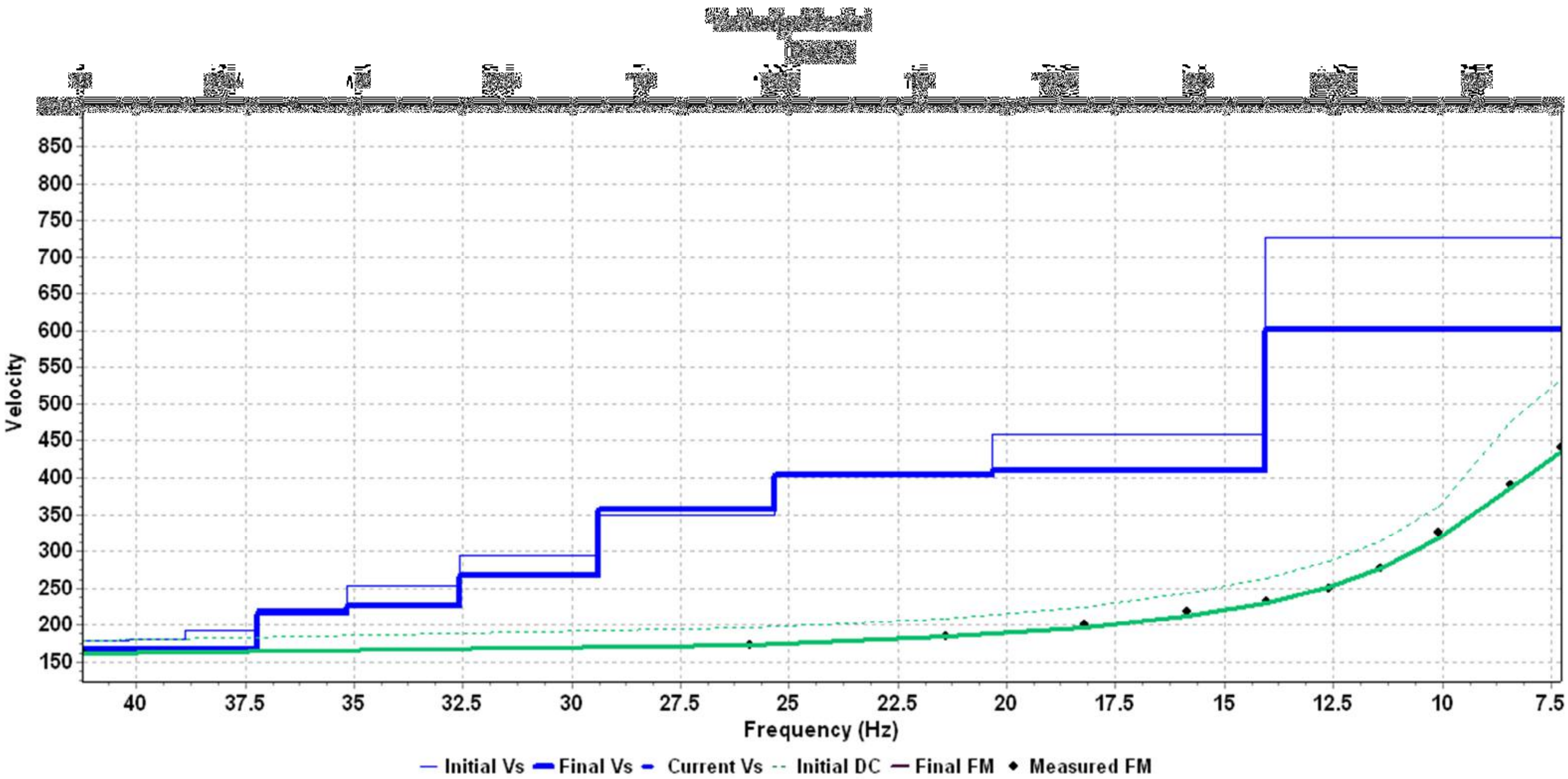
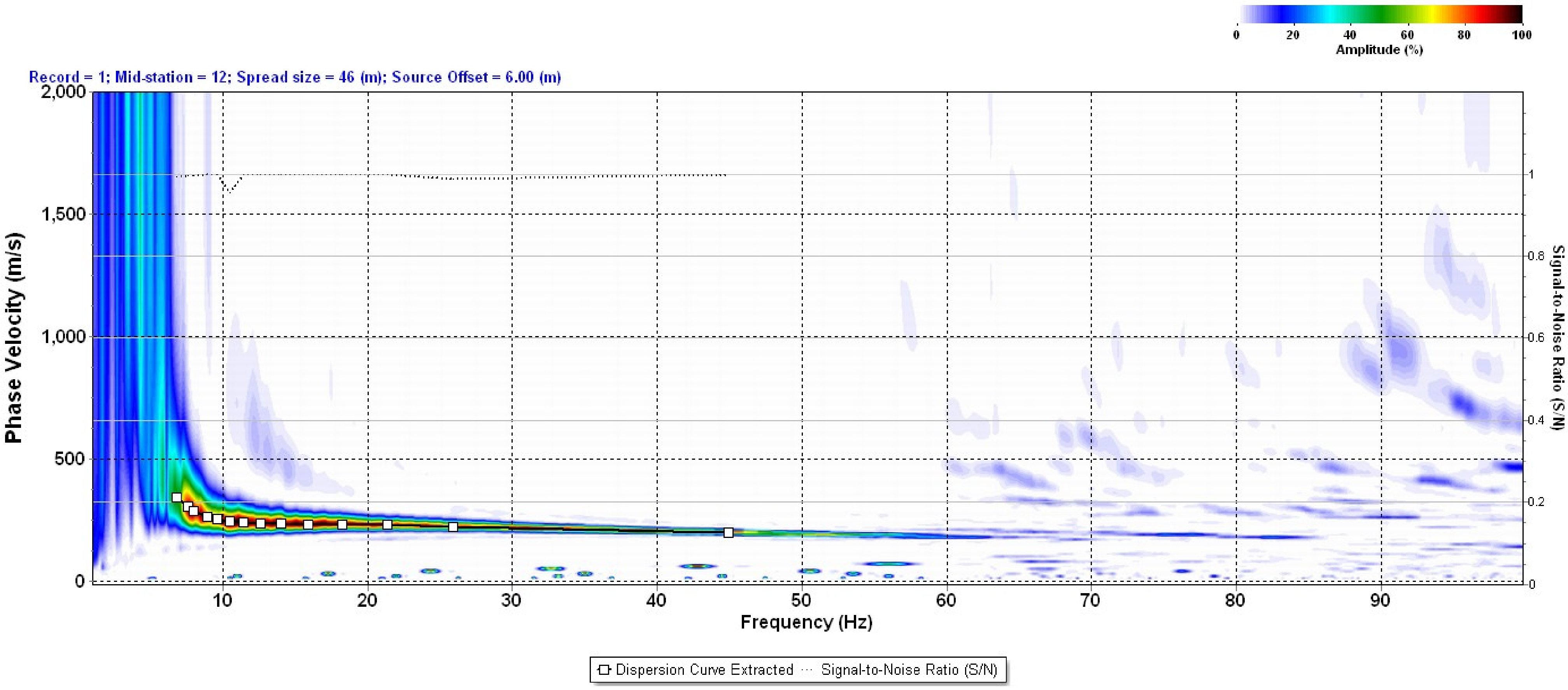


MI-26 Overtone Image



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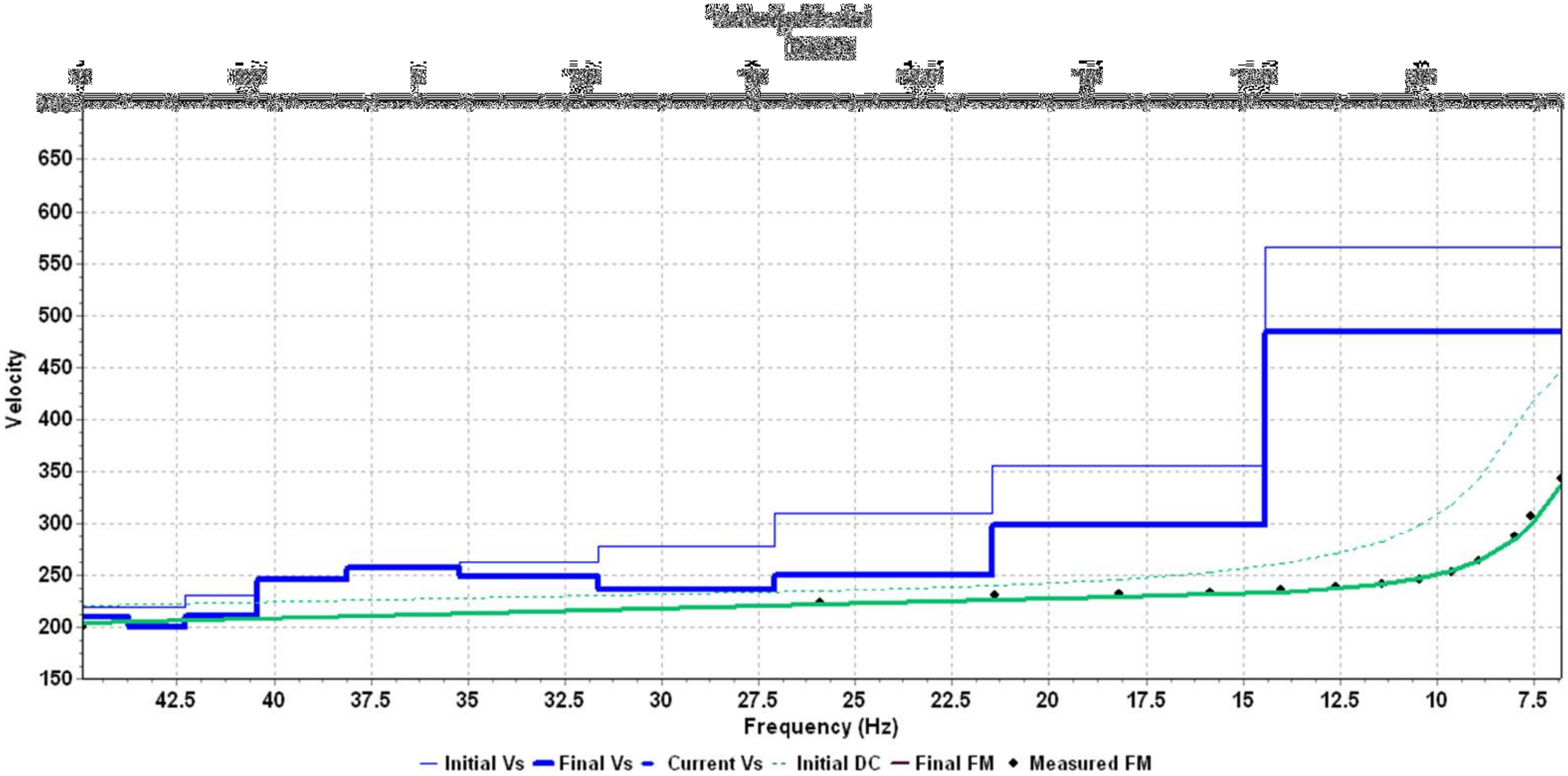

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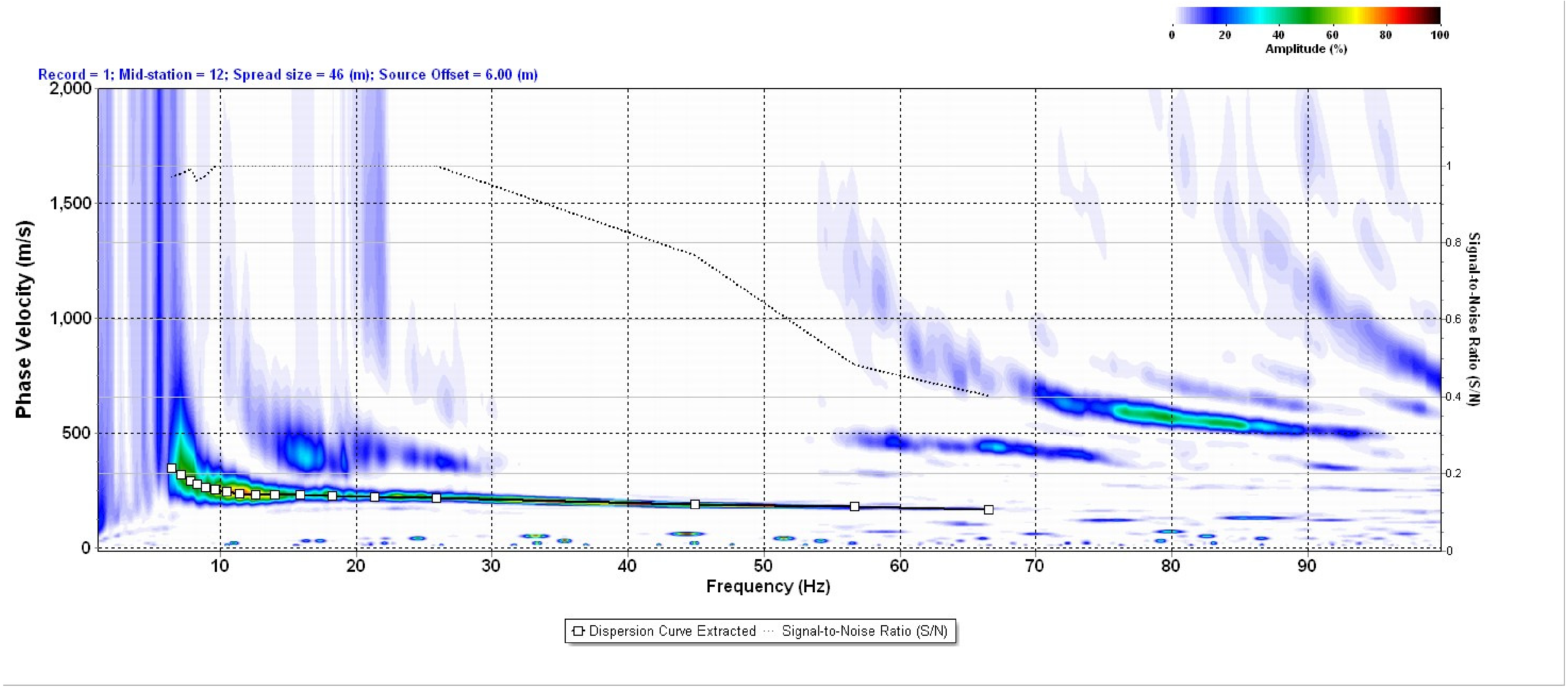

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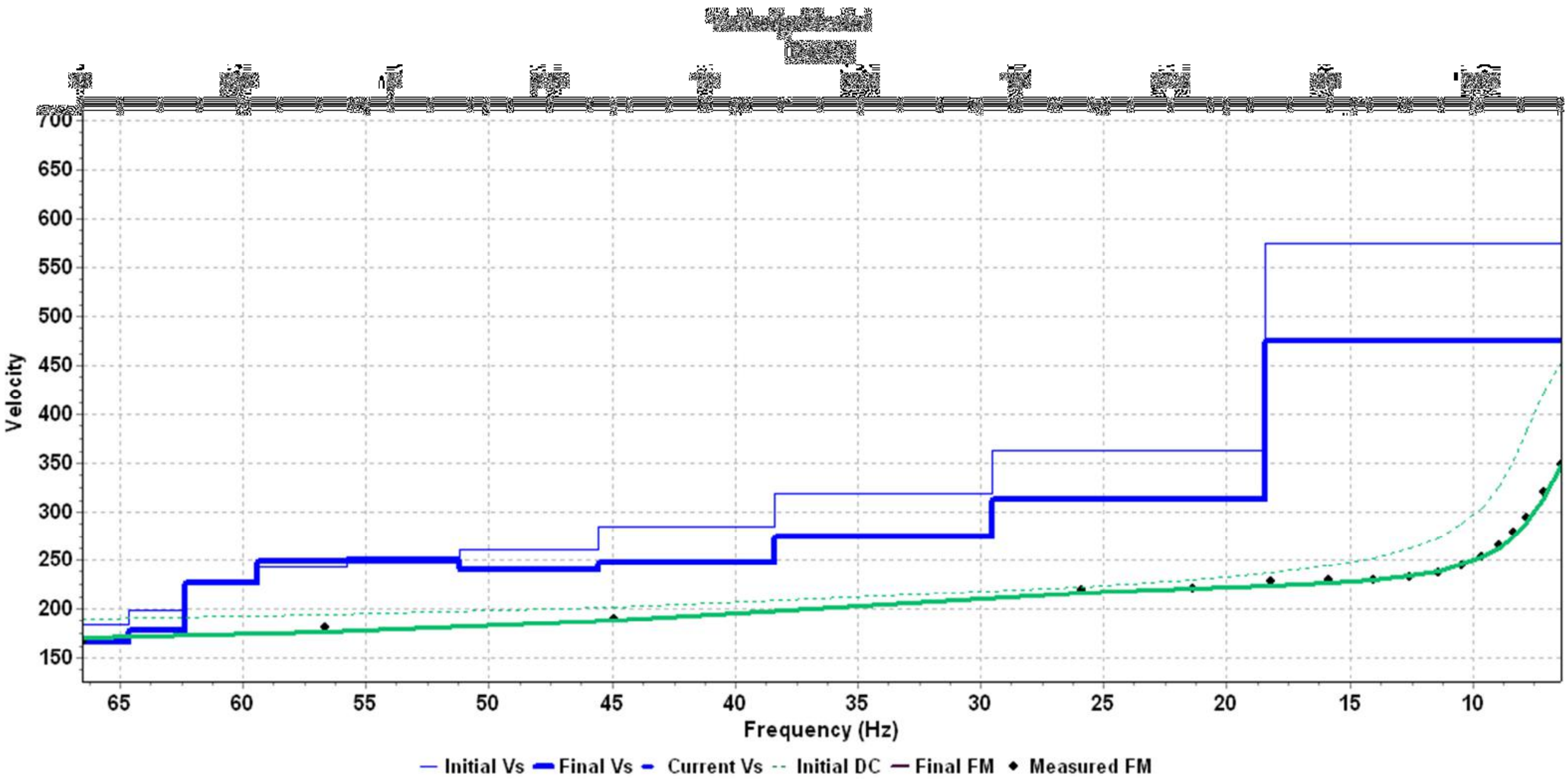
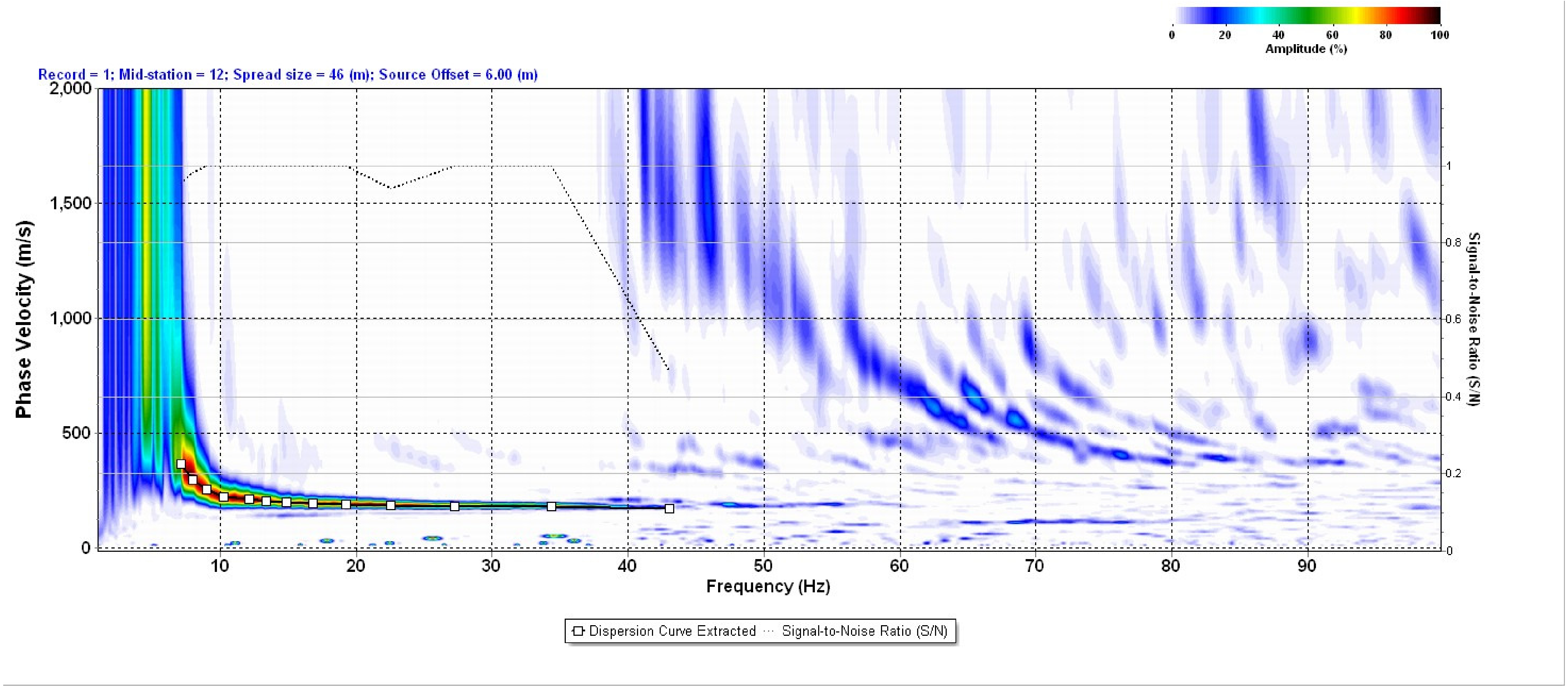


MI-28 Overtone Image



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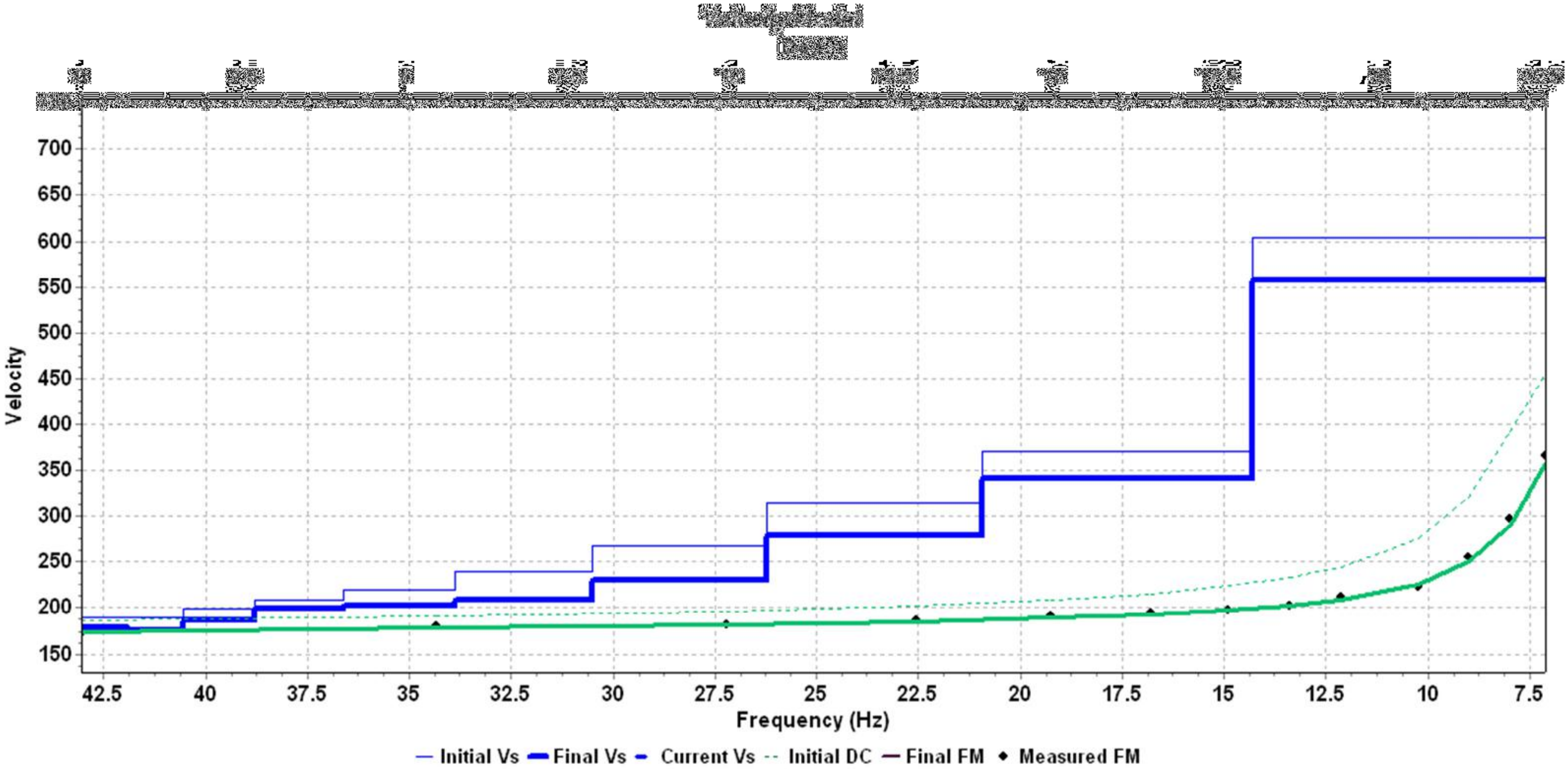

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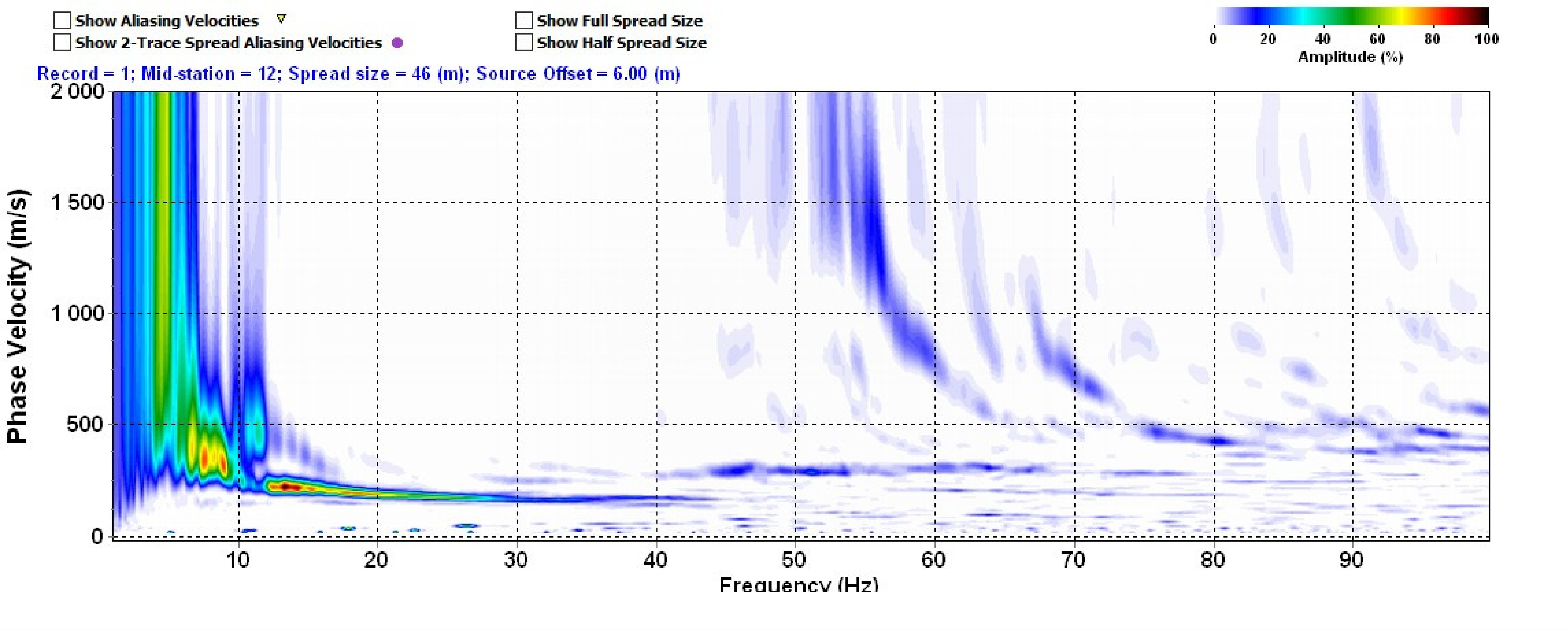

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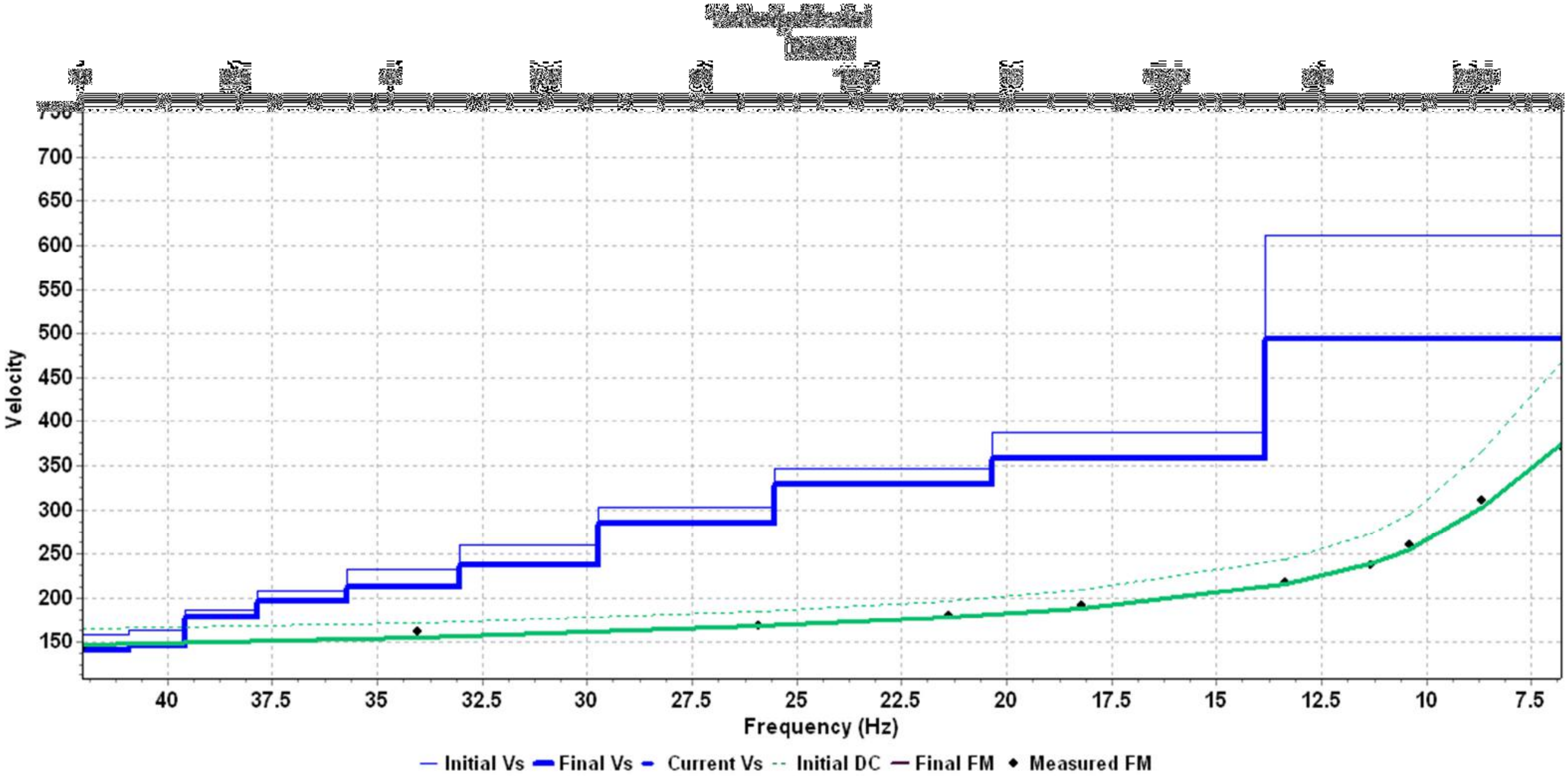

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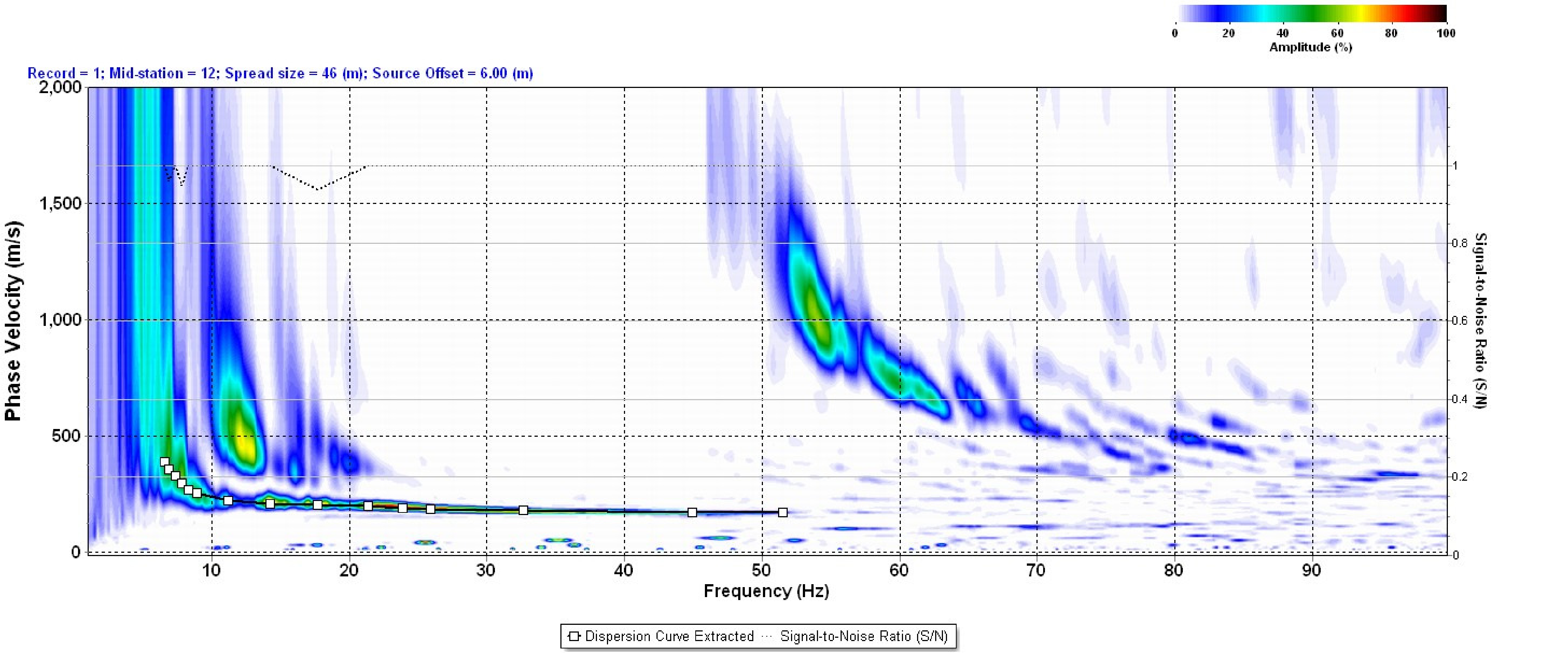
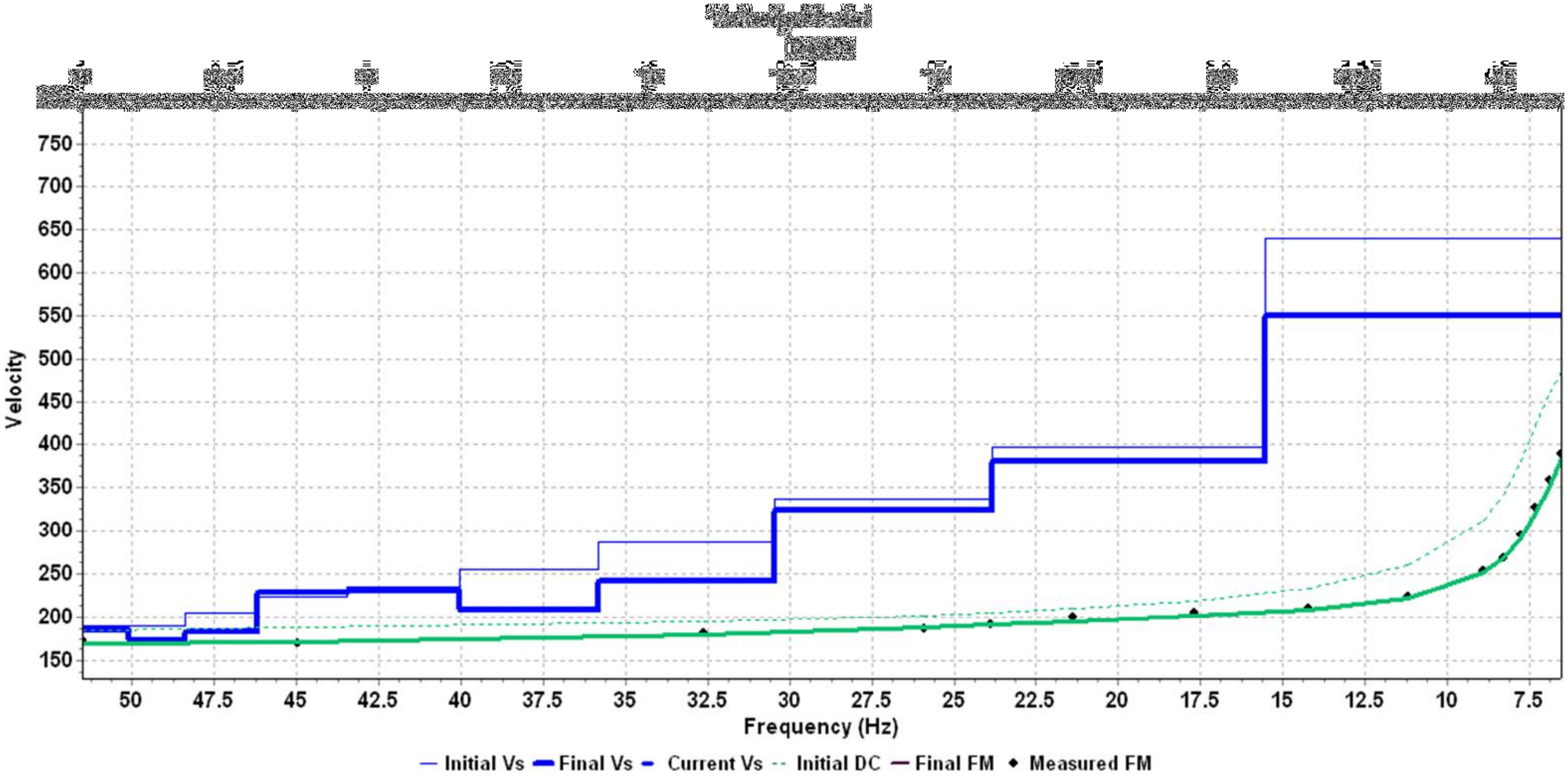
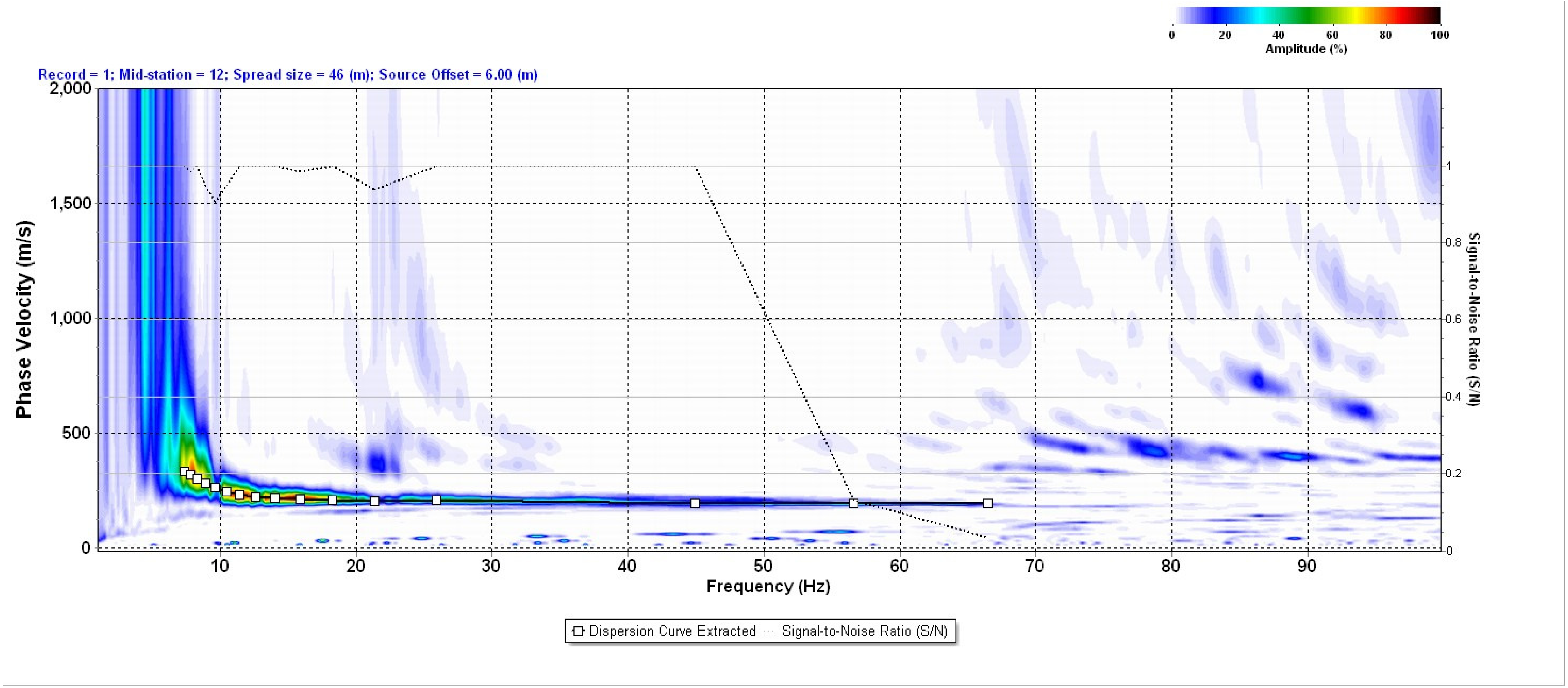


MI-30 Velocity Model



MI-31 Overtone Image



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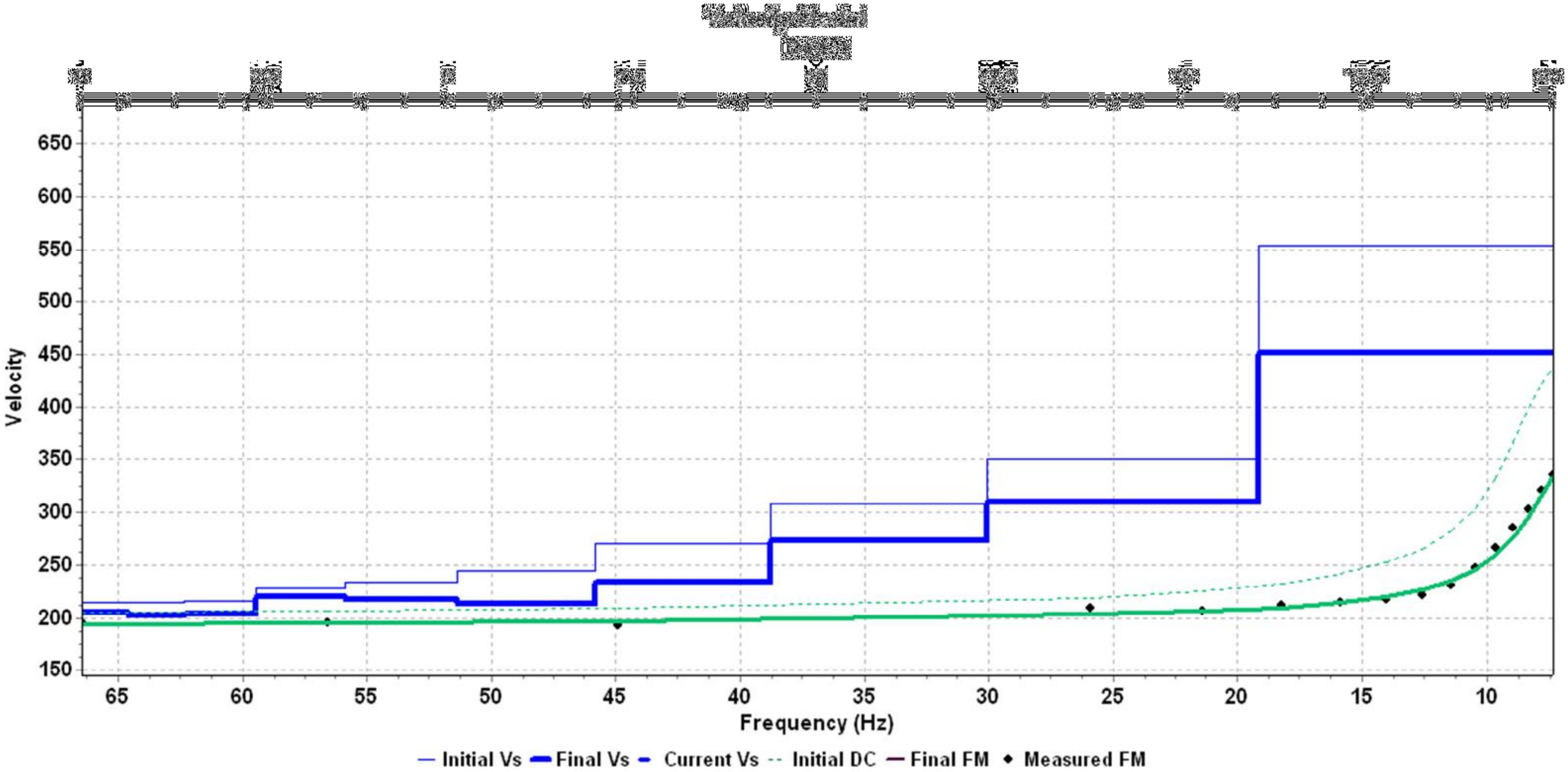

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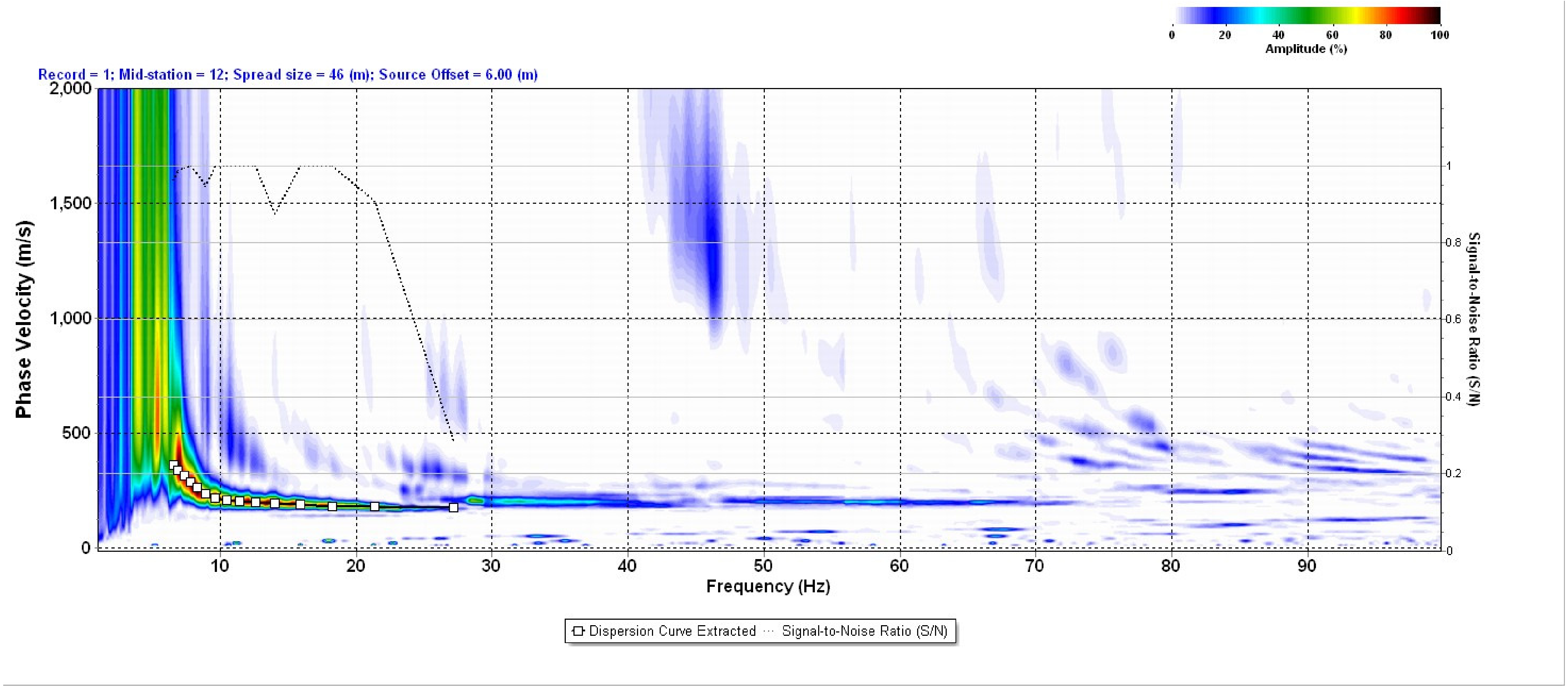

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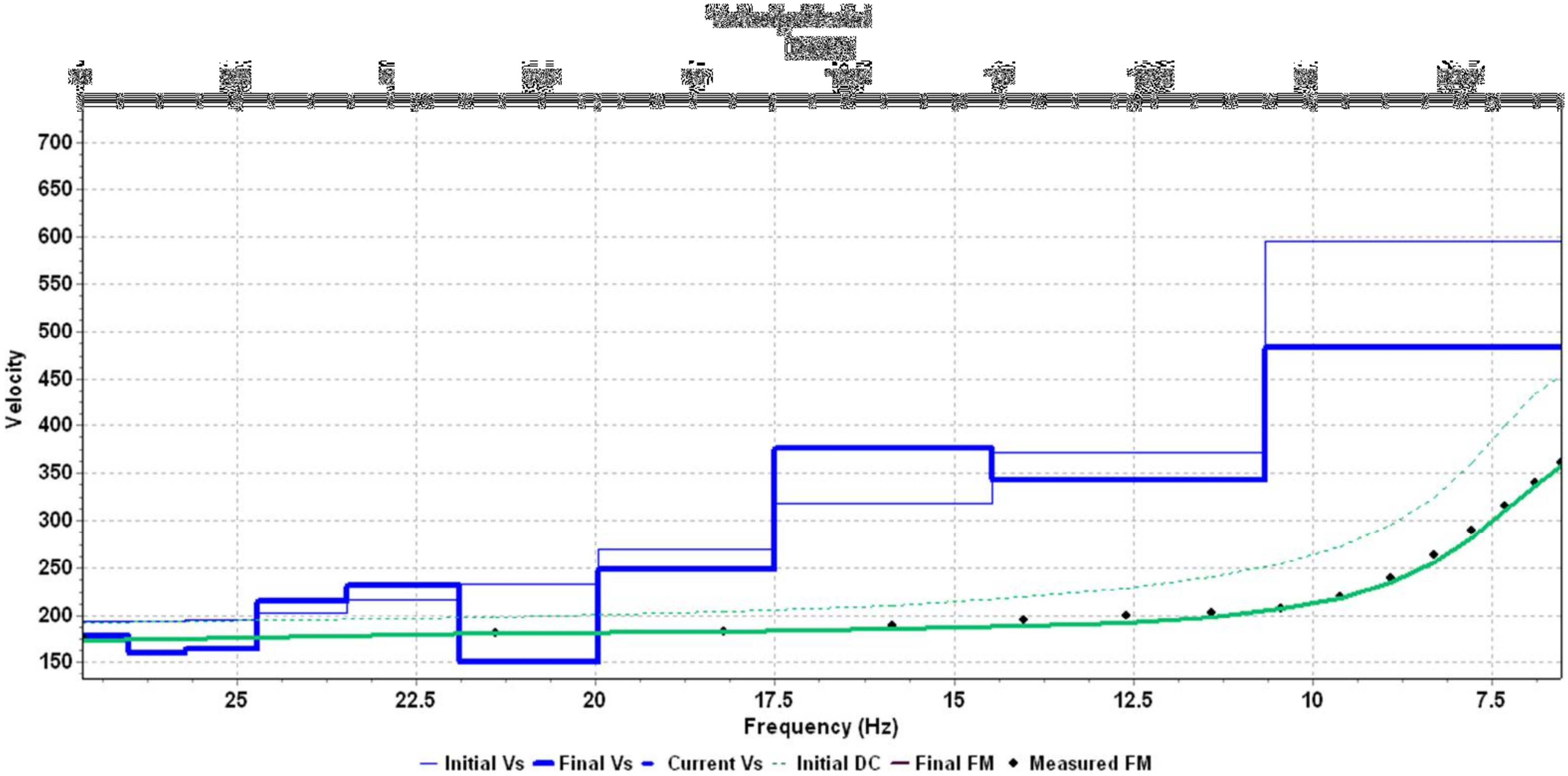

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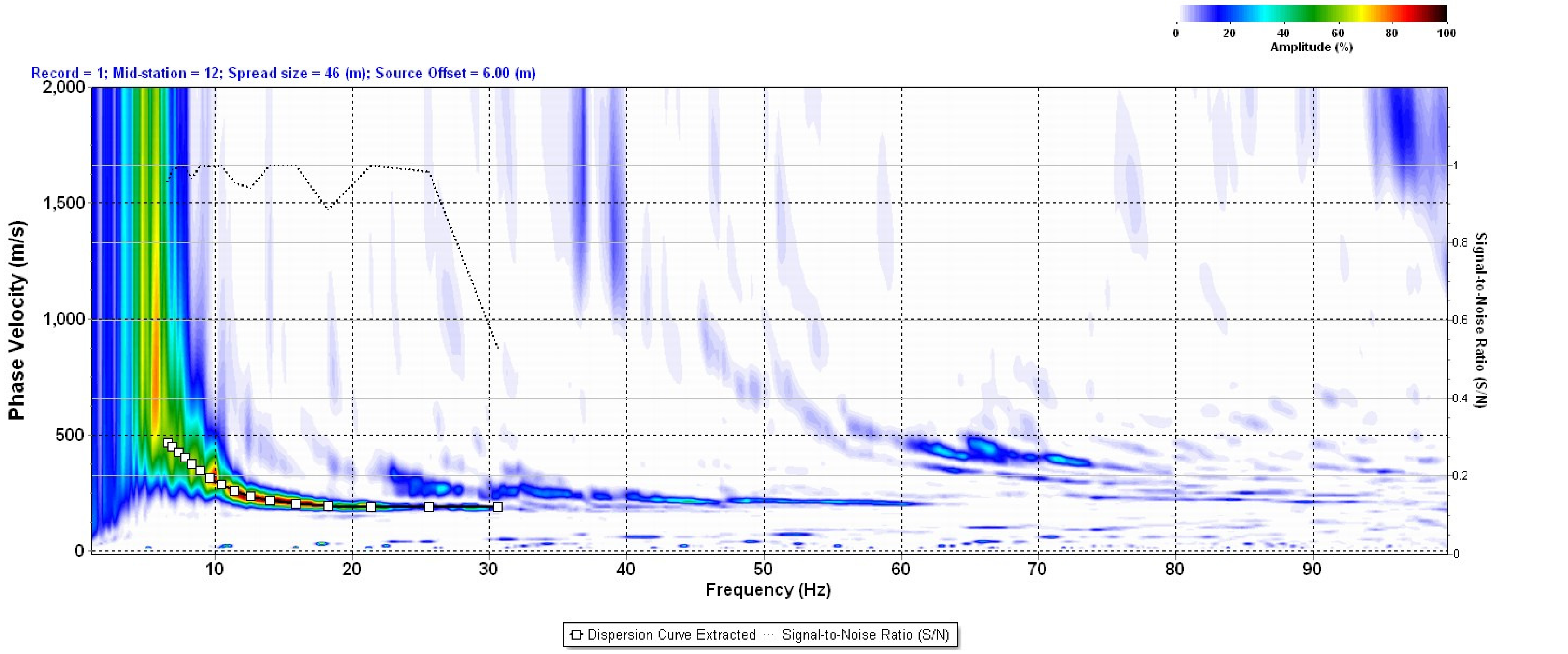

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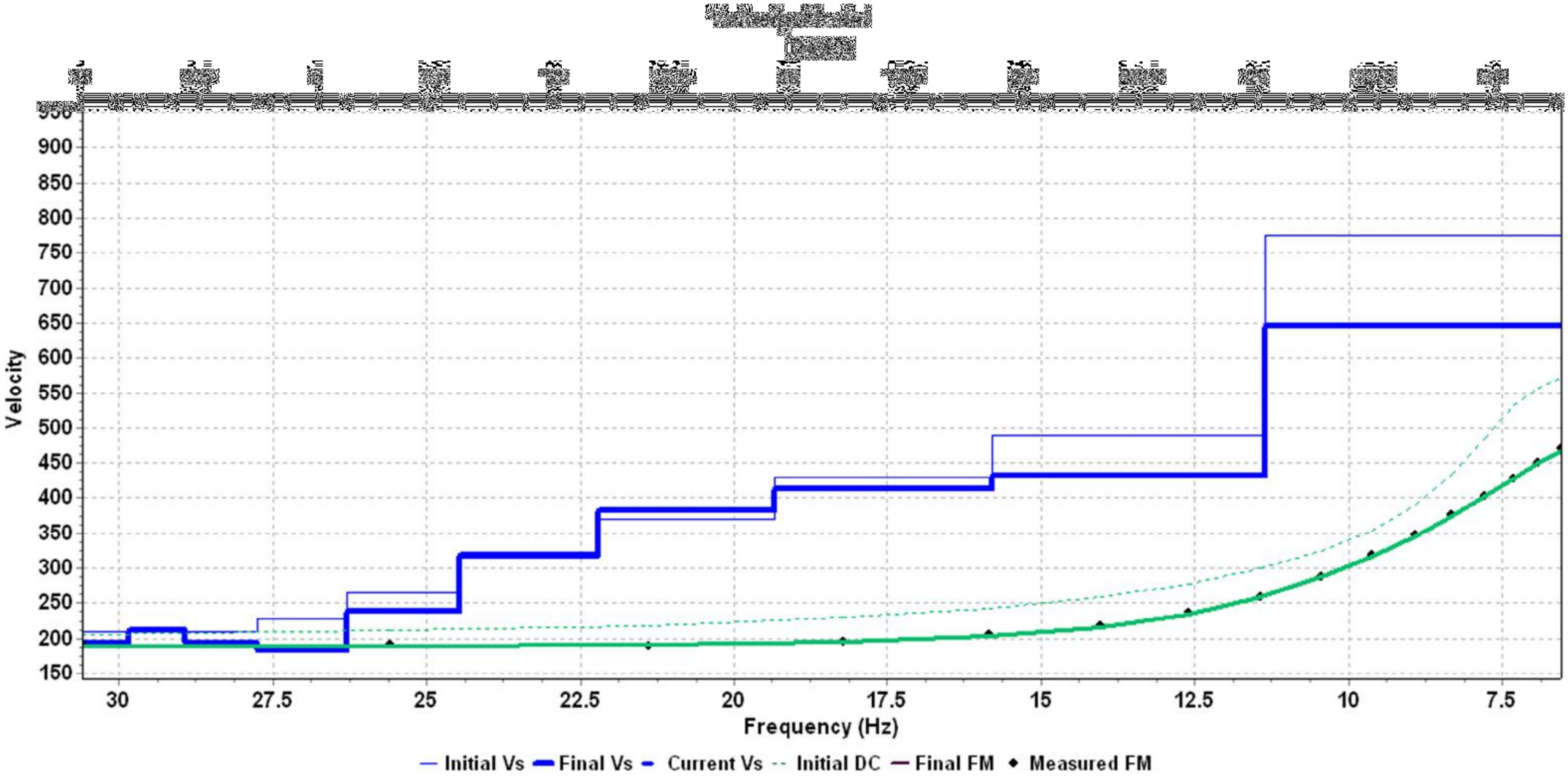

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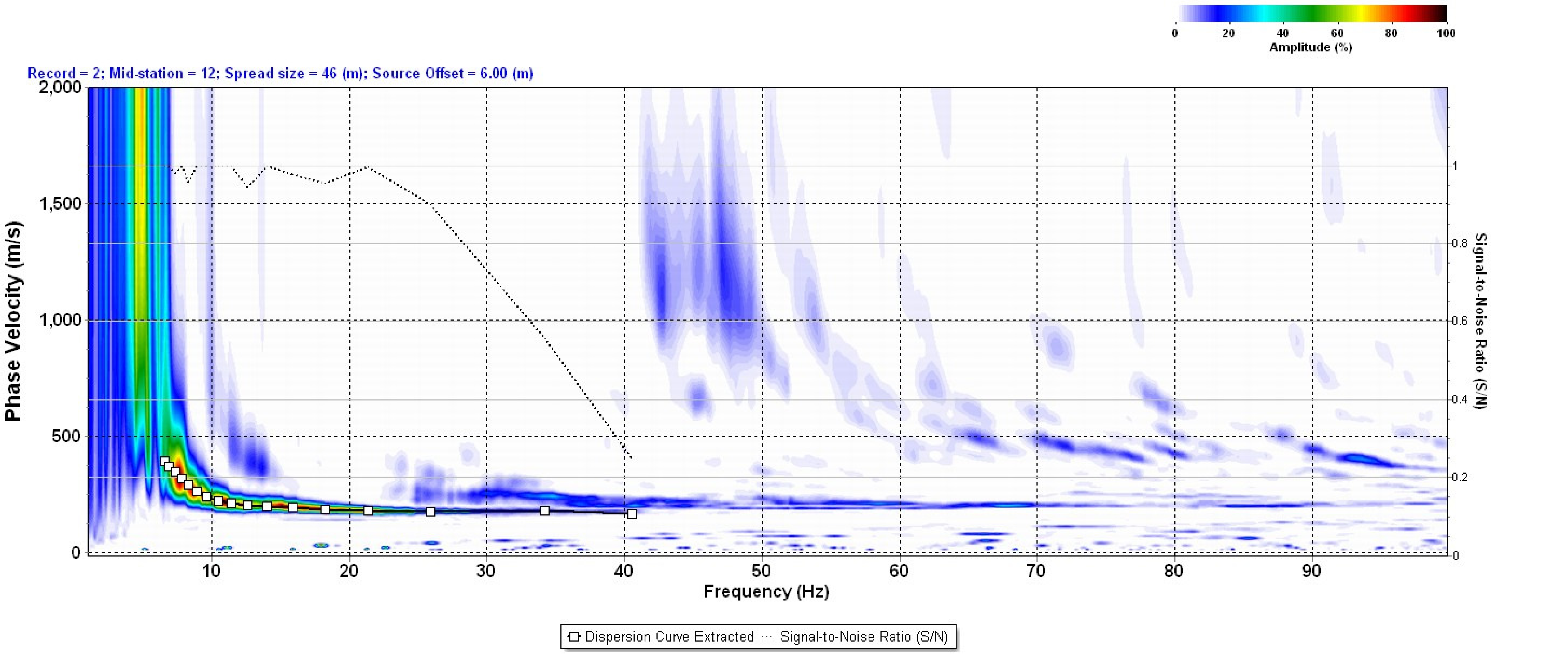

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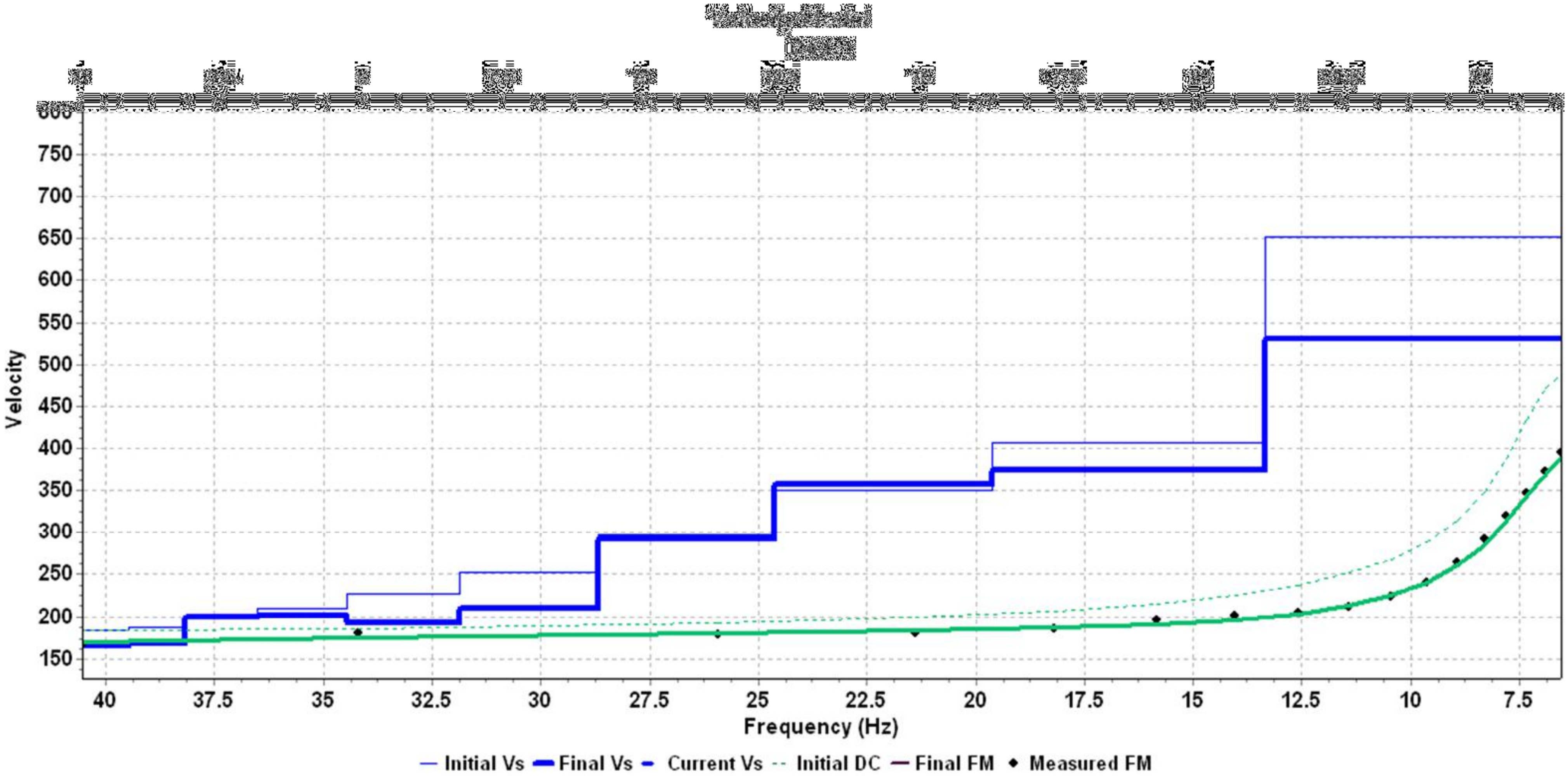

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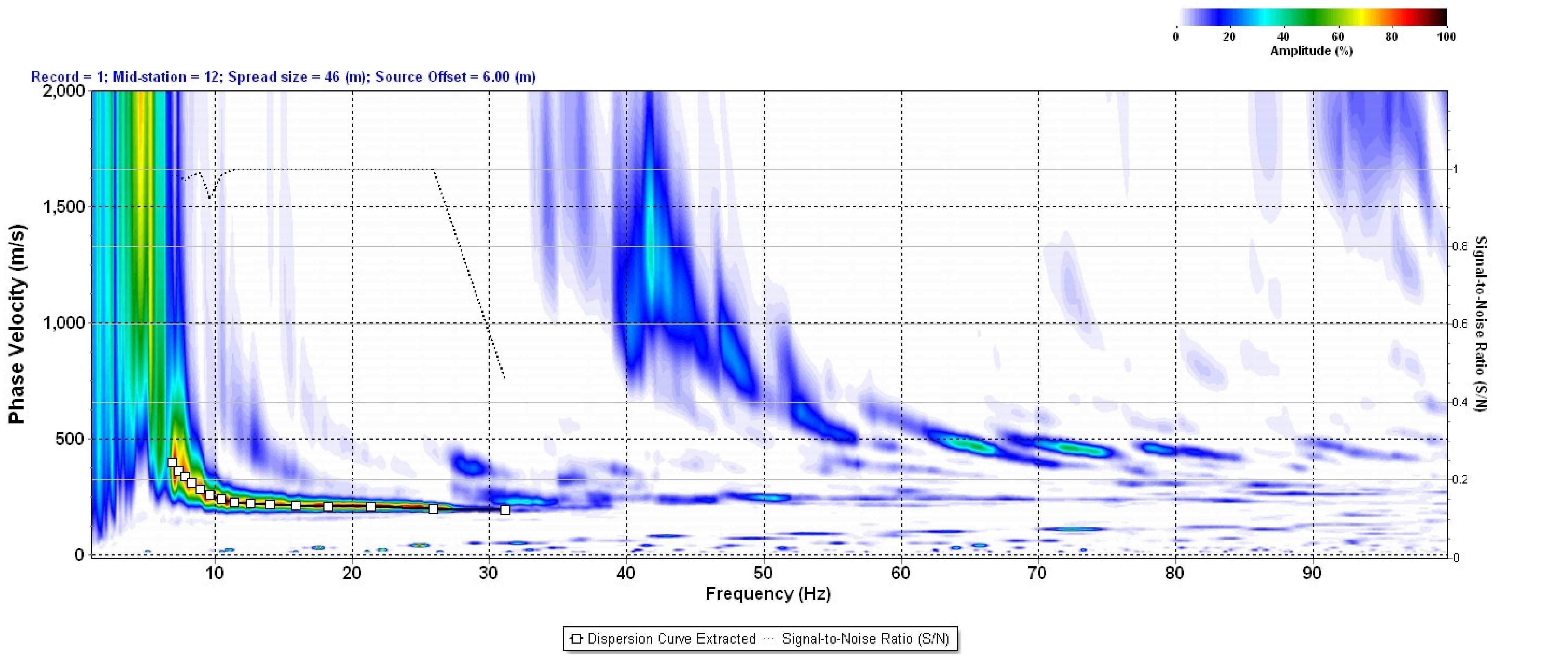

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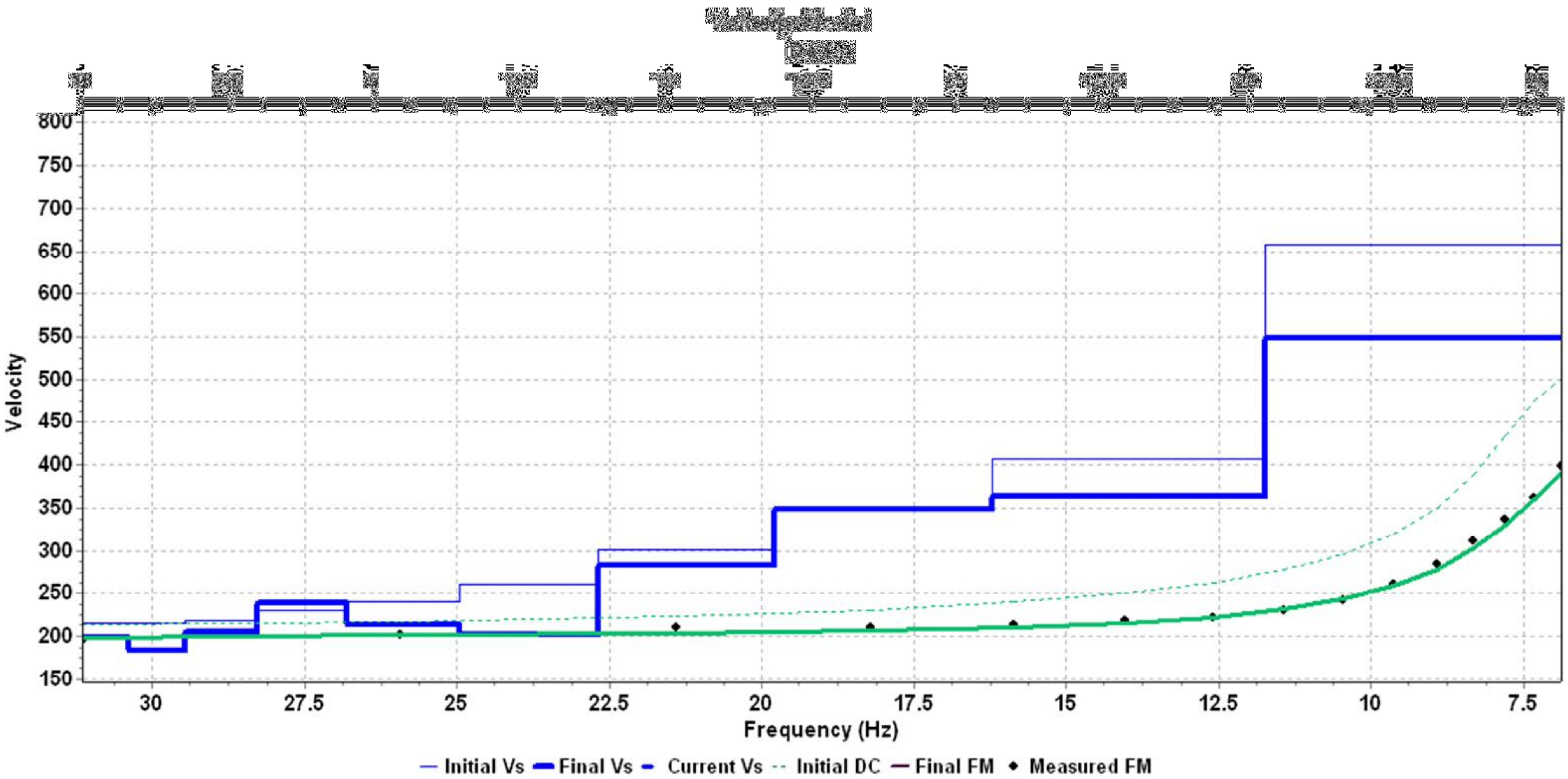
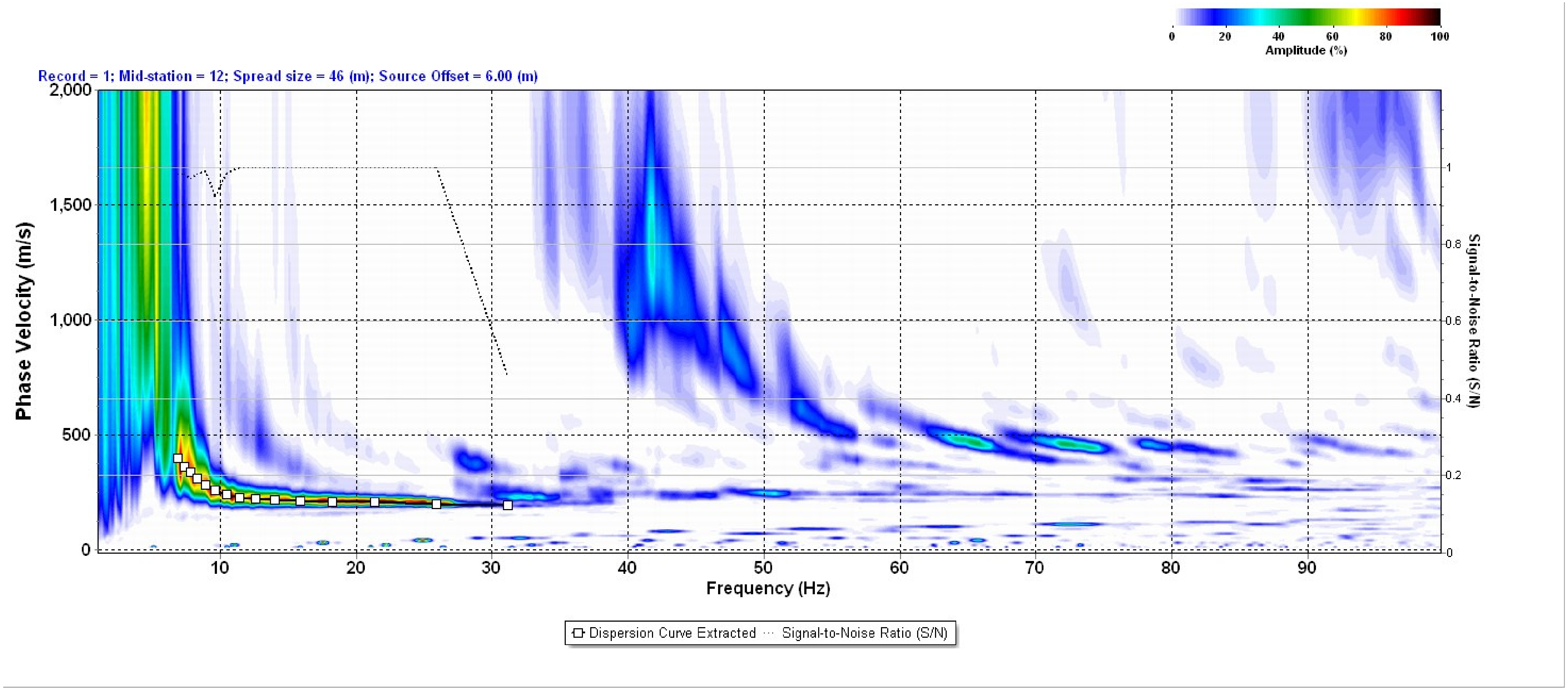
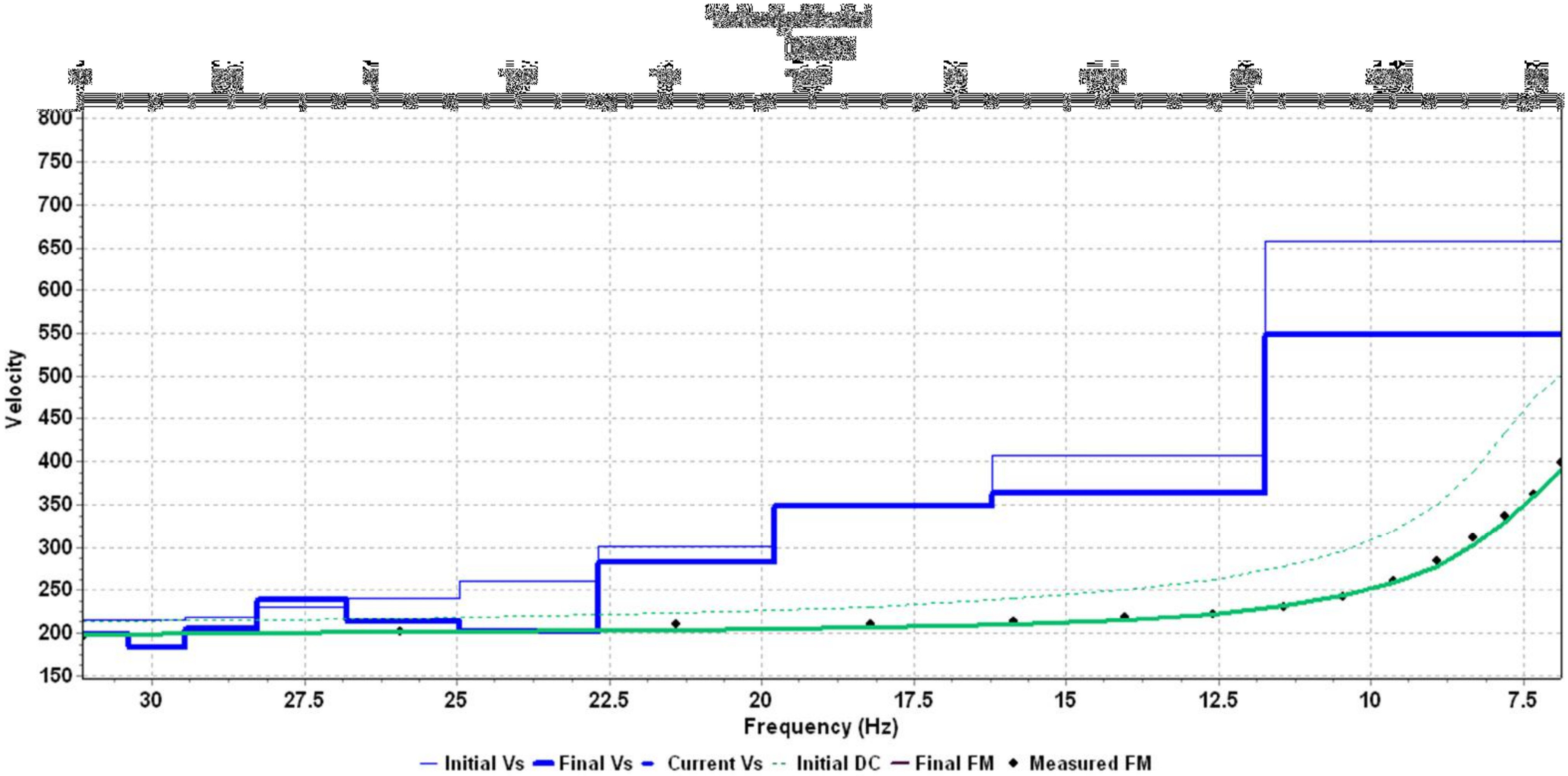


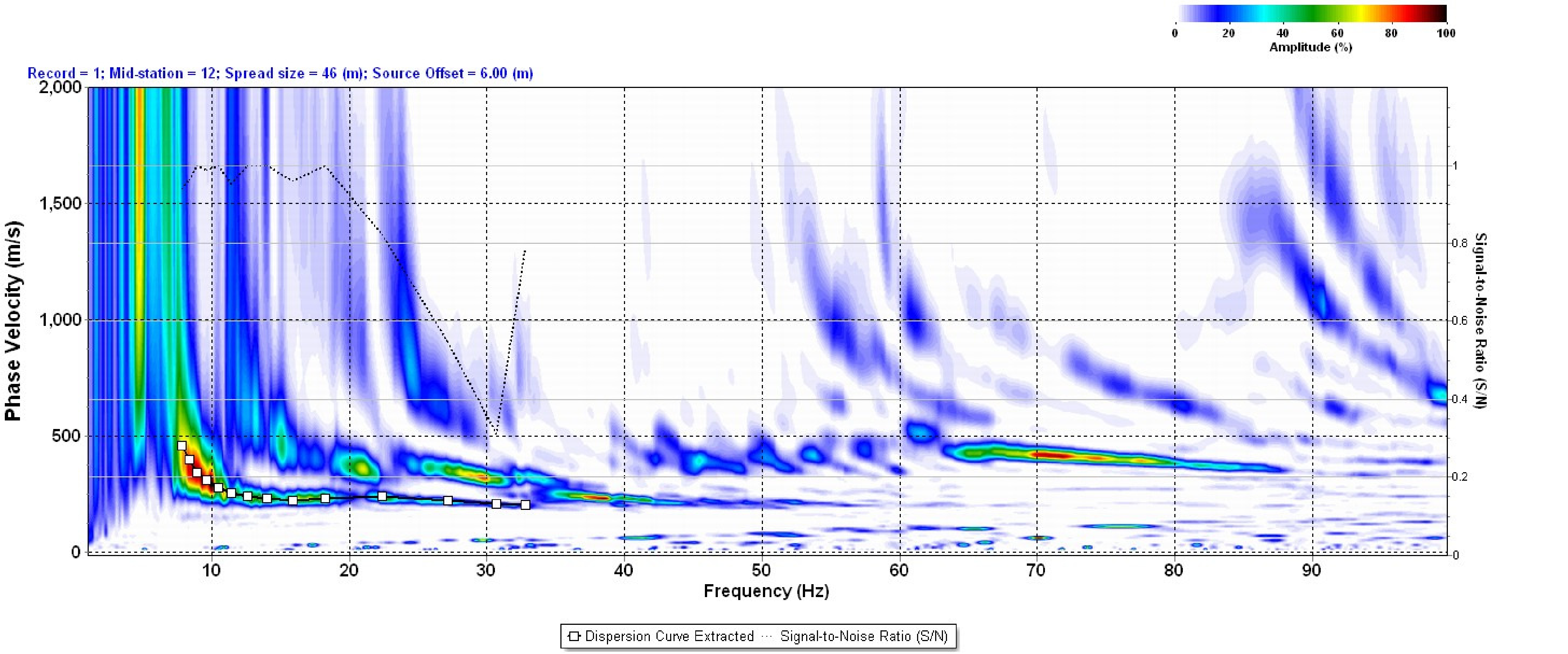
MI-36 Overtone Image



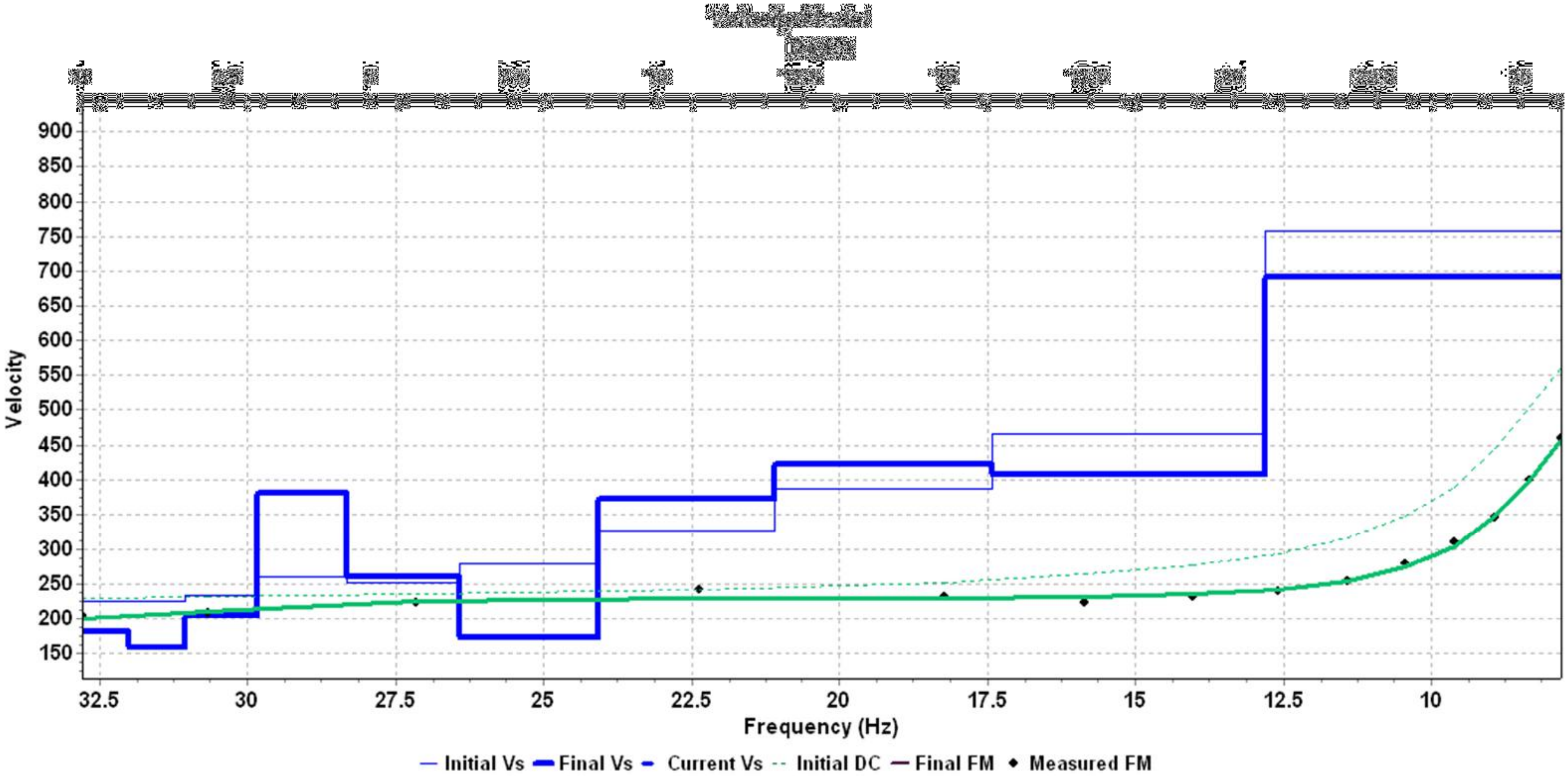
MI-36 Velocity Model



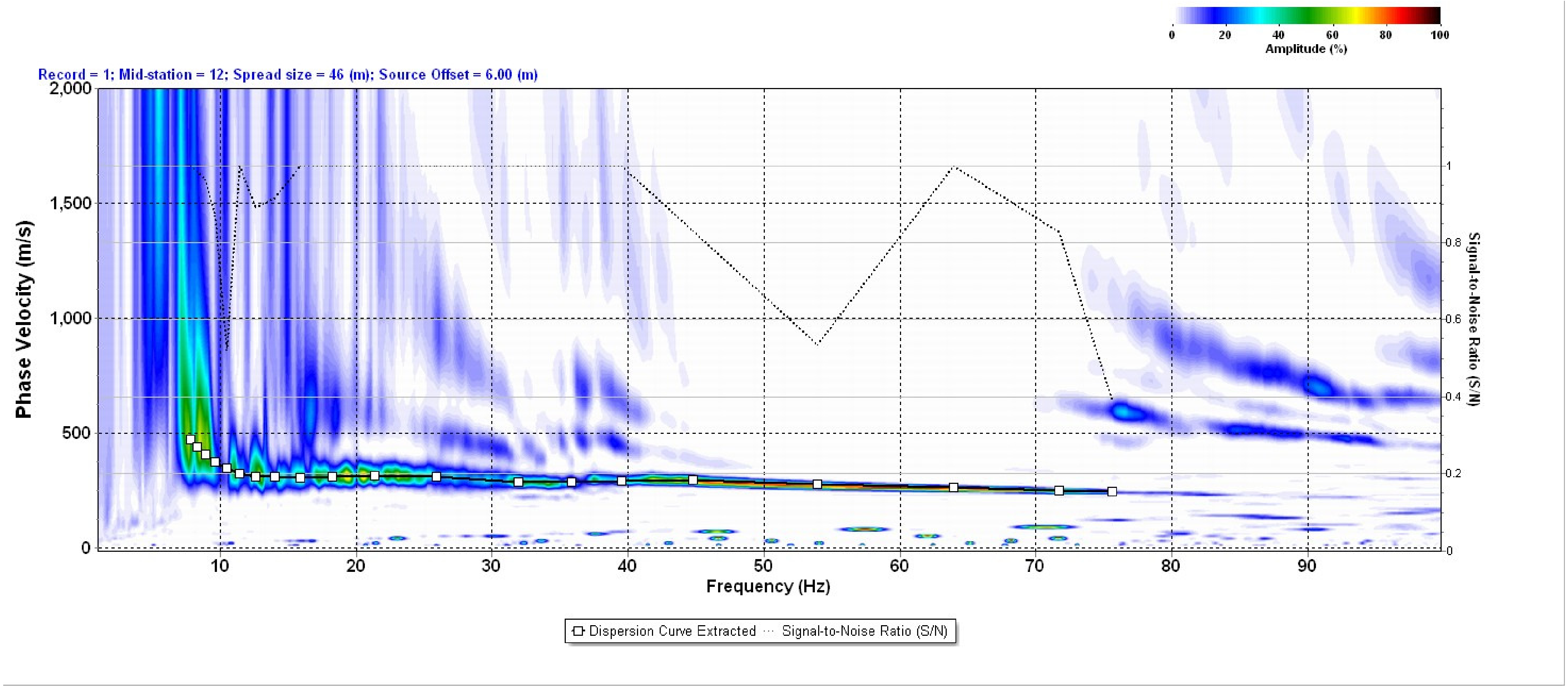
MI-37 Overtone Image



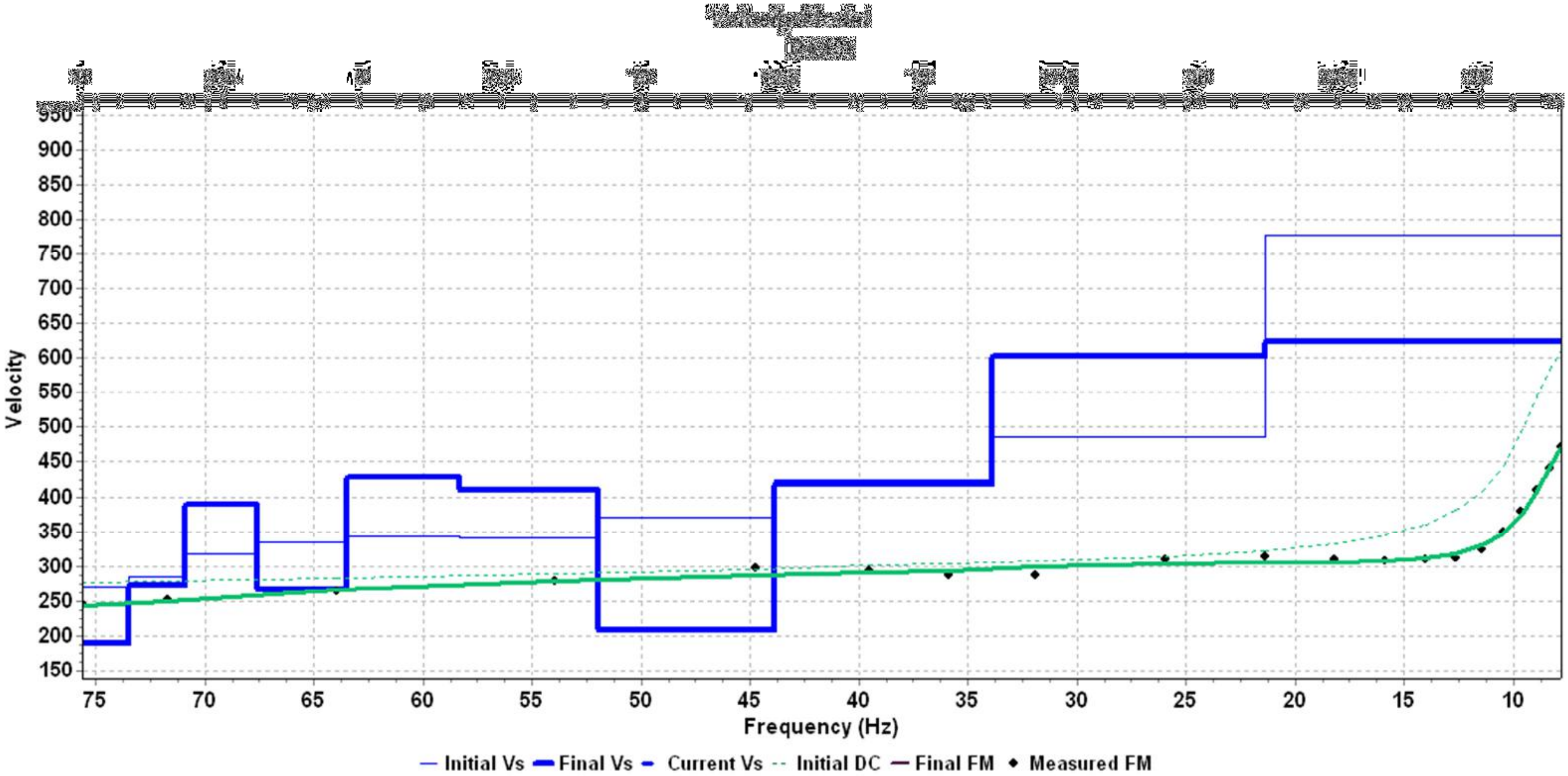
MI-37 Velocity Model



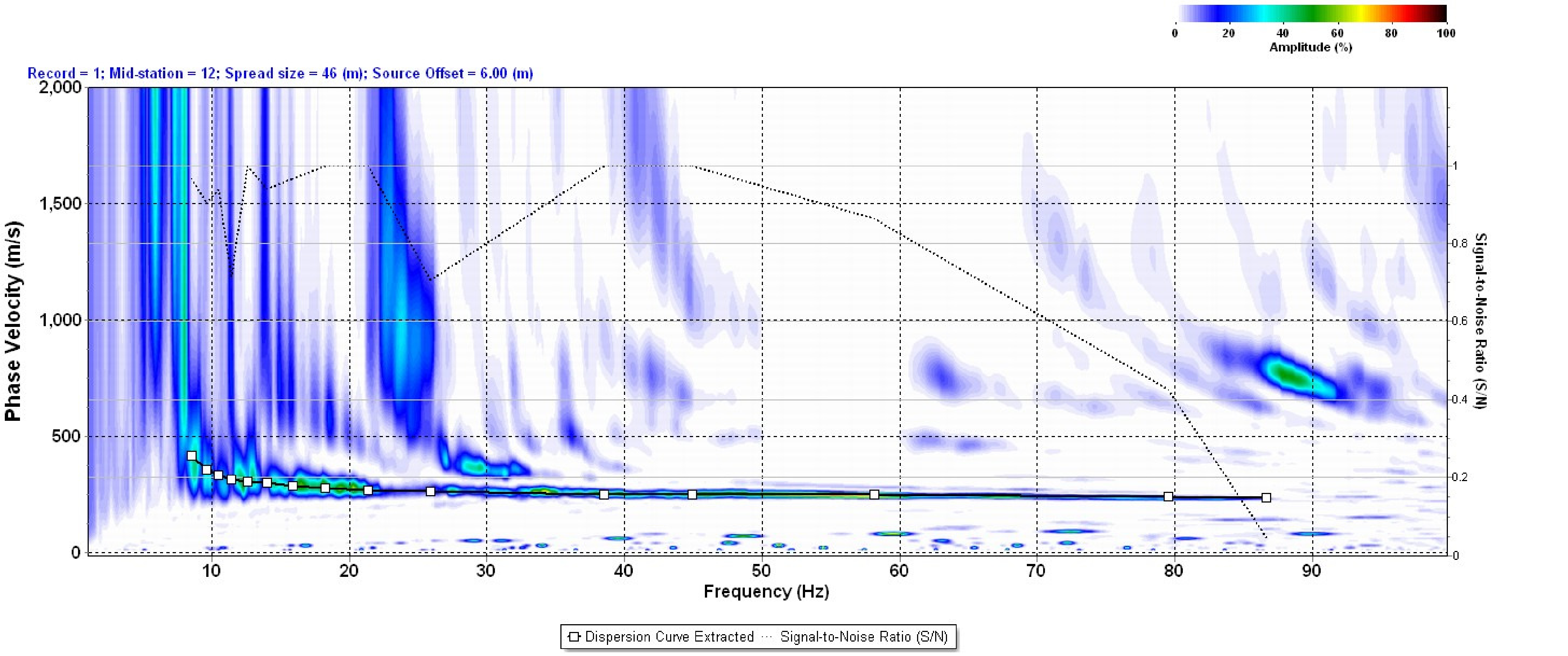
MI-38 Overtone Image



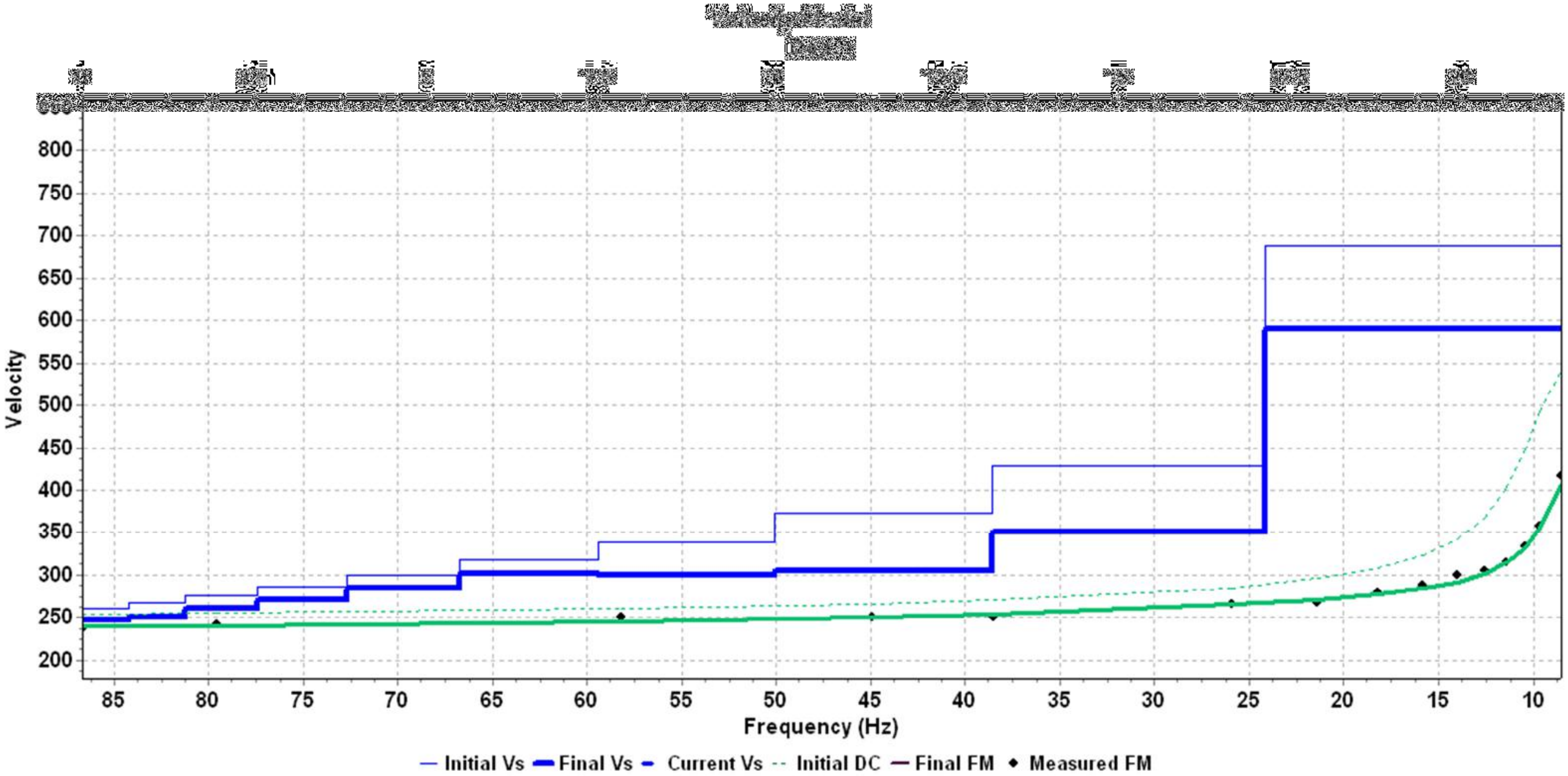
MI-38 Velocity Model



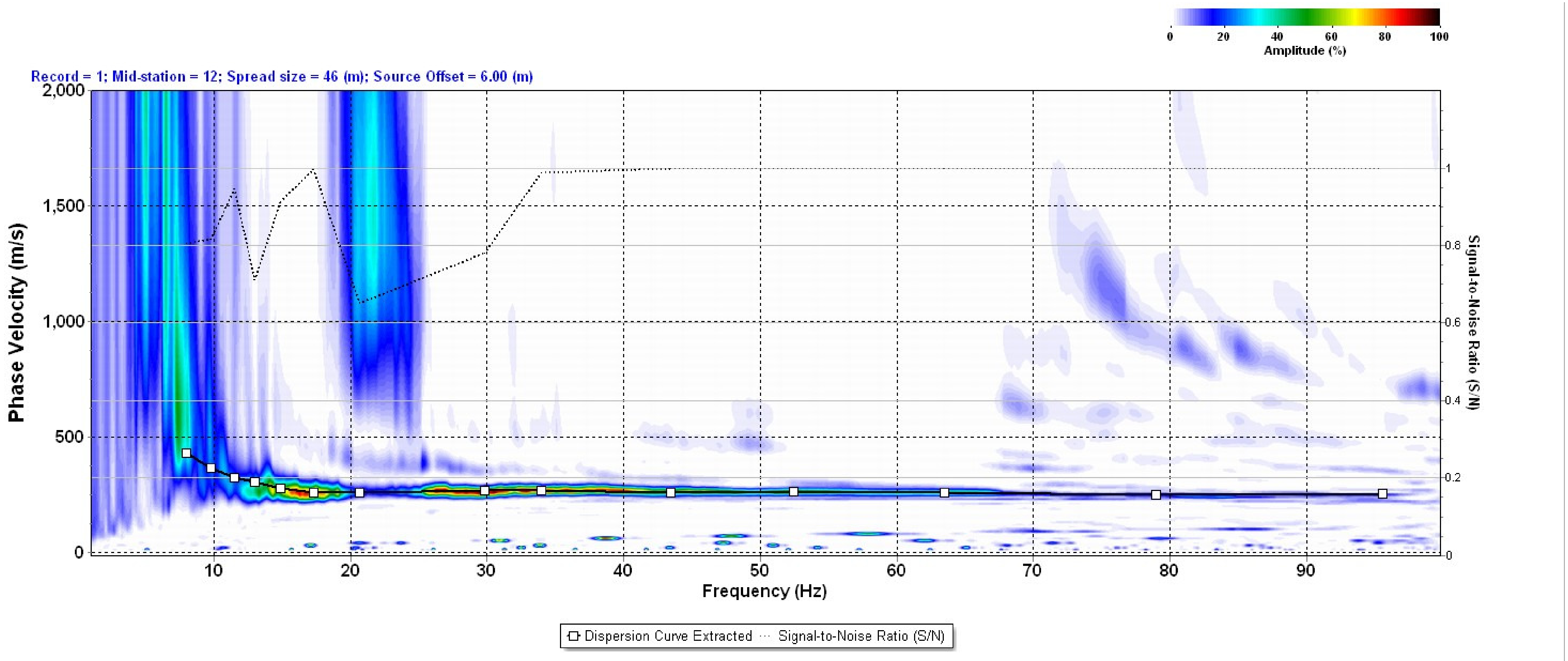
MI-39 Overtone Image



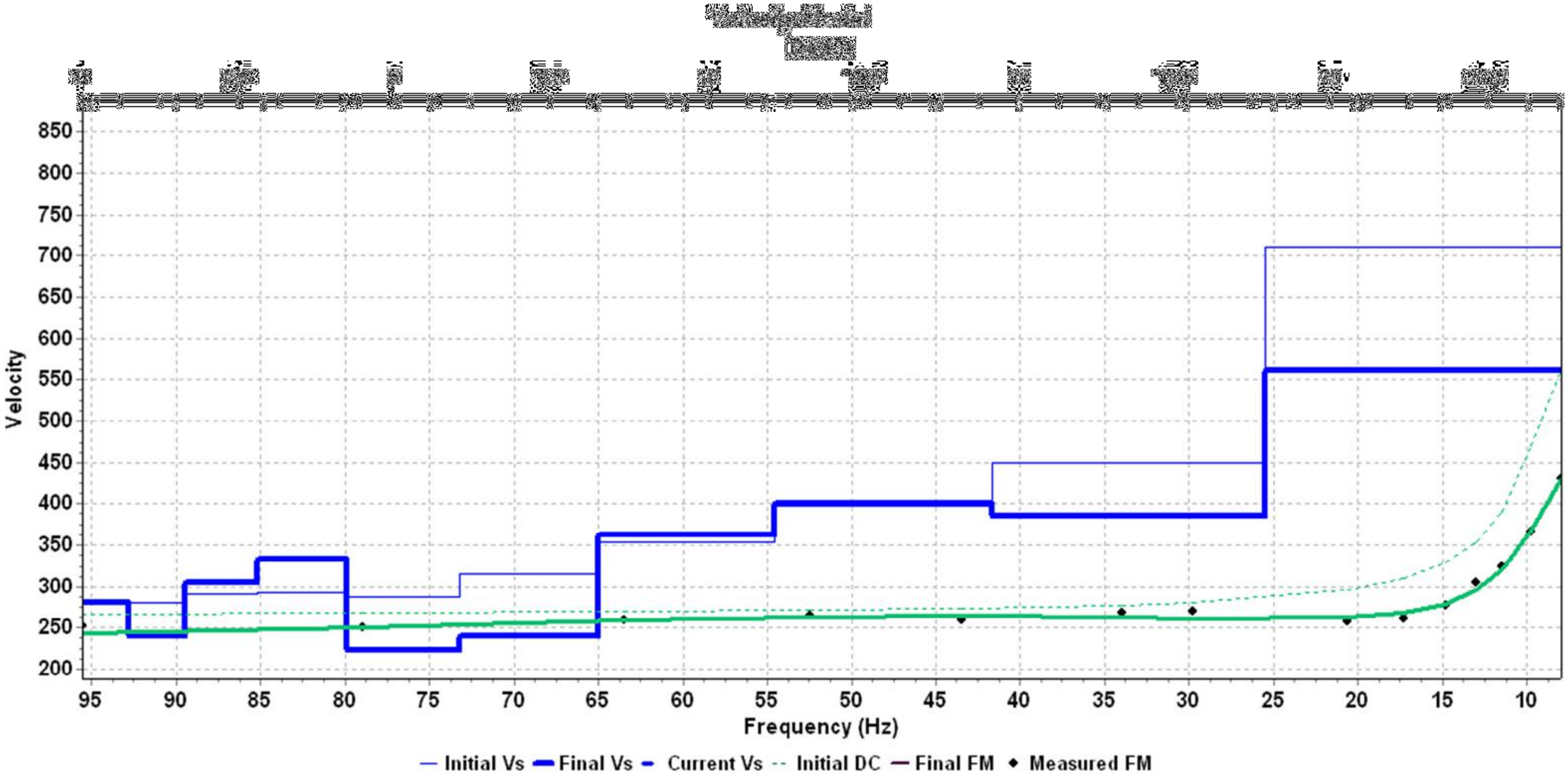
MI-39 Velocity Model



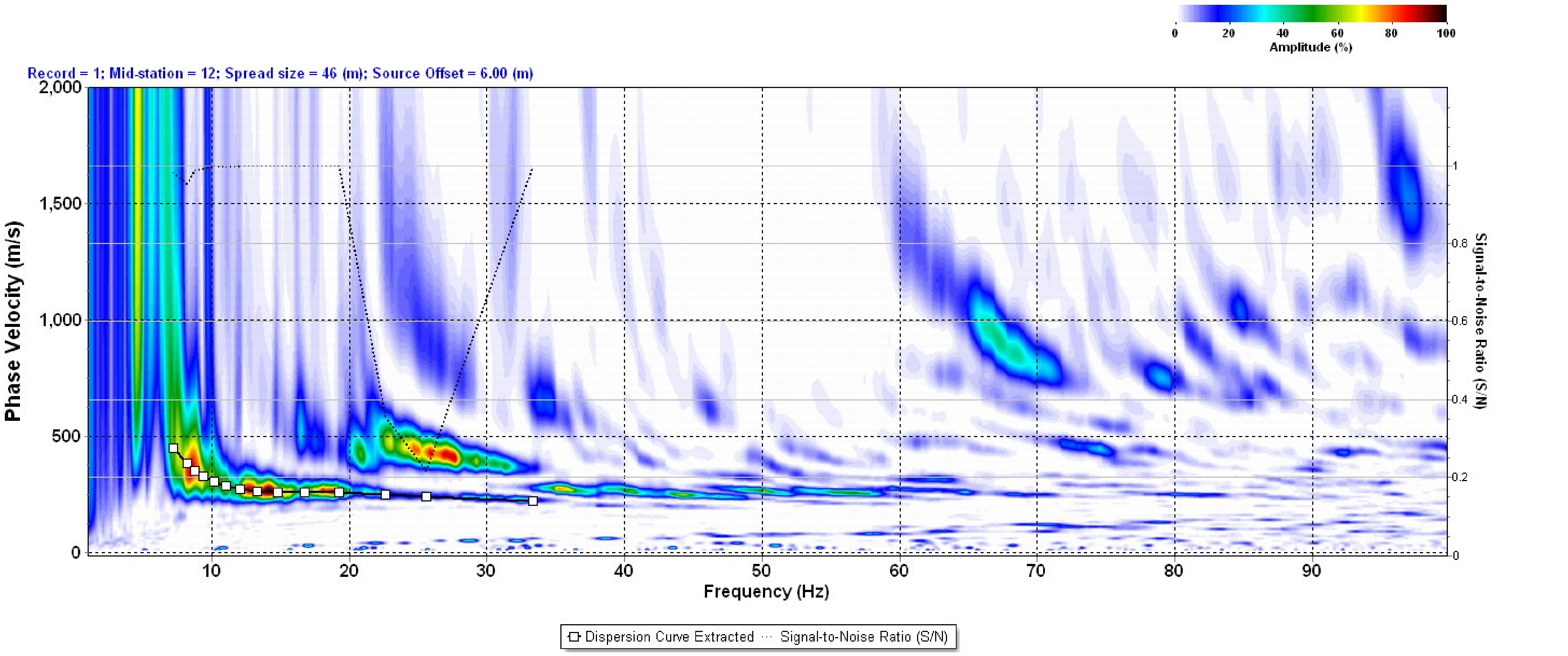
MI-40 Overtone Image



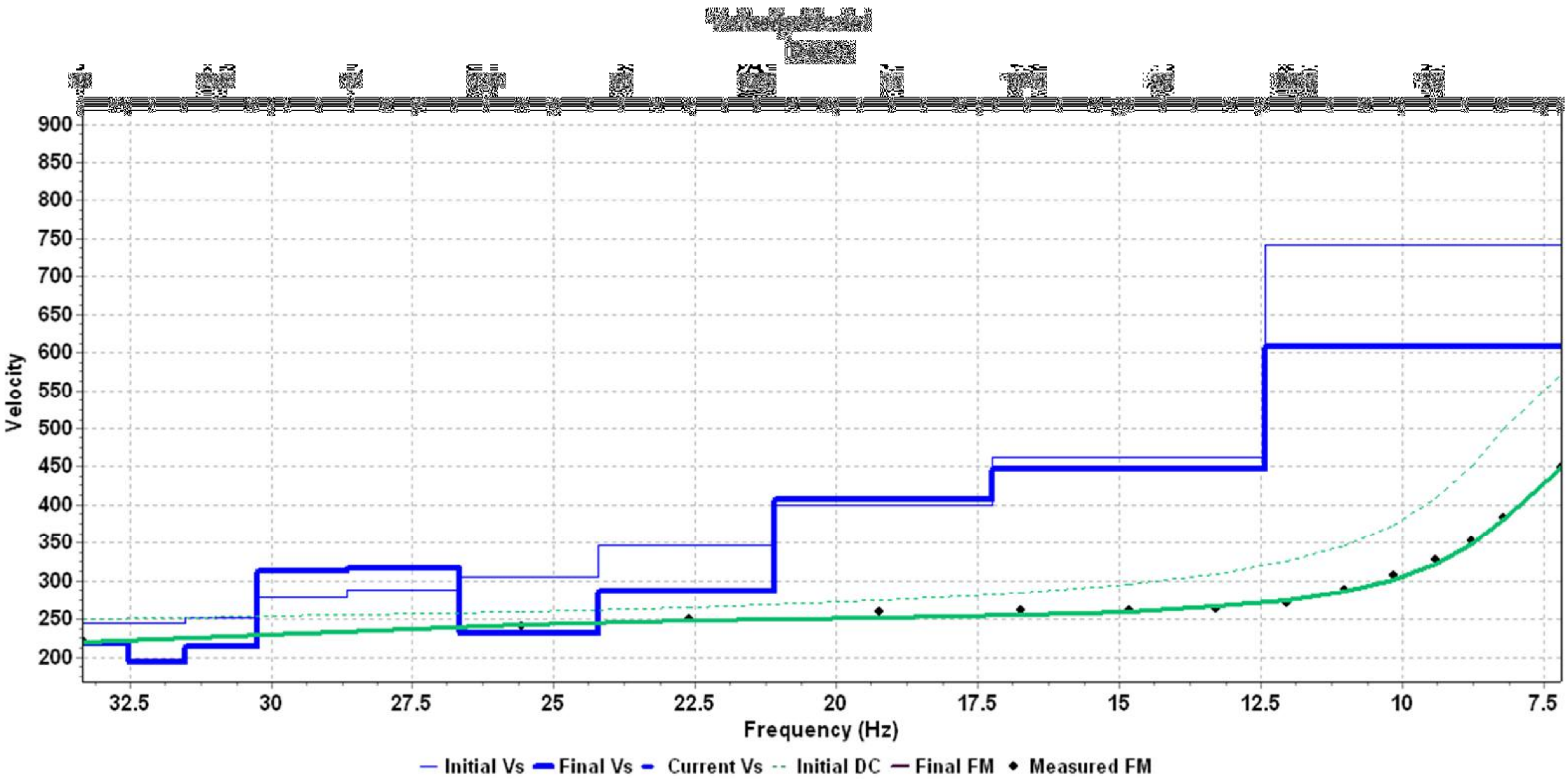
MI-40 Velocity Model



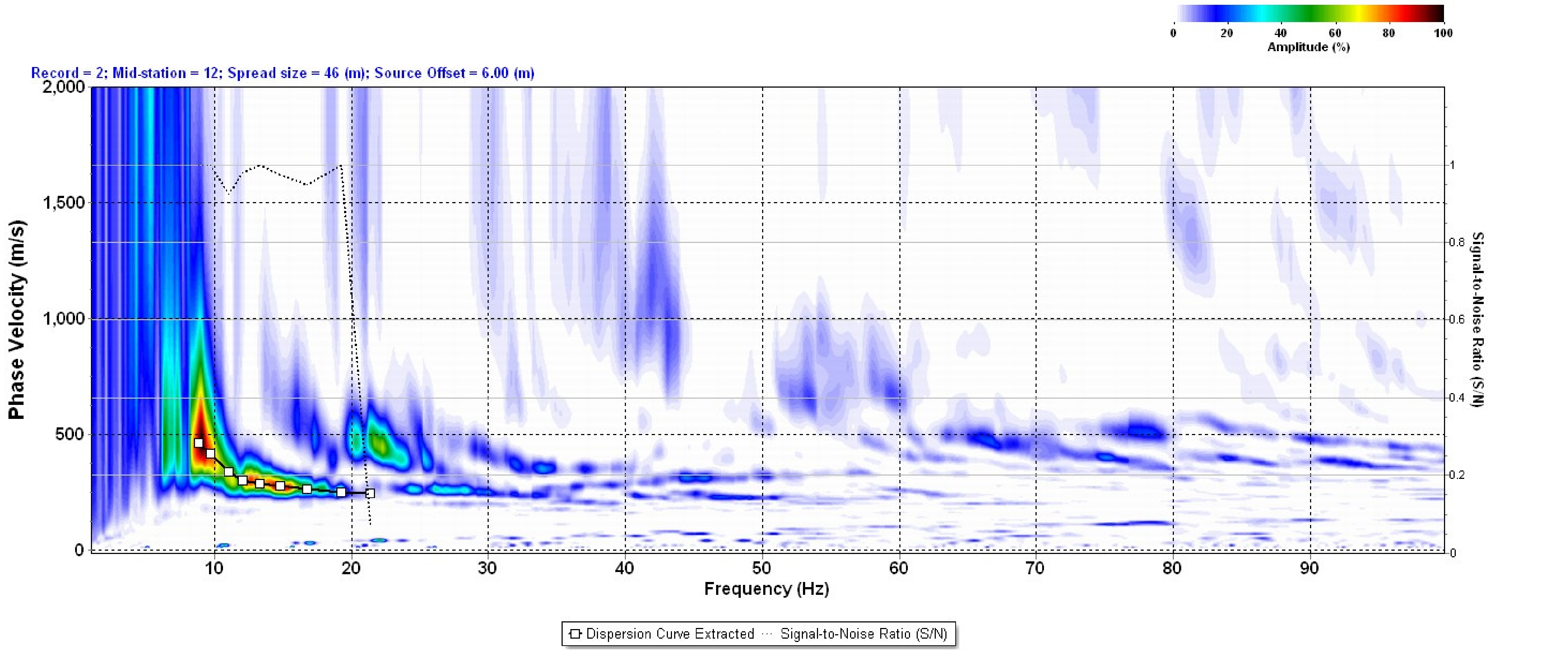
MI-41 Overtone Image



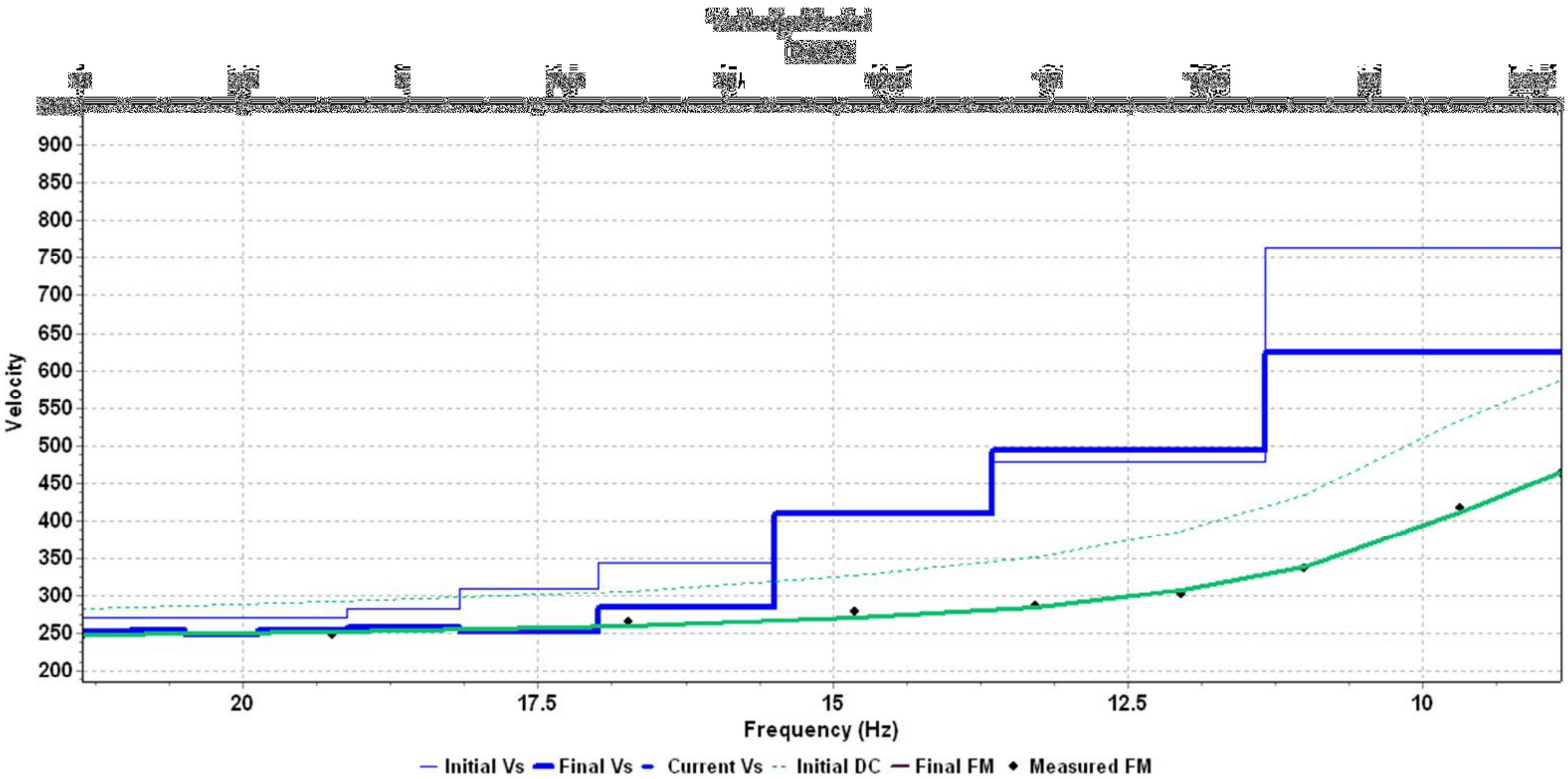
MI-41 Velocity Model



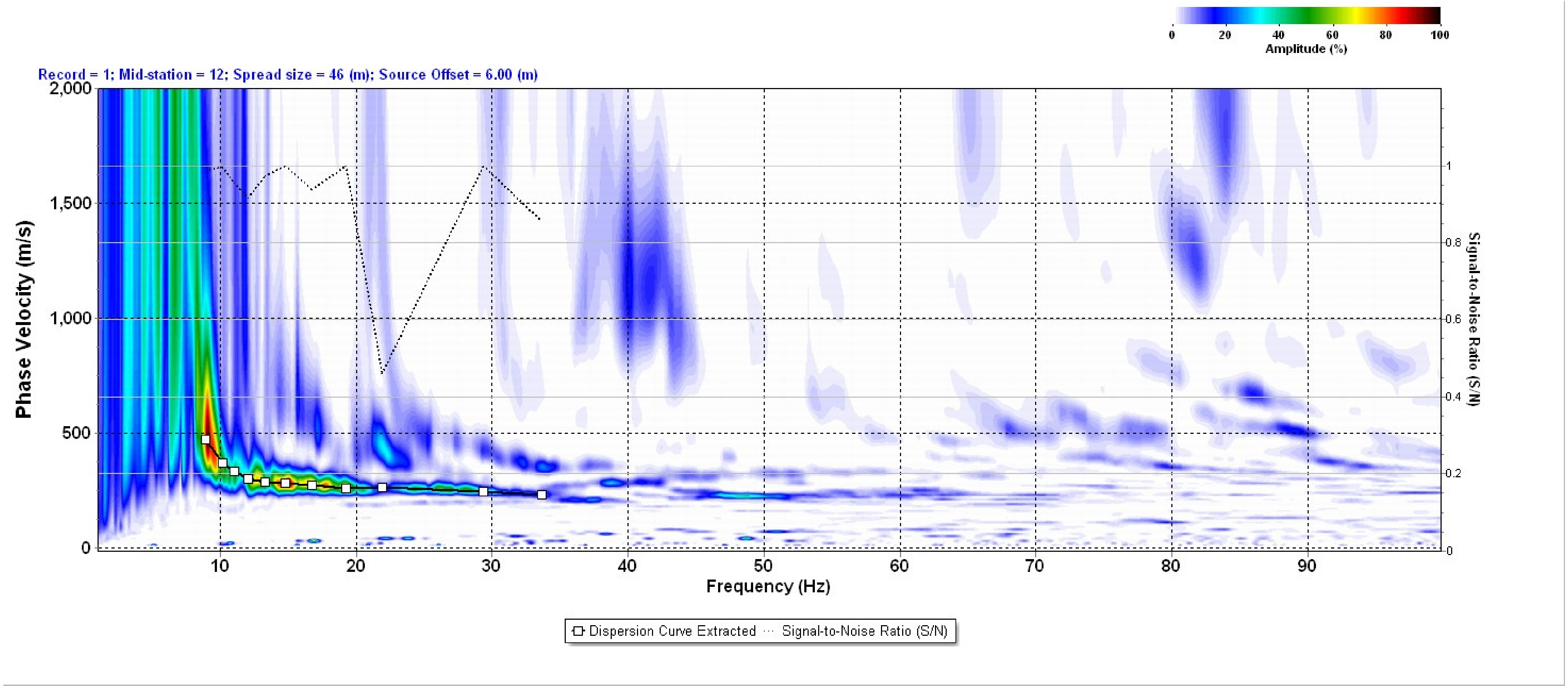
MI-42 Overtone Image



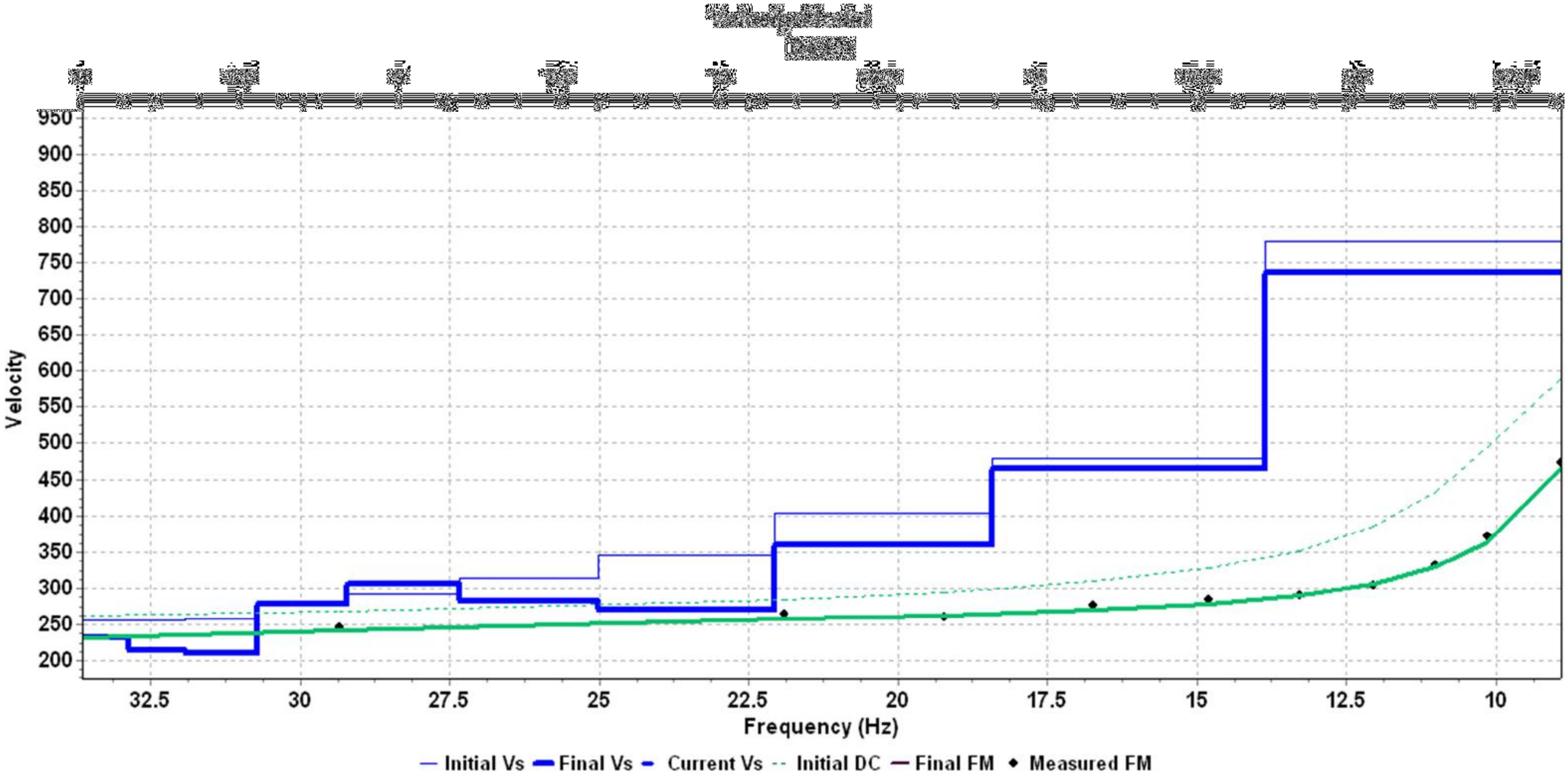
MI-42 Velocity Model



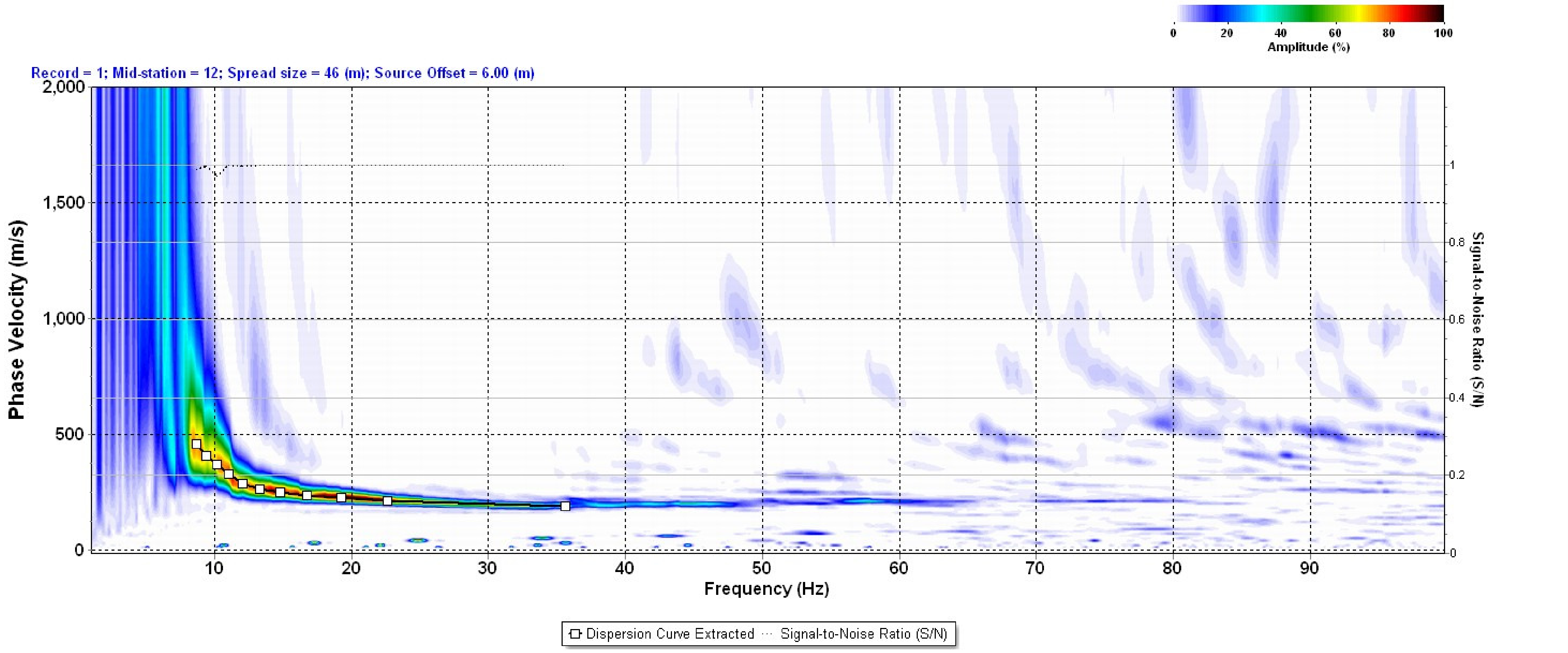
MI-42 Overtone Image (Hammer)



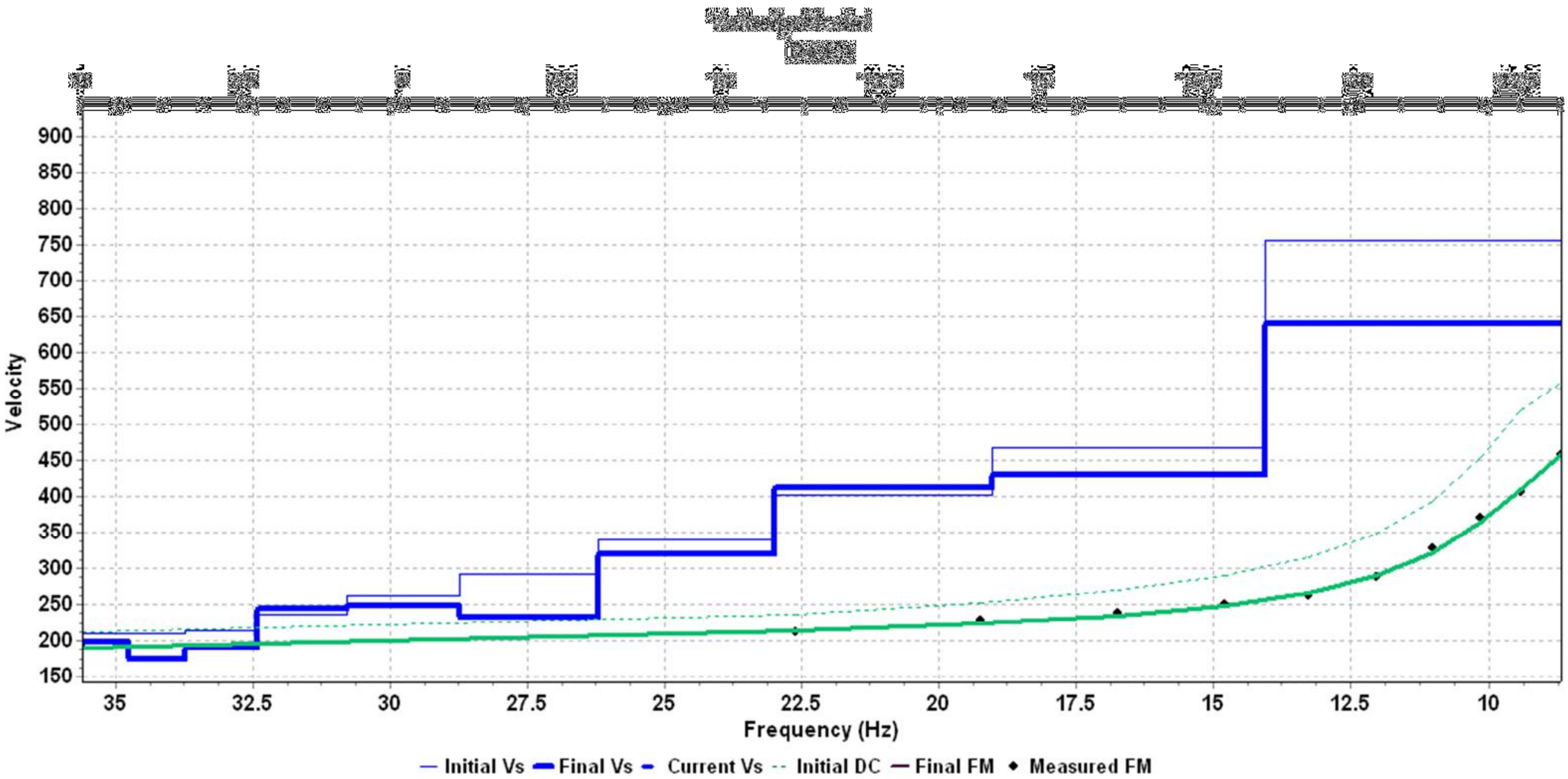
MI-42 Velocity Model (Hammer)



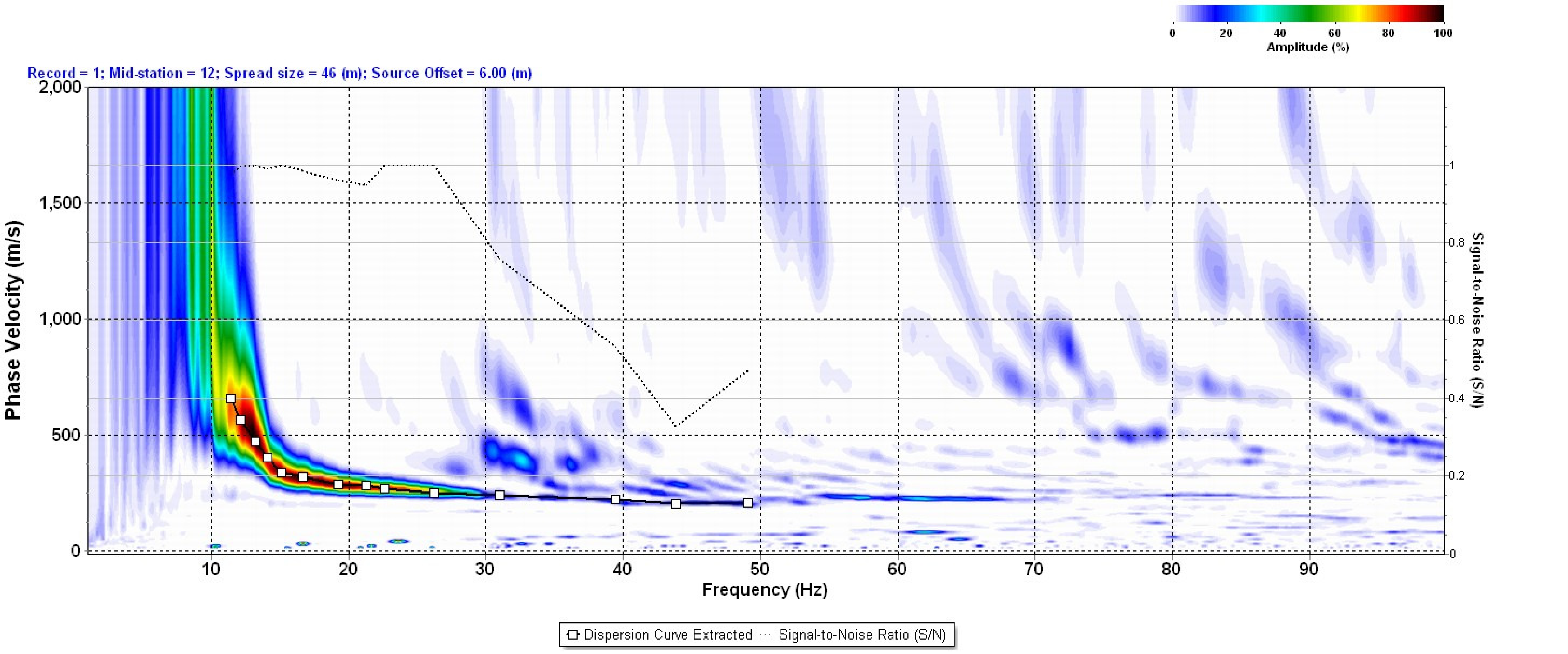
MI-43 Overtone Image



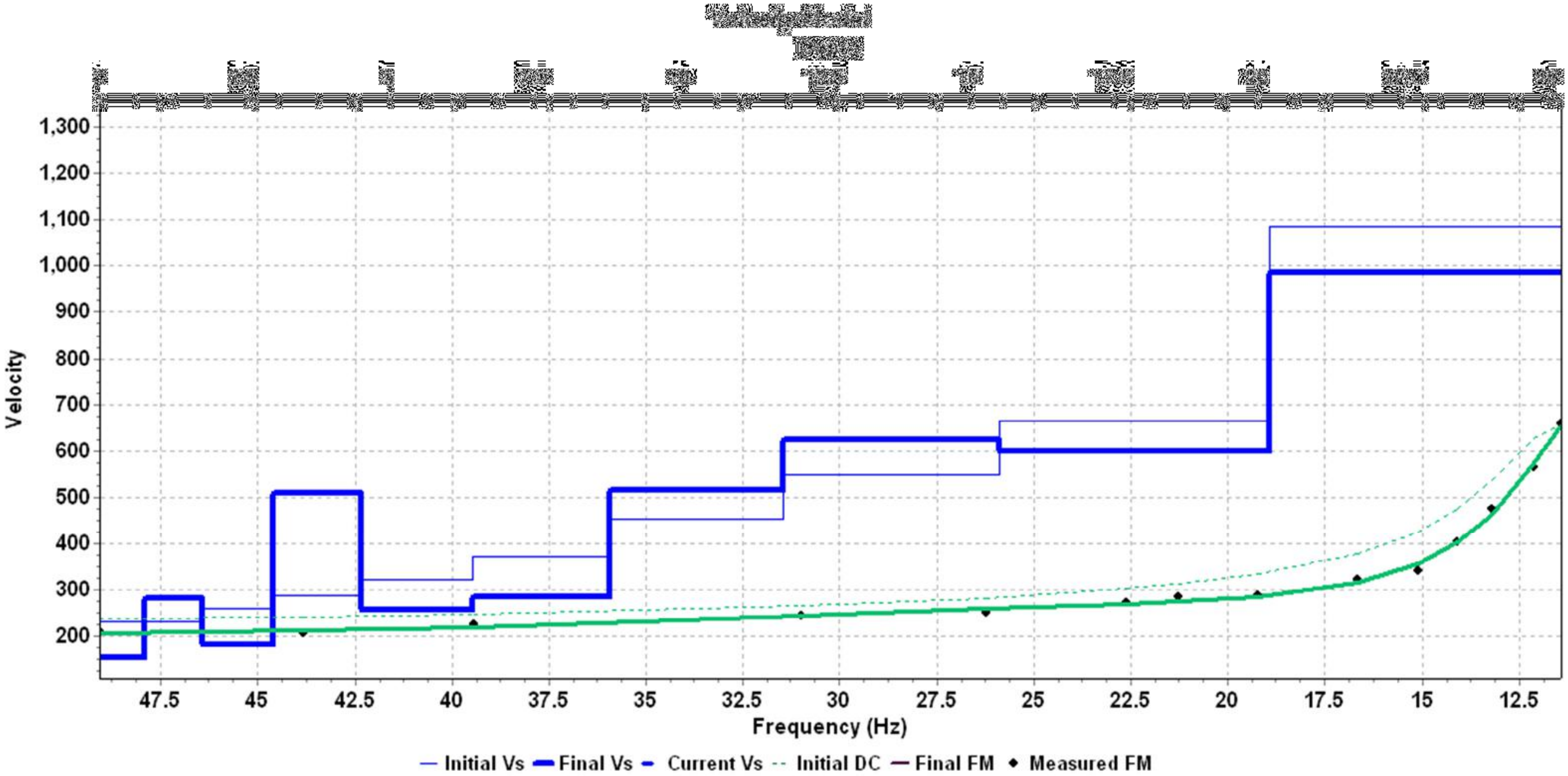
MI-43 Velocity Model



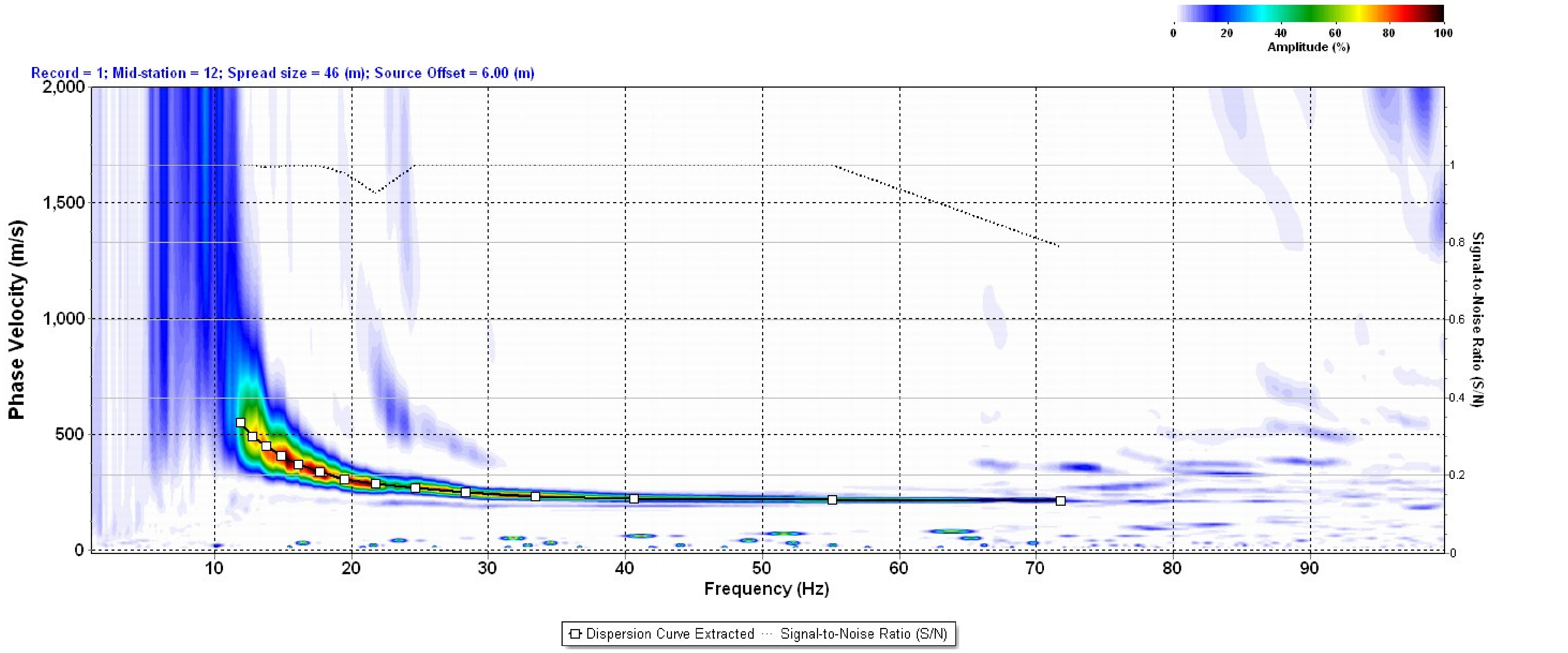
MI-44 Overtone Image



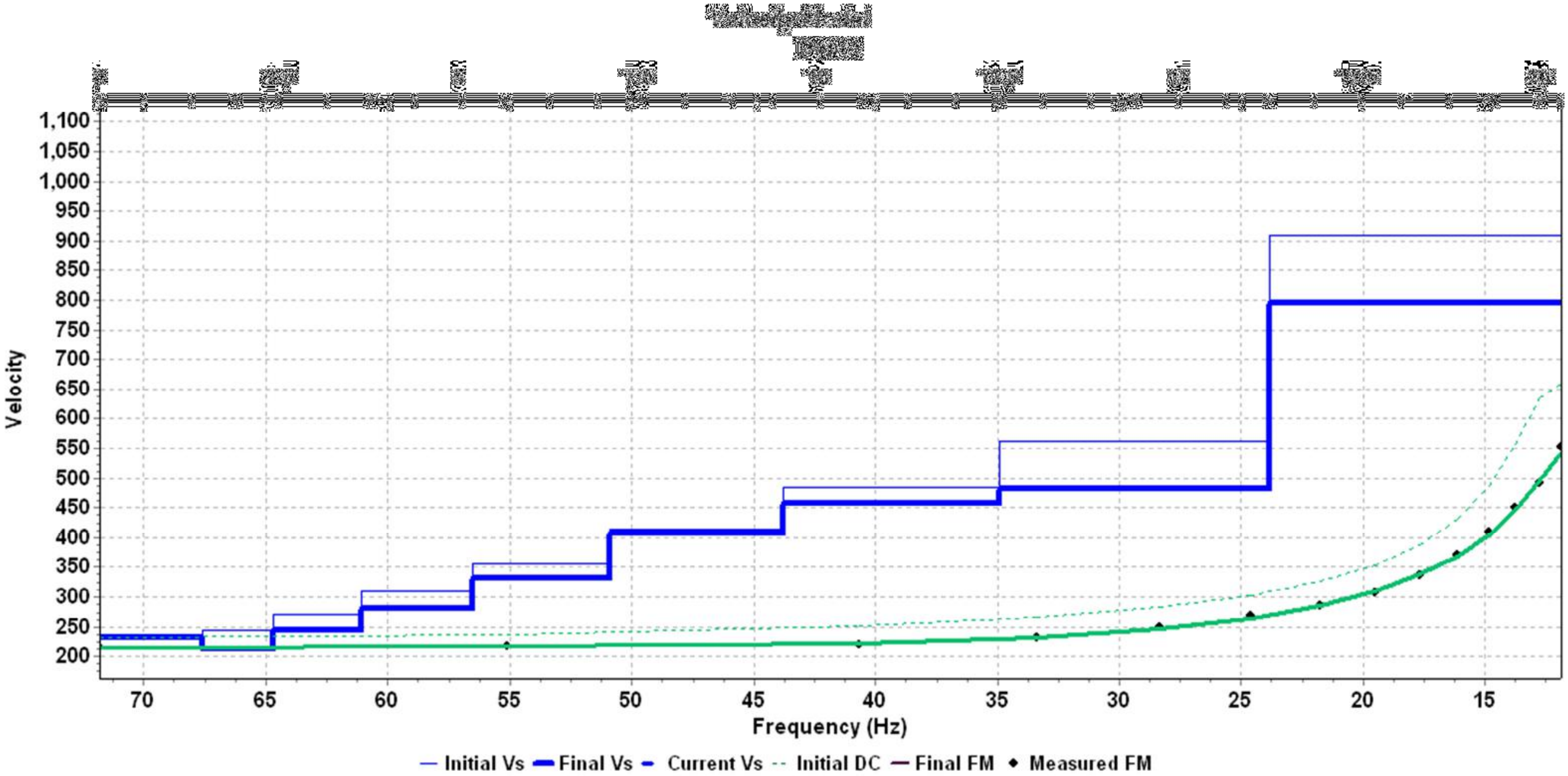
MI-44 Velocity Model



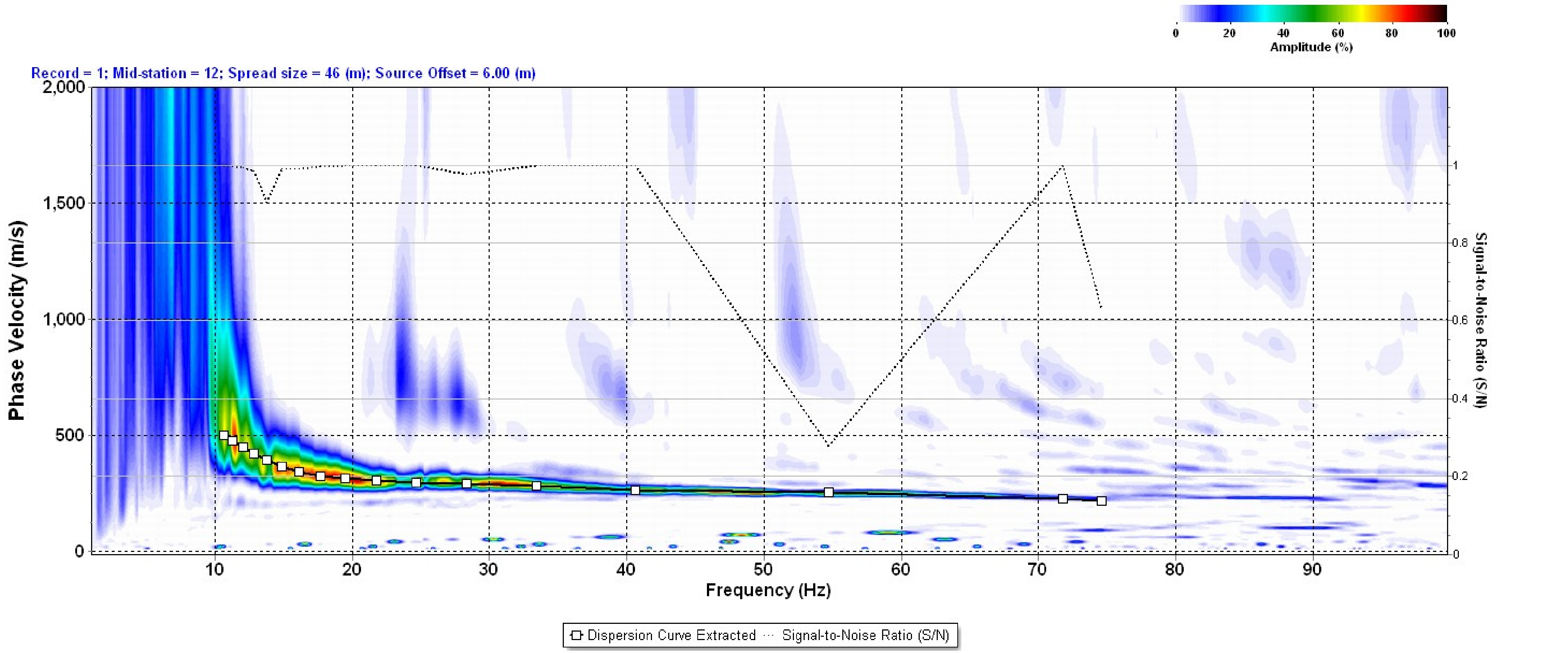
MI-45 Overtone Image



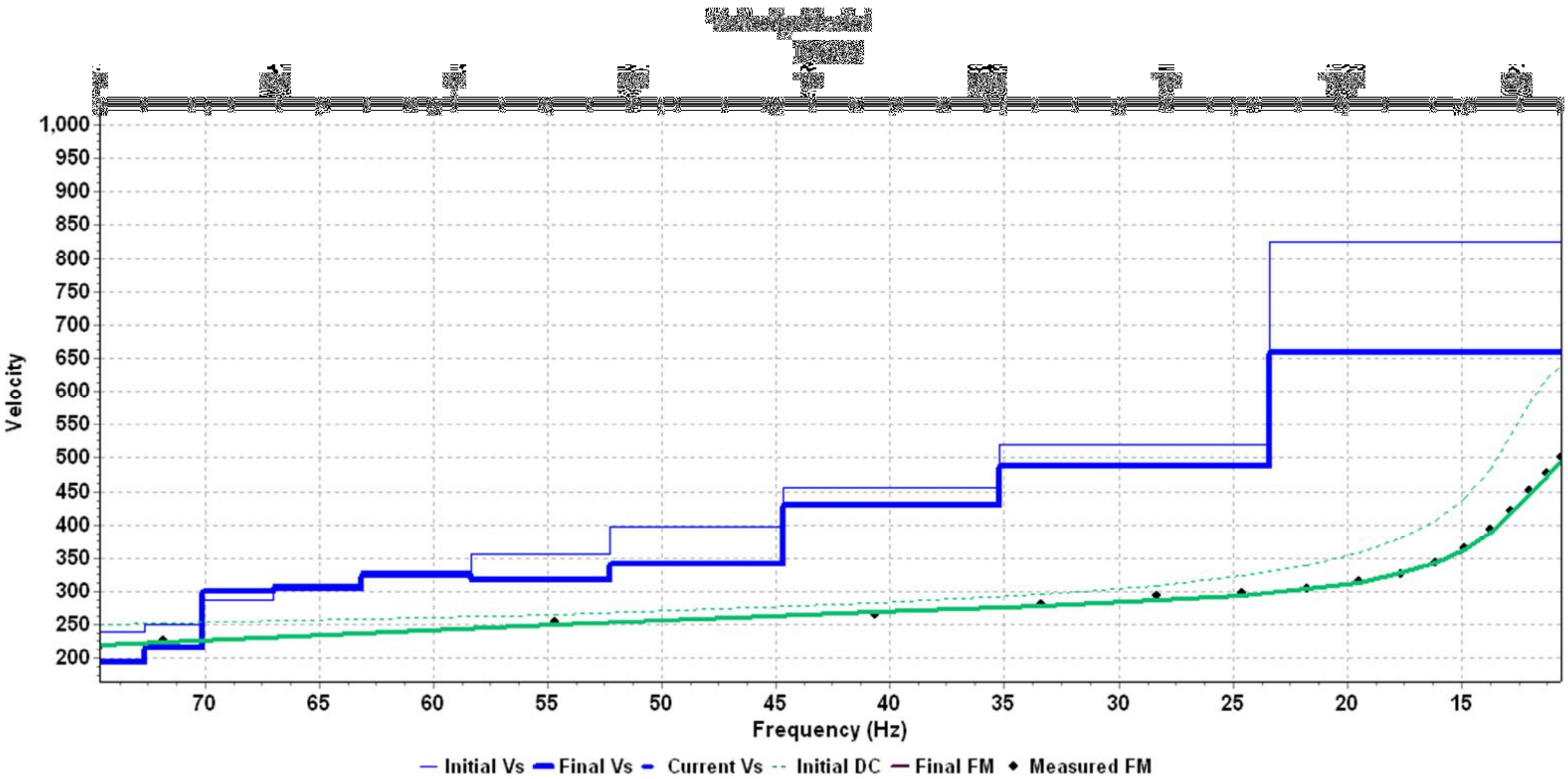
MI-45 Velocity Model



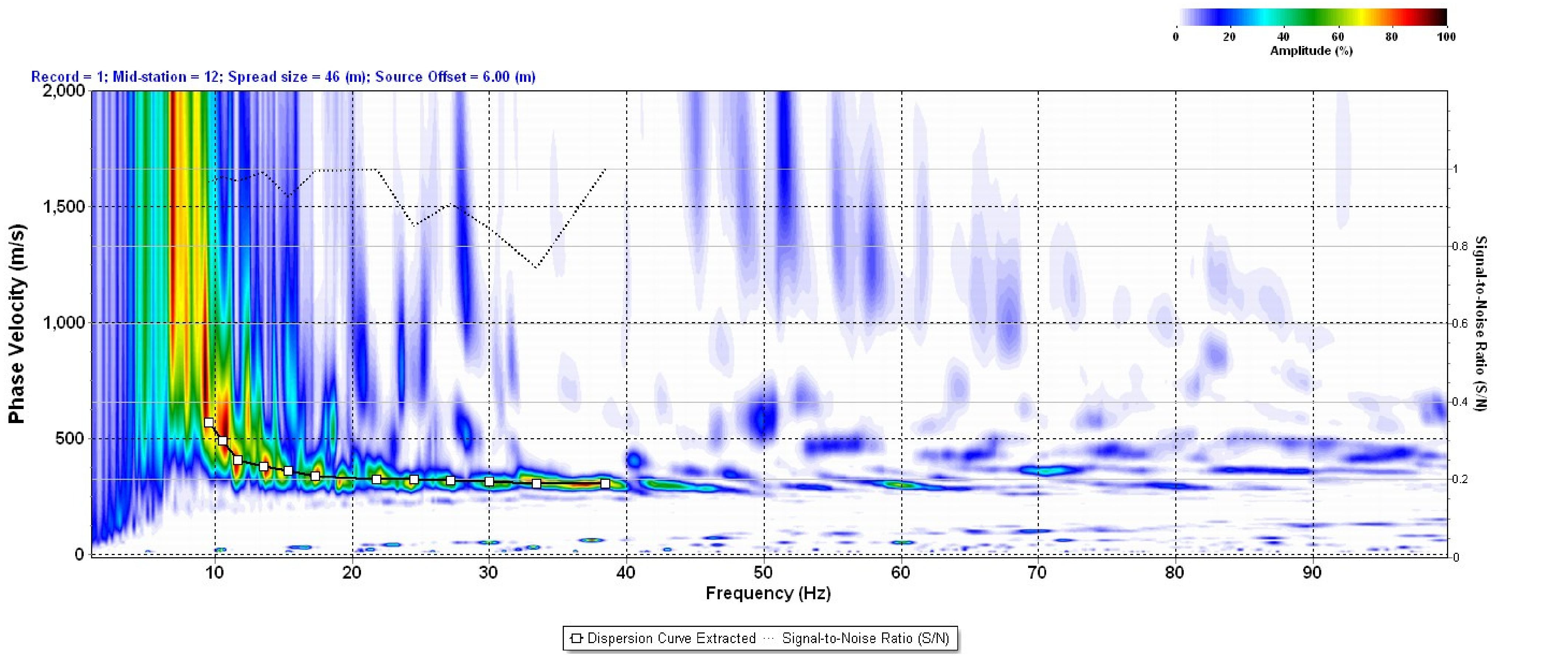
MI-46 Overtone Image



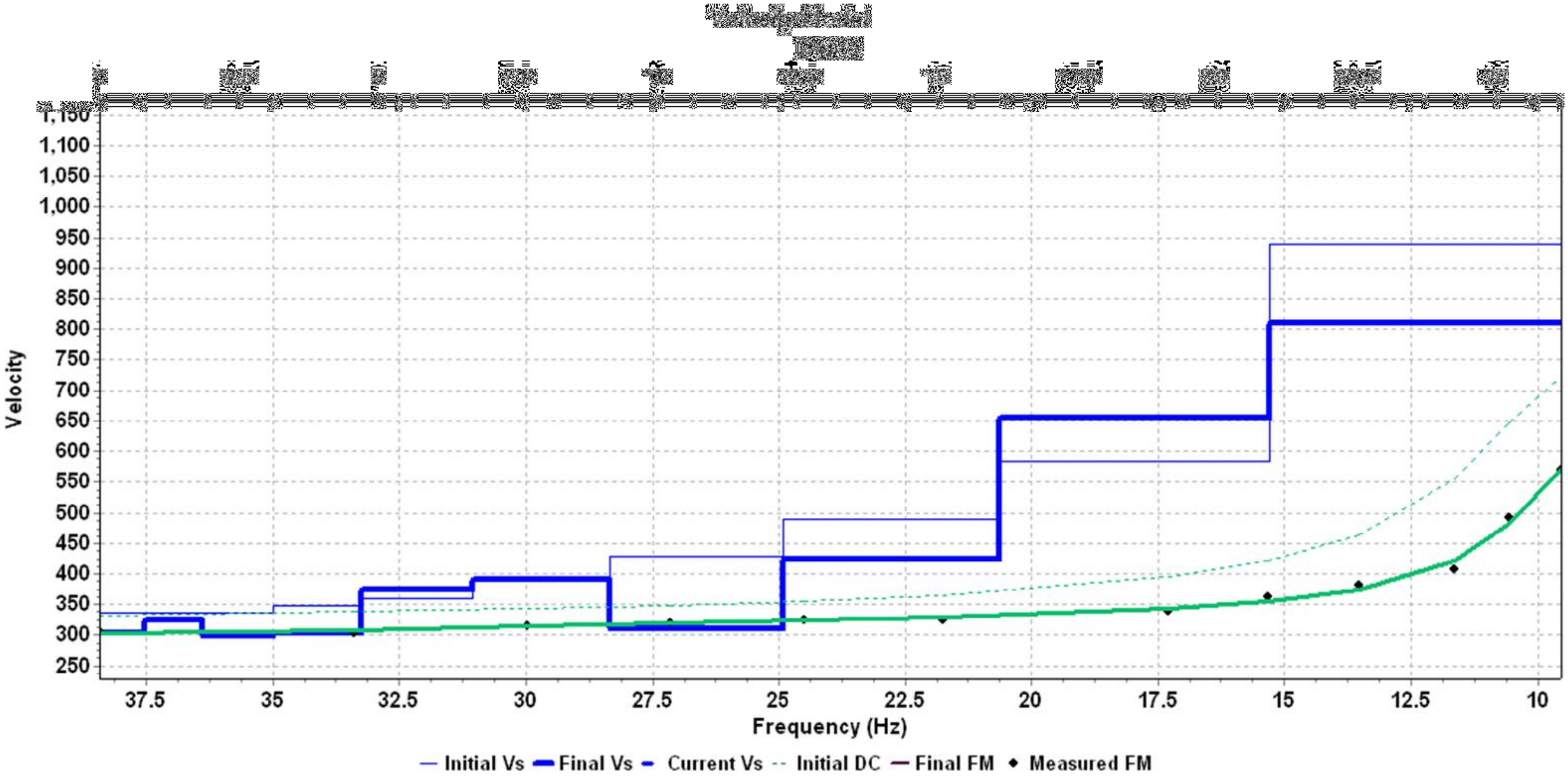
MI-46 Velocity Model



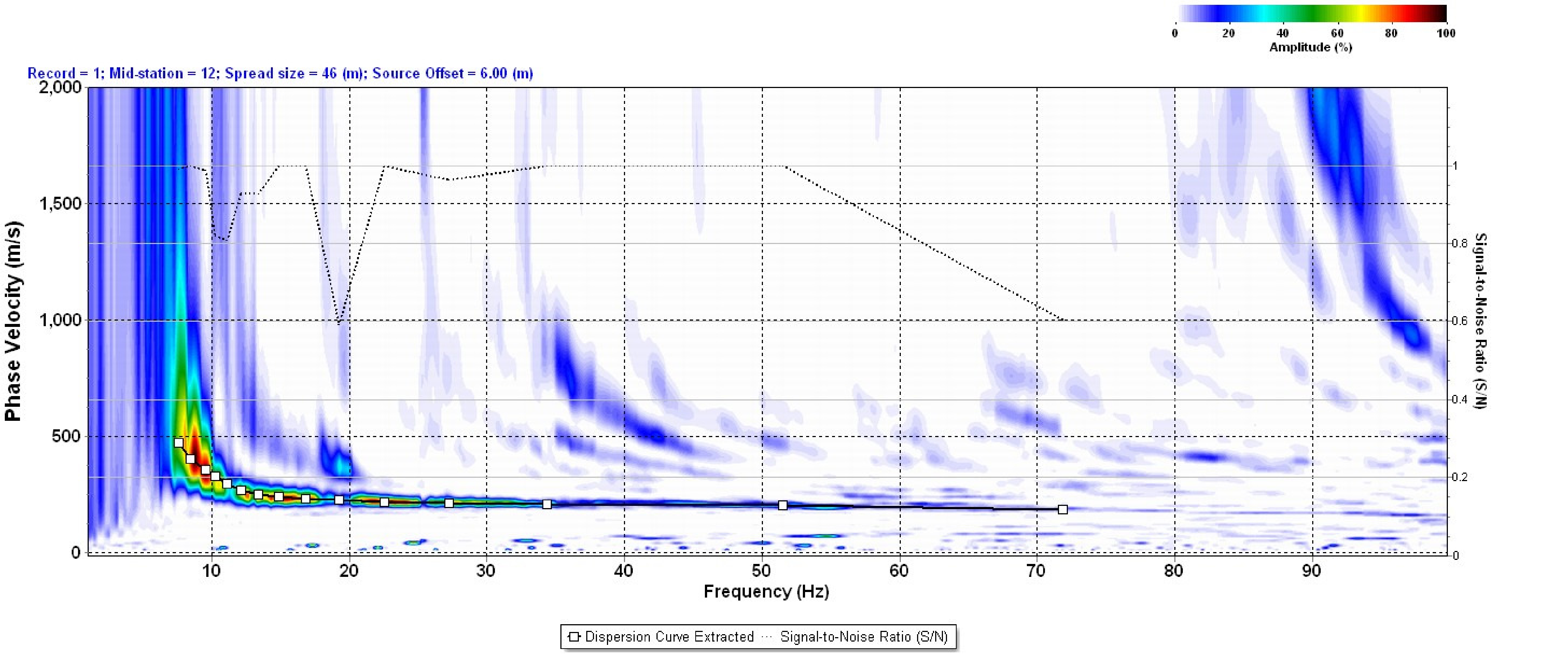
MI-47 Overtone Image



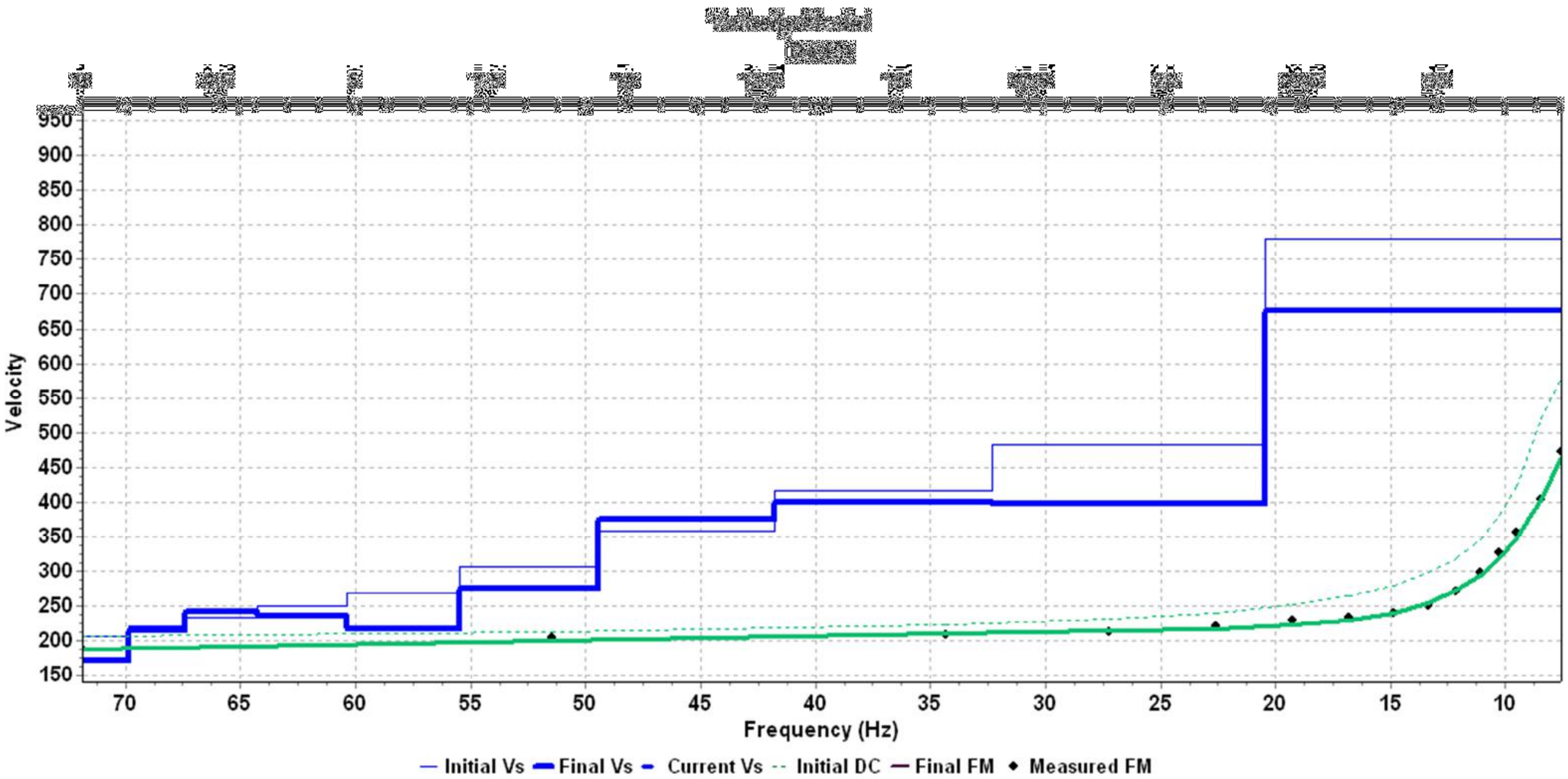
MI-47 Velocity Model



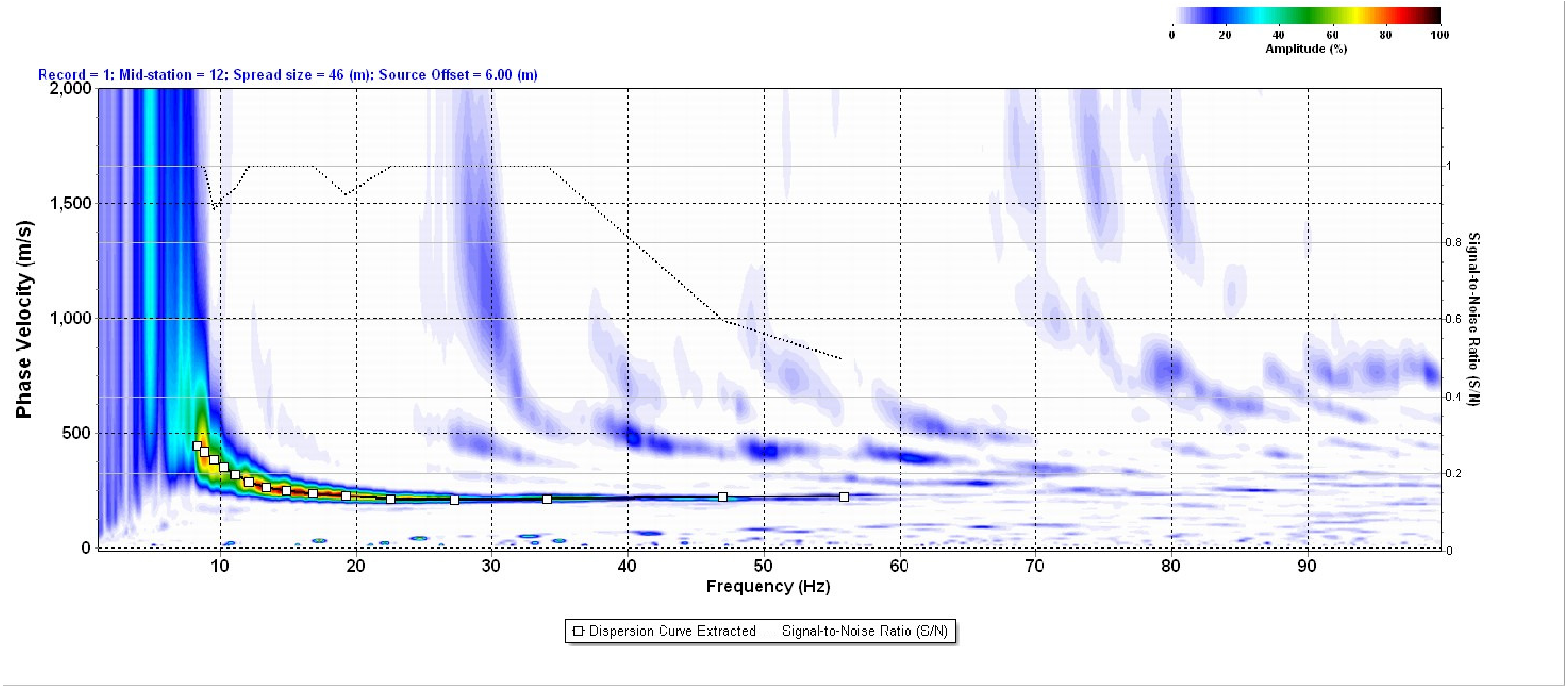
MI-48 Overtone Image



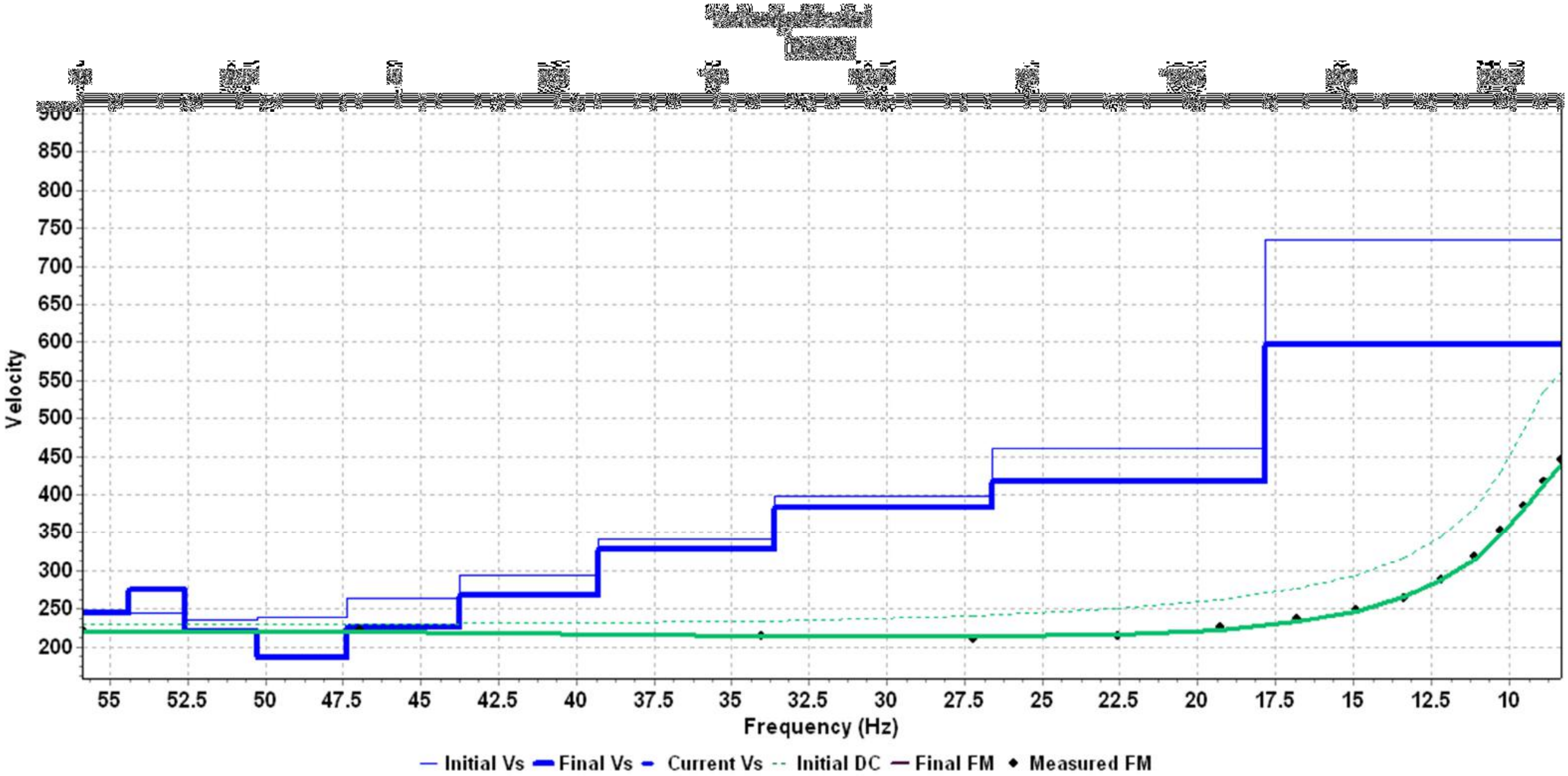
MI-48 Velocity Model



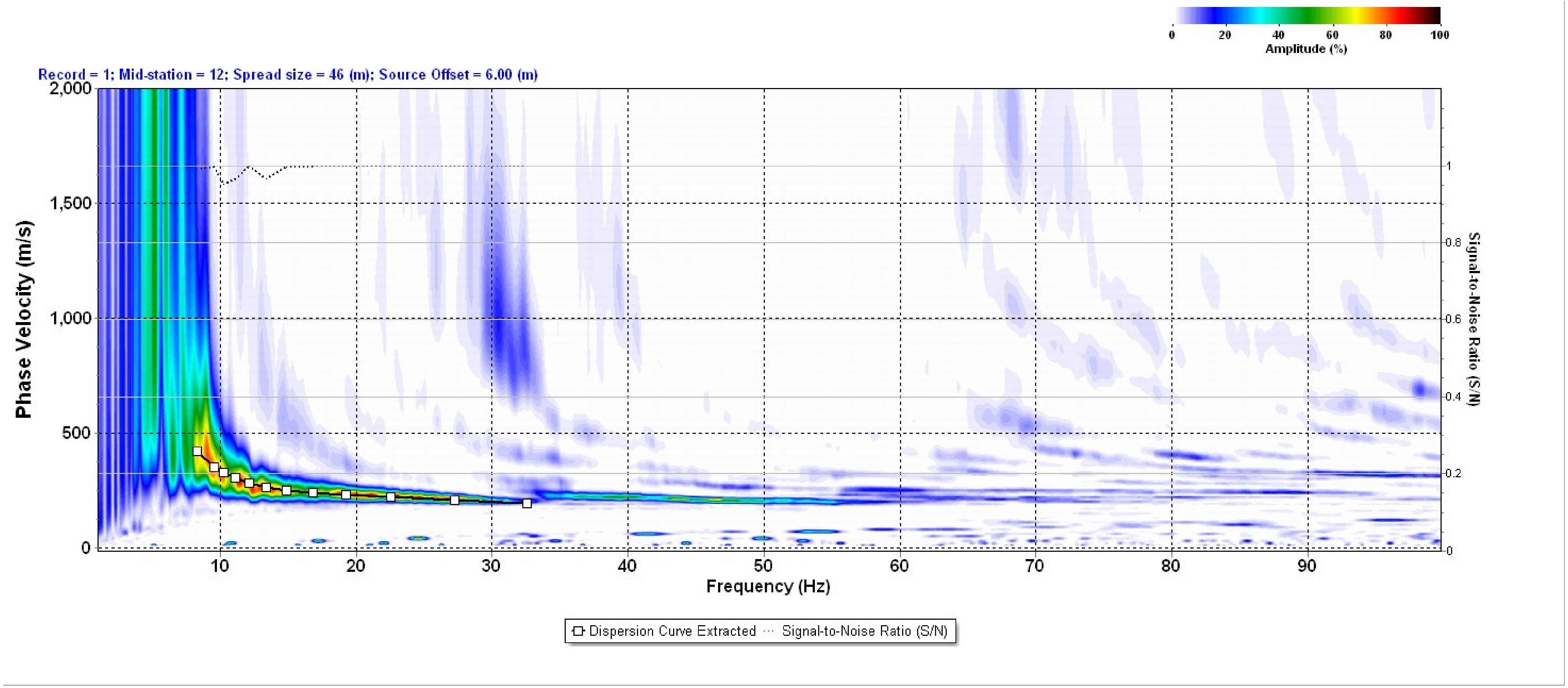
MI-49 Overtone Image



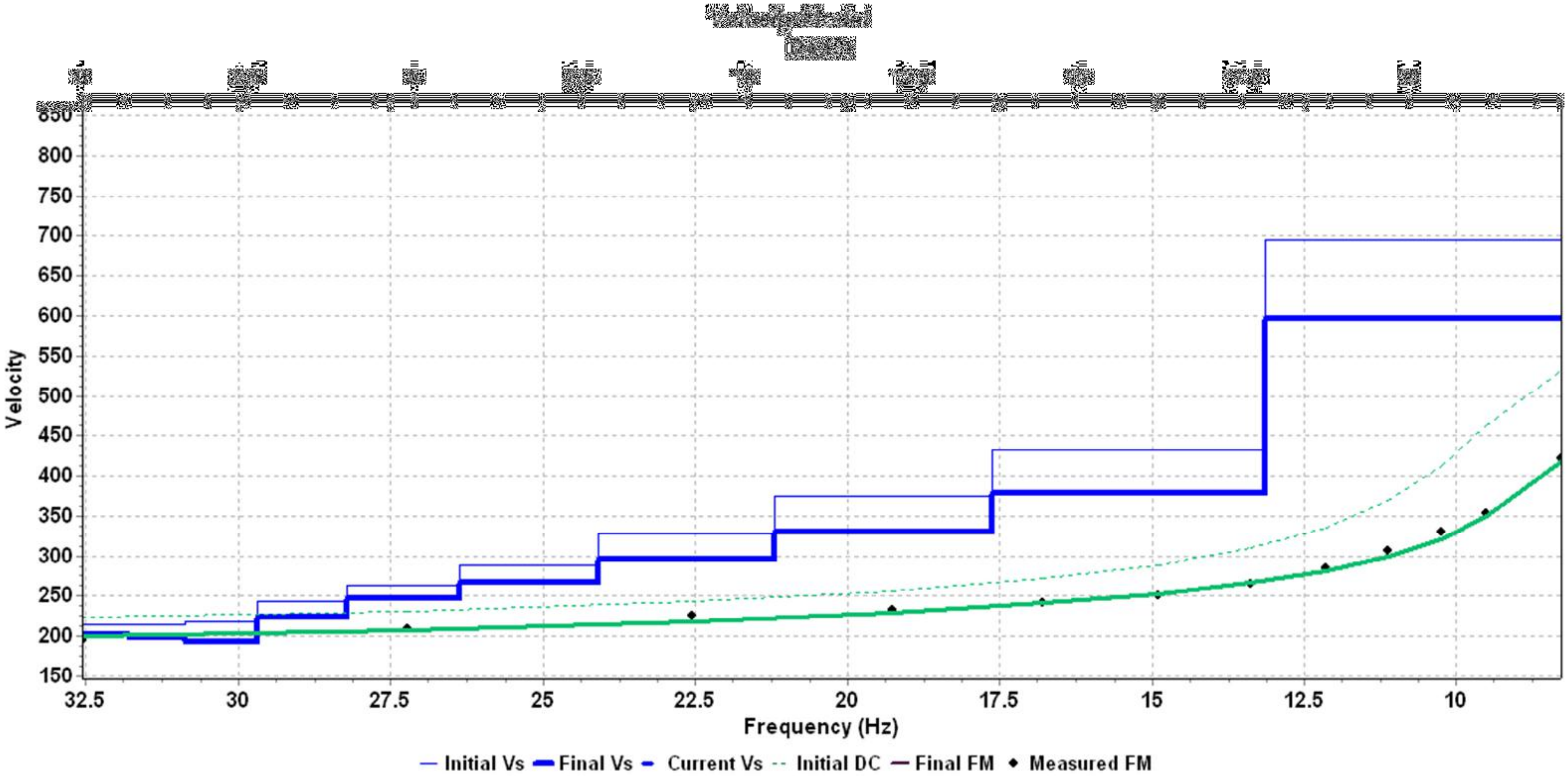
MI-49 Velocity Model



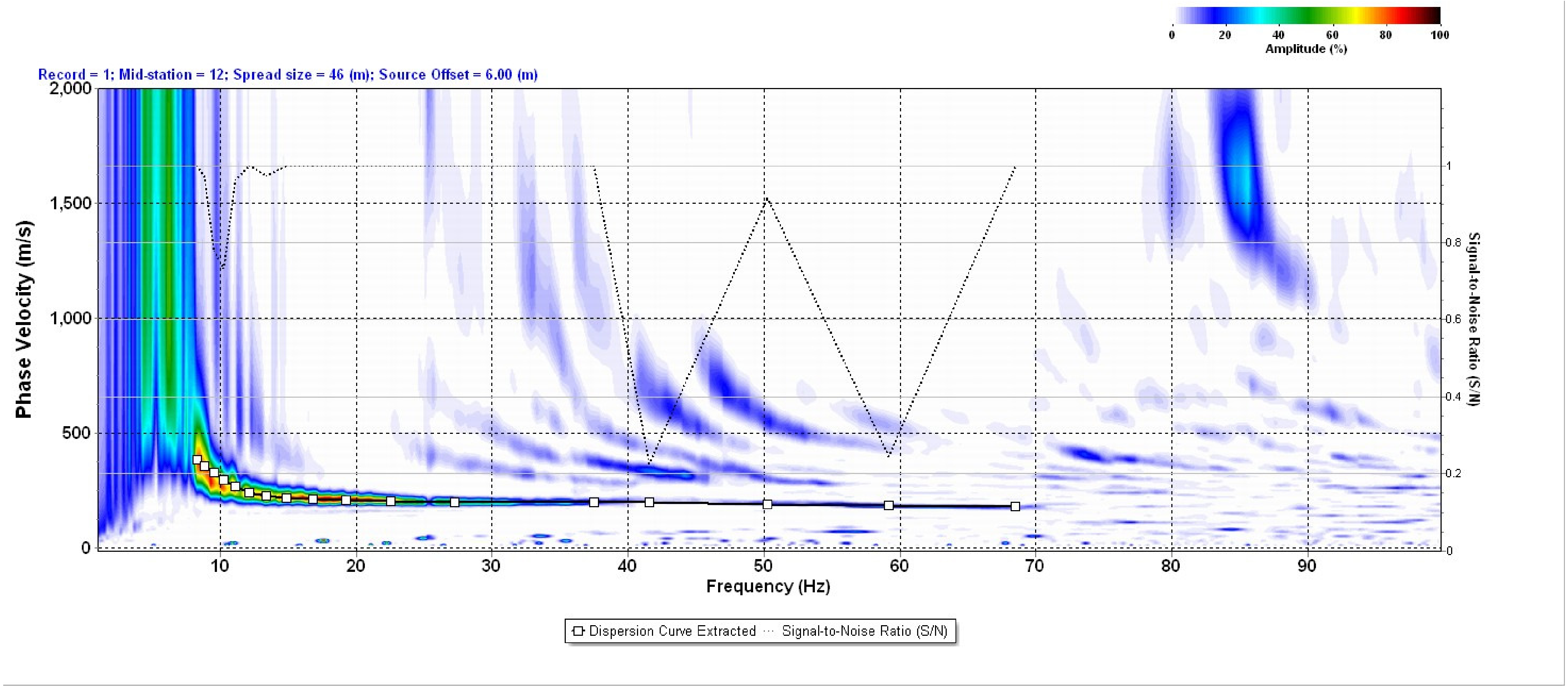
MI-50 Overtone Image



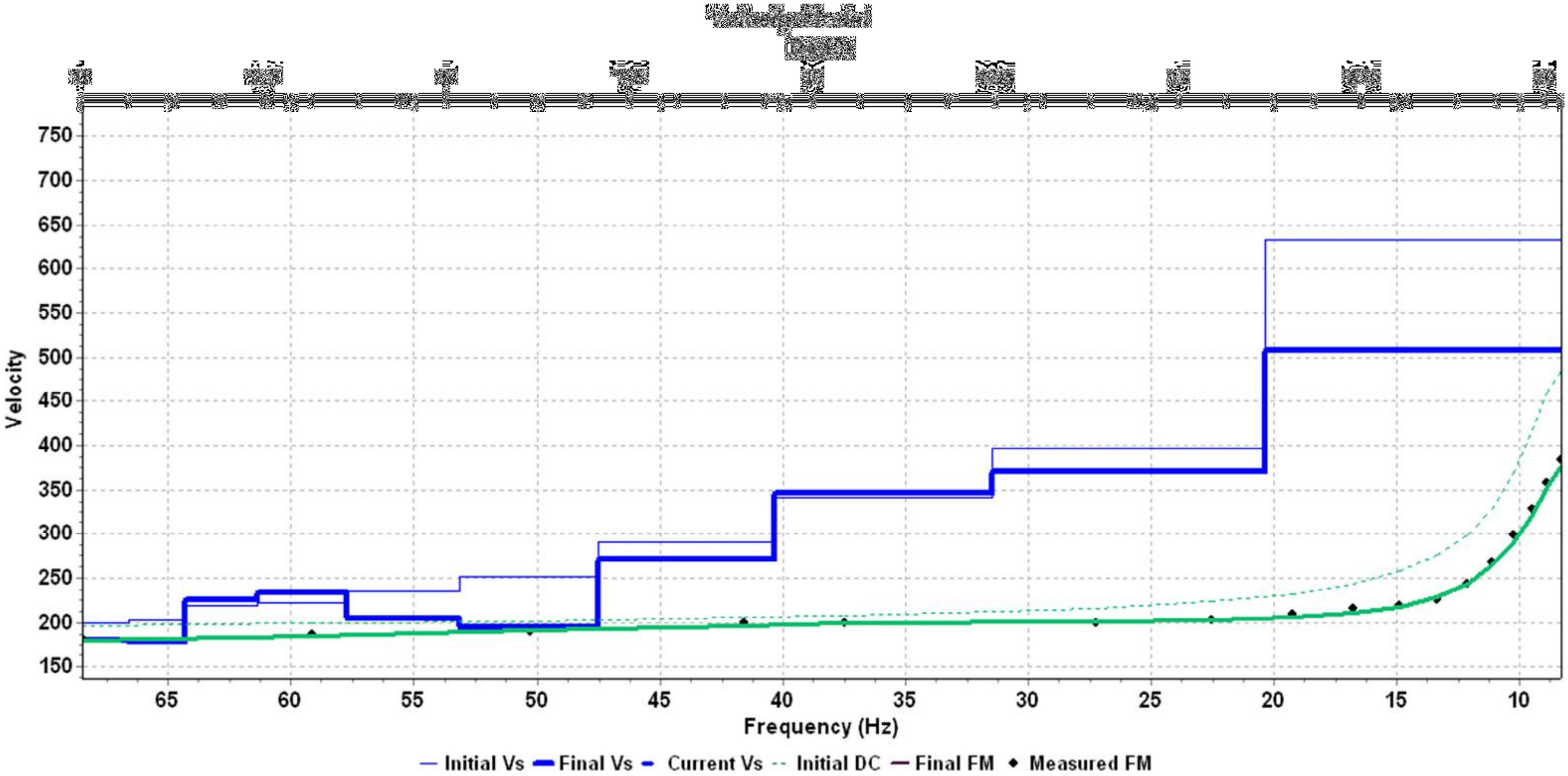
MI-50 Velocity Model



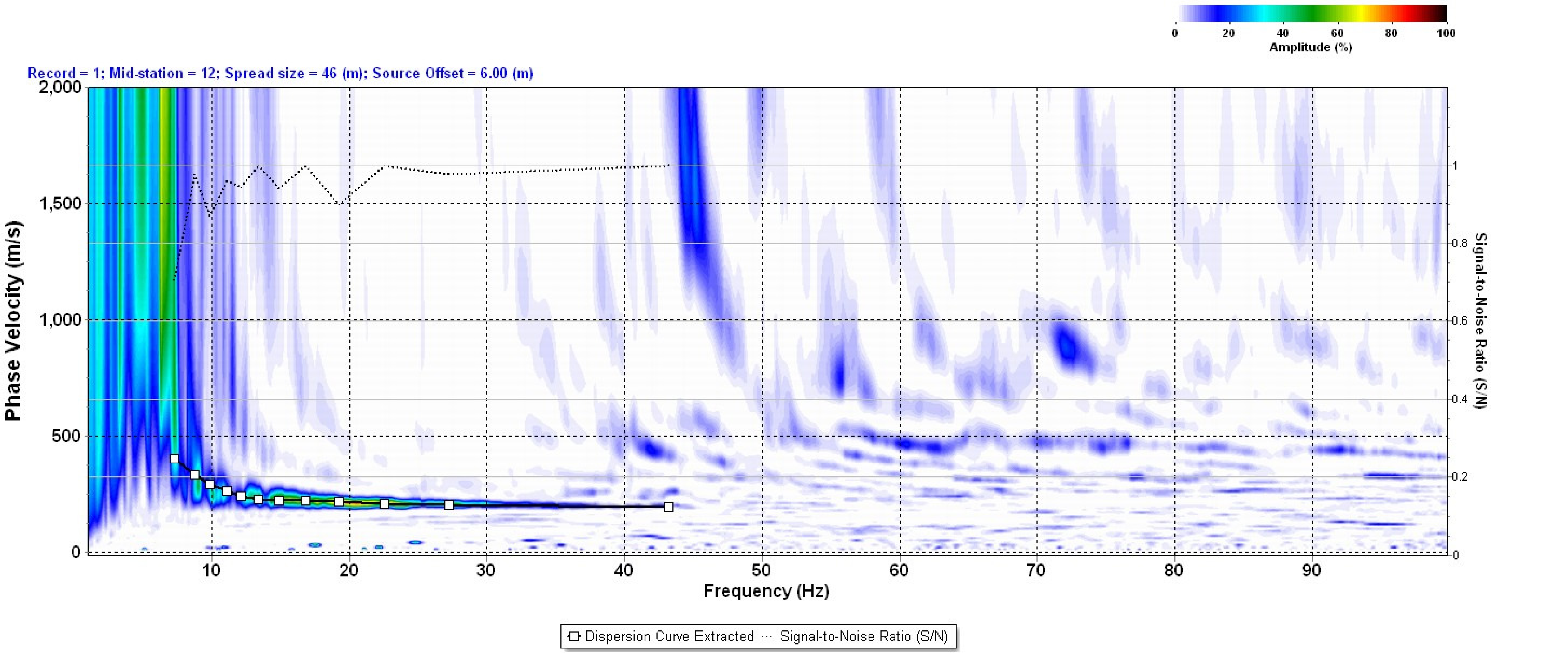
MI-51 Overtone Image



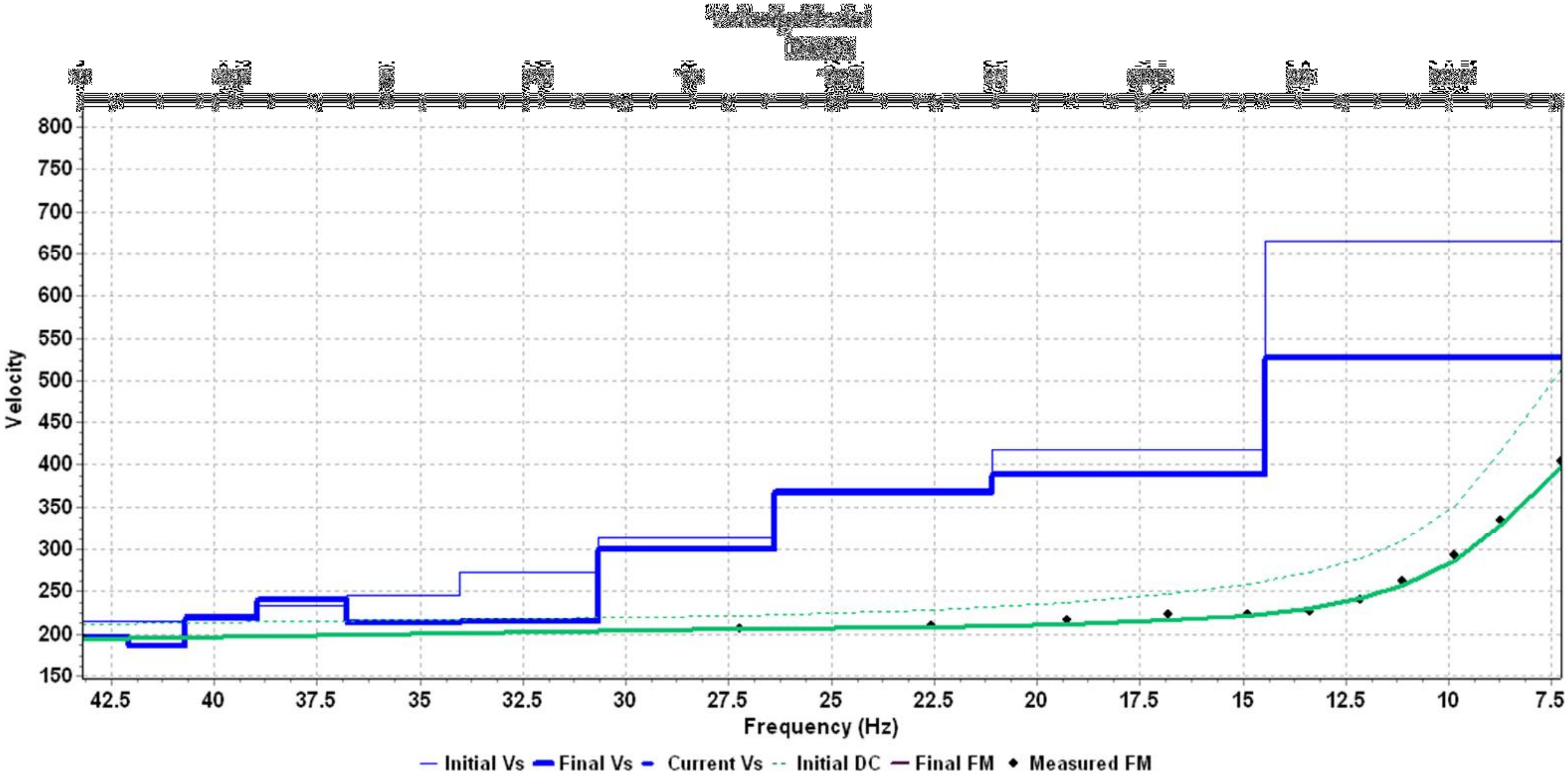
MI-51 Velocity Model



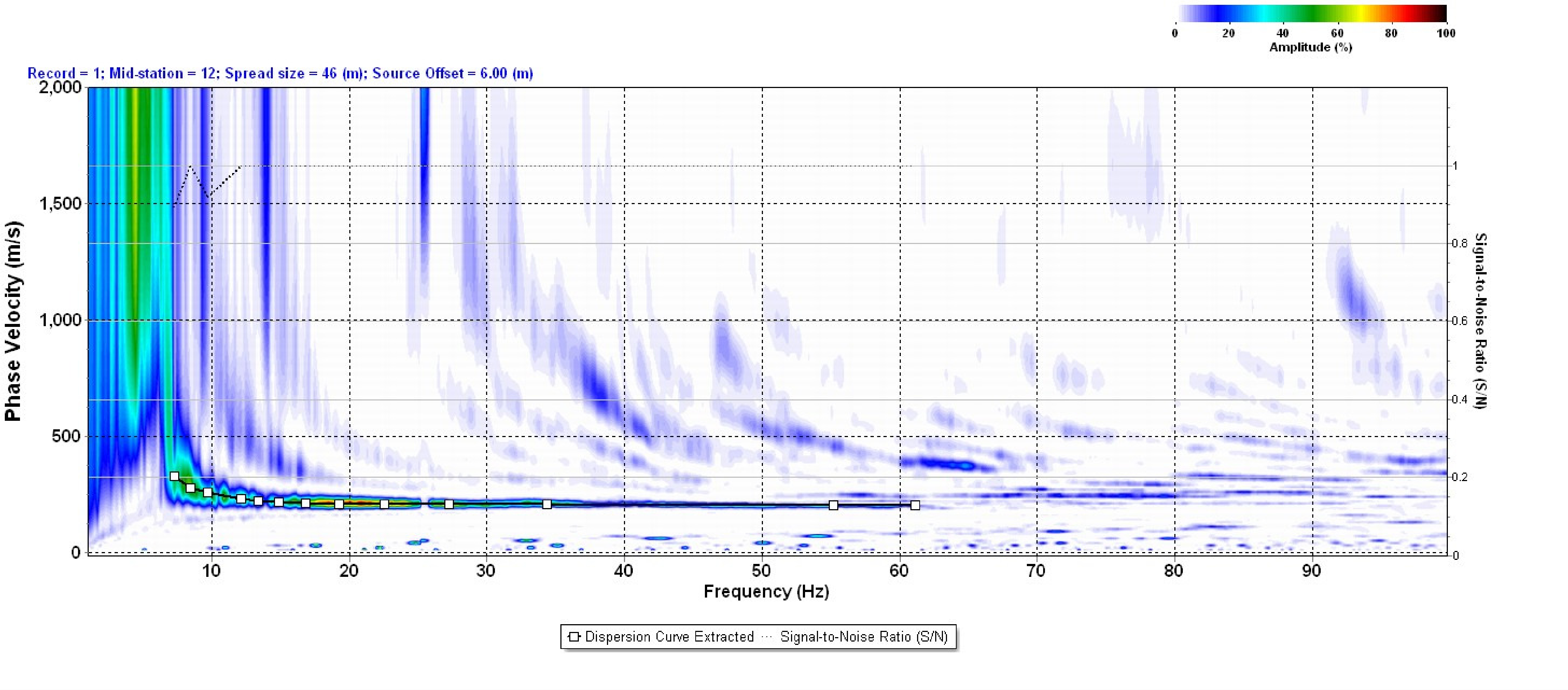
MI-52 Overtone Image



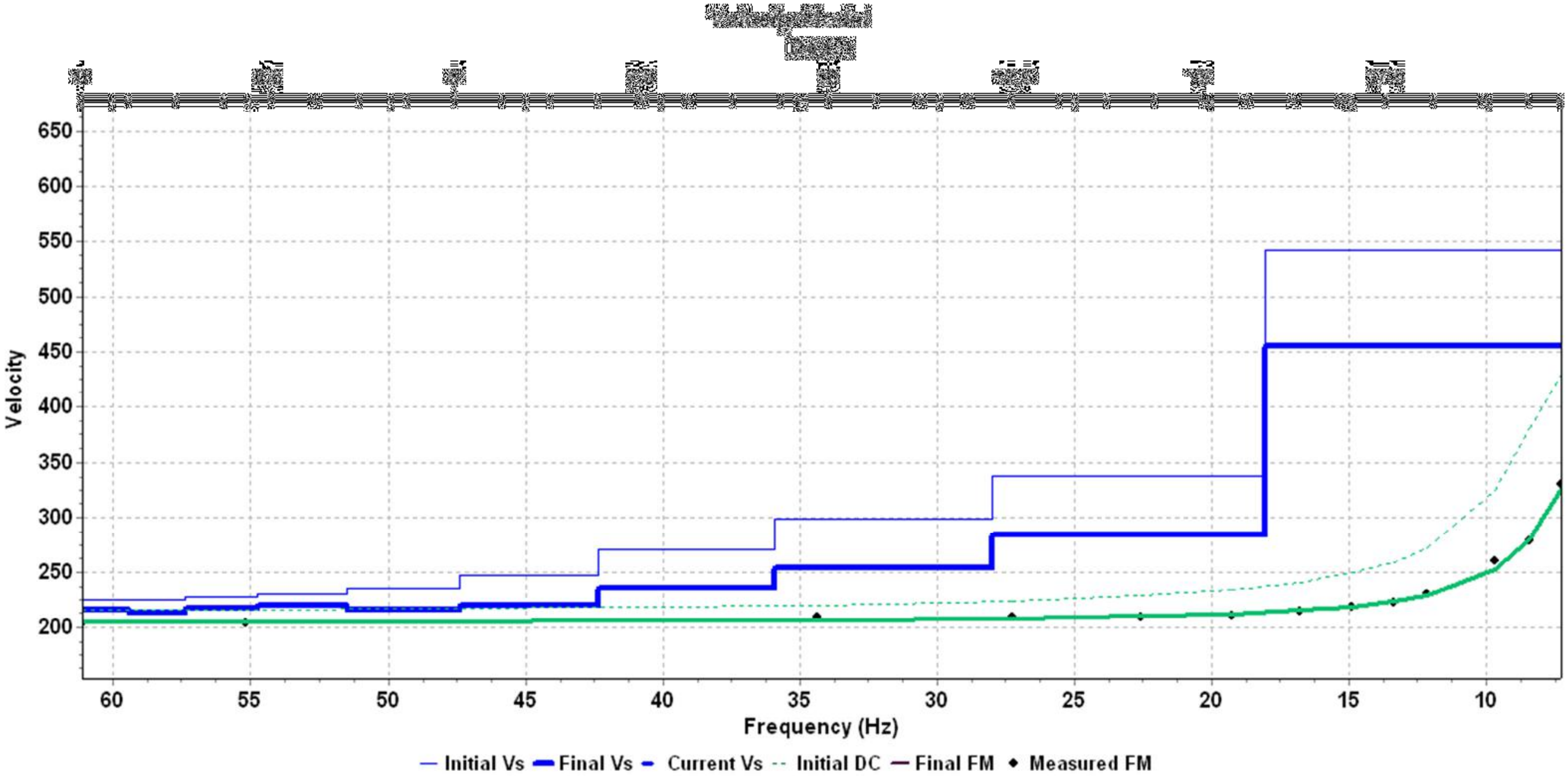
MI-52 Velocity Model



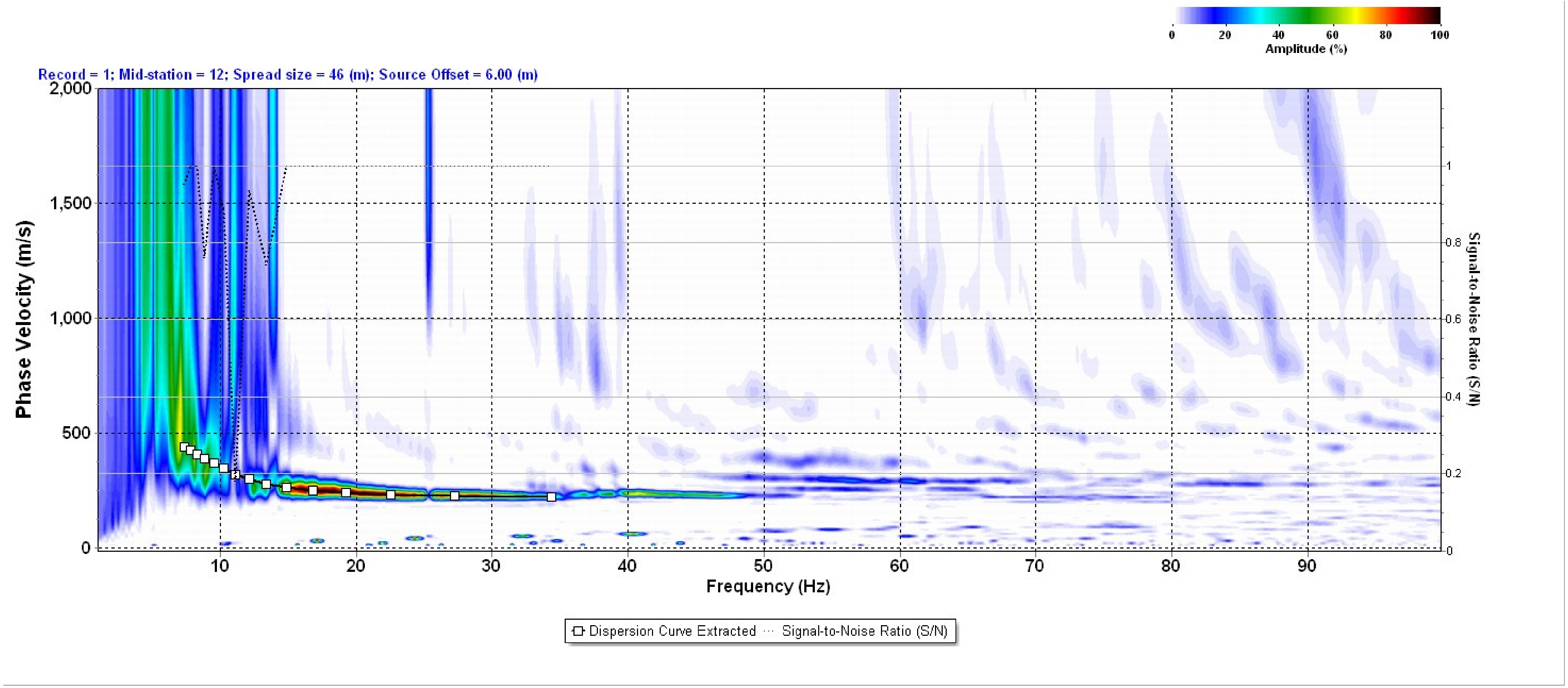
MI-53 Overtone Image



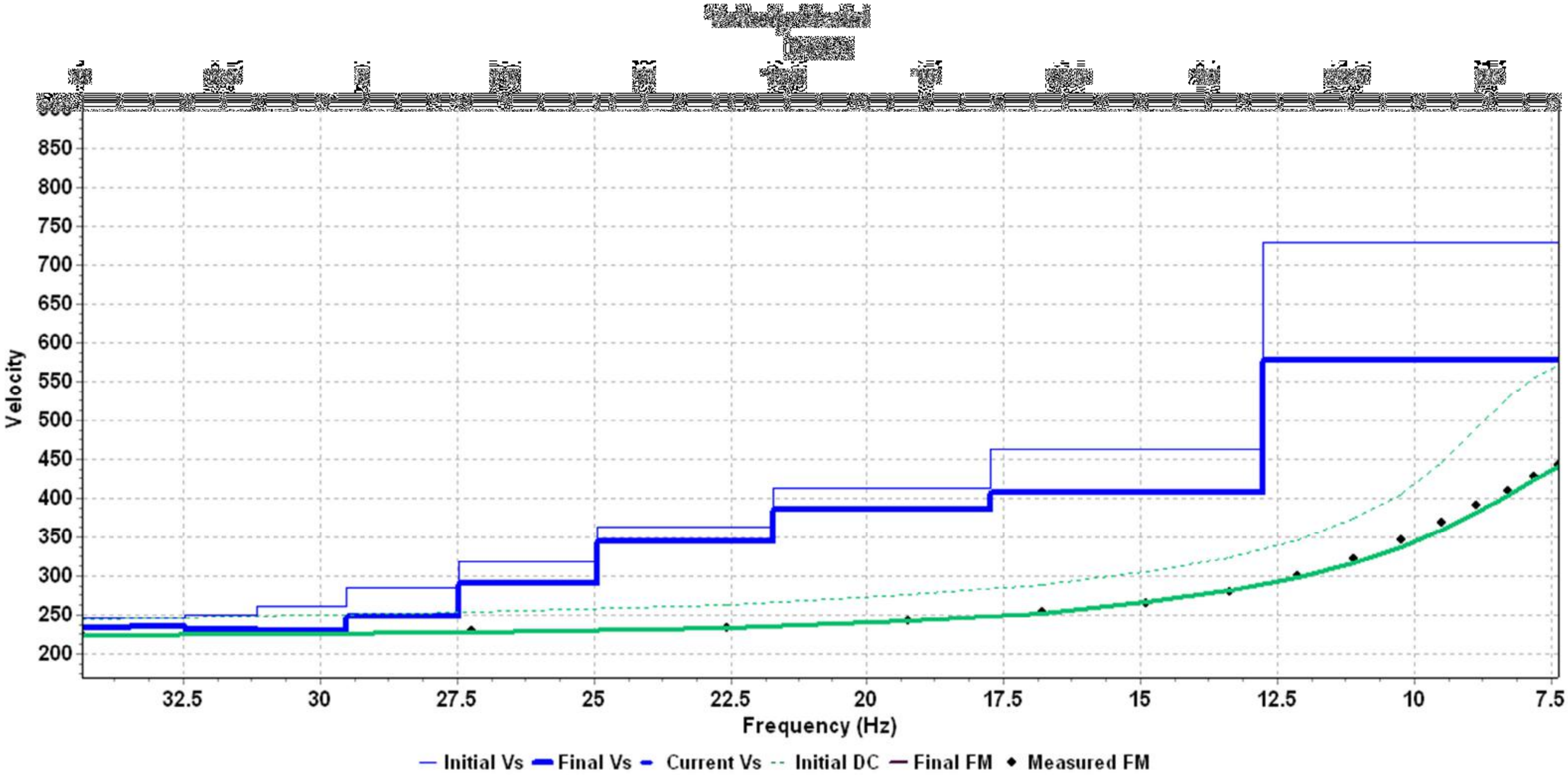
MI-53 Velocity Model



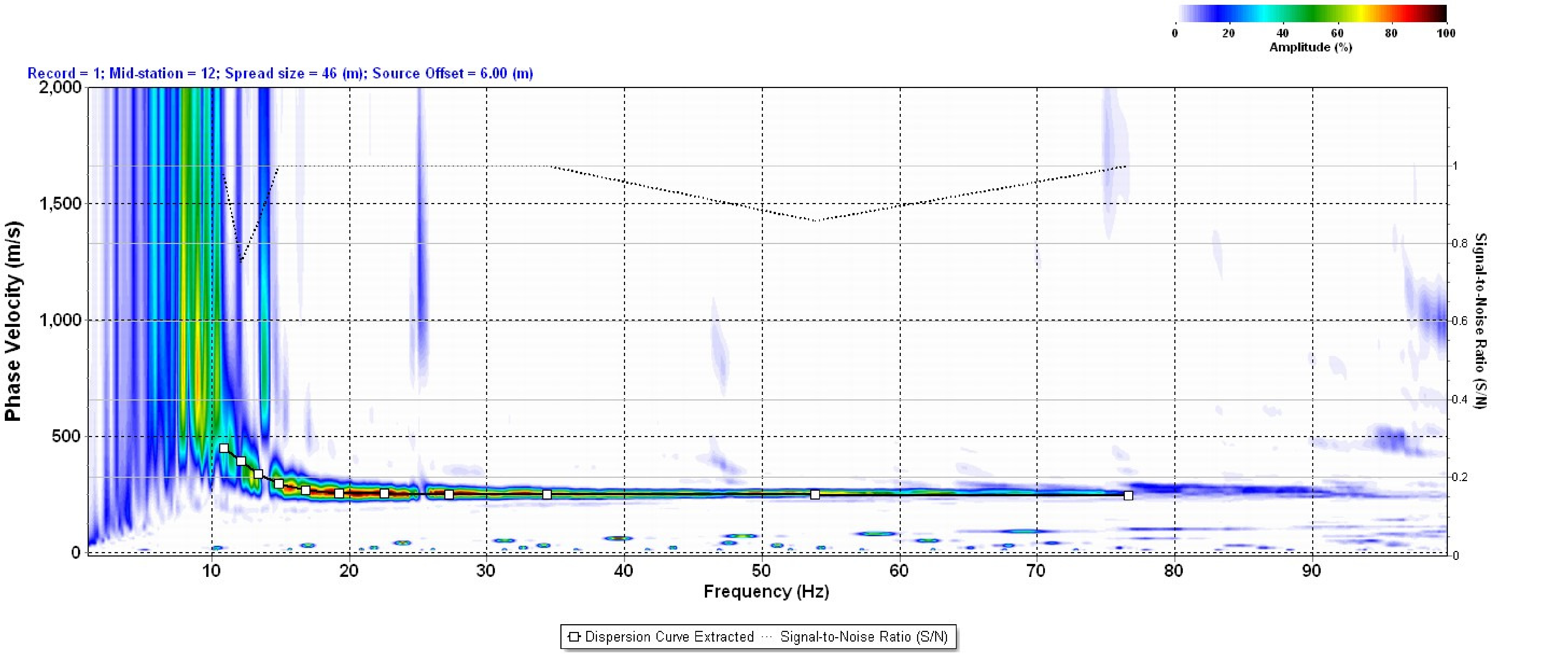
MI-54 Overtone Image



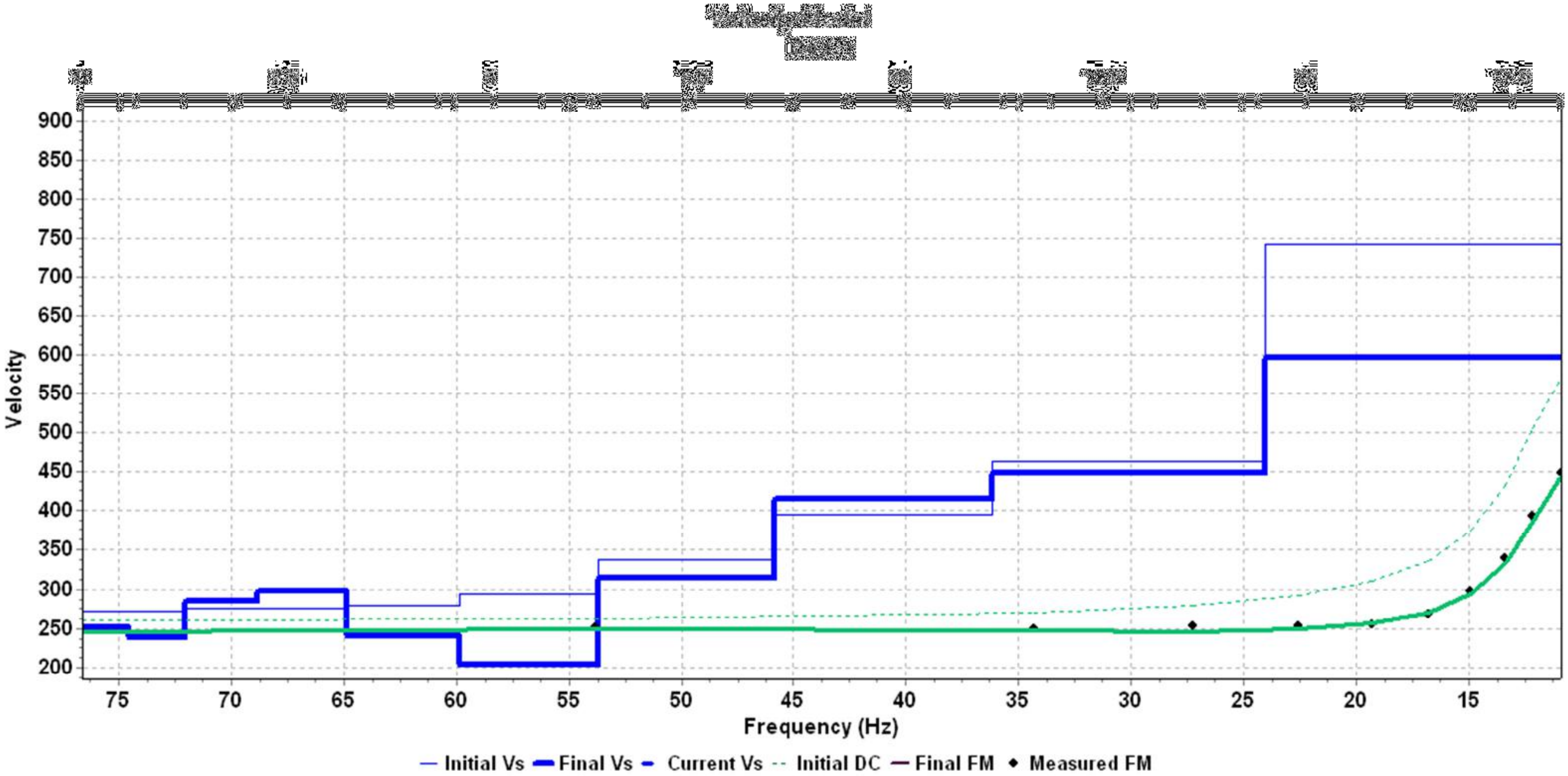
MI-54 Velocity Model



MI-55 Overtone Image

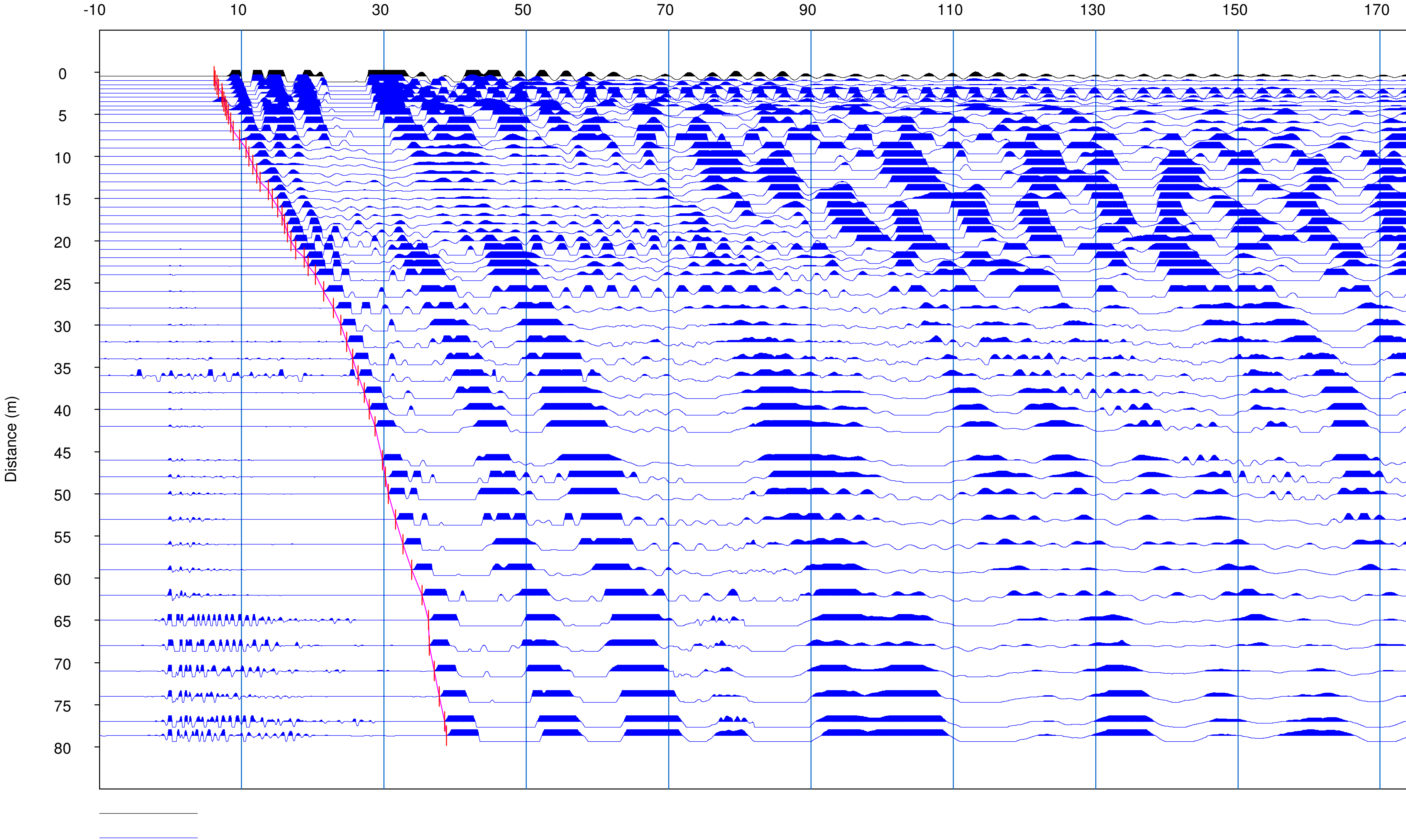


MI-55 Velocity Model

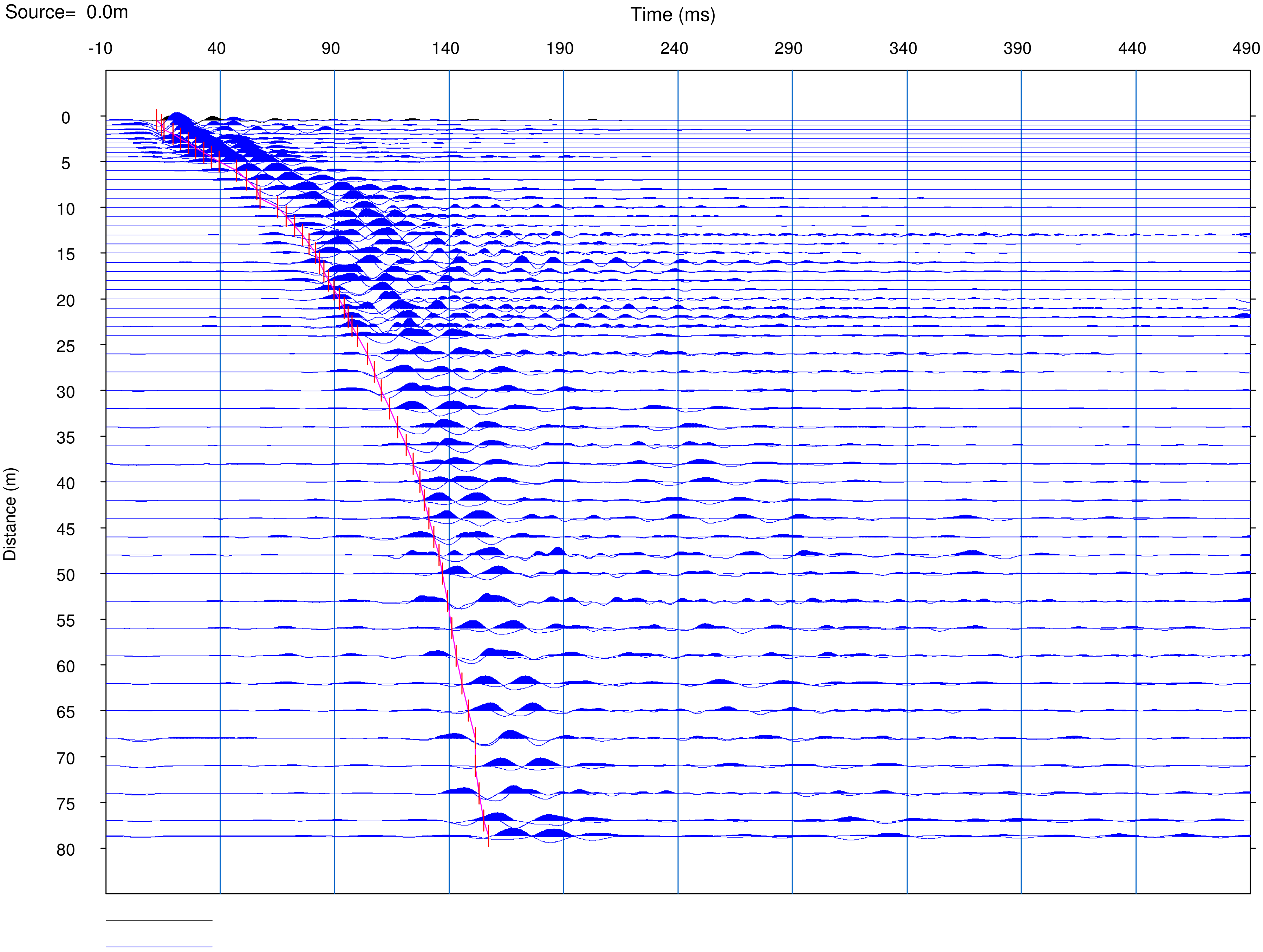


Appendix 2: Downhole s and p-wave First Arrival Picks

Source= 0.0m

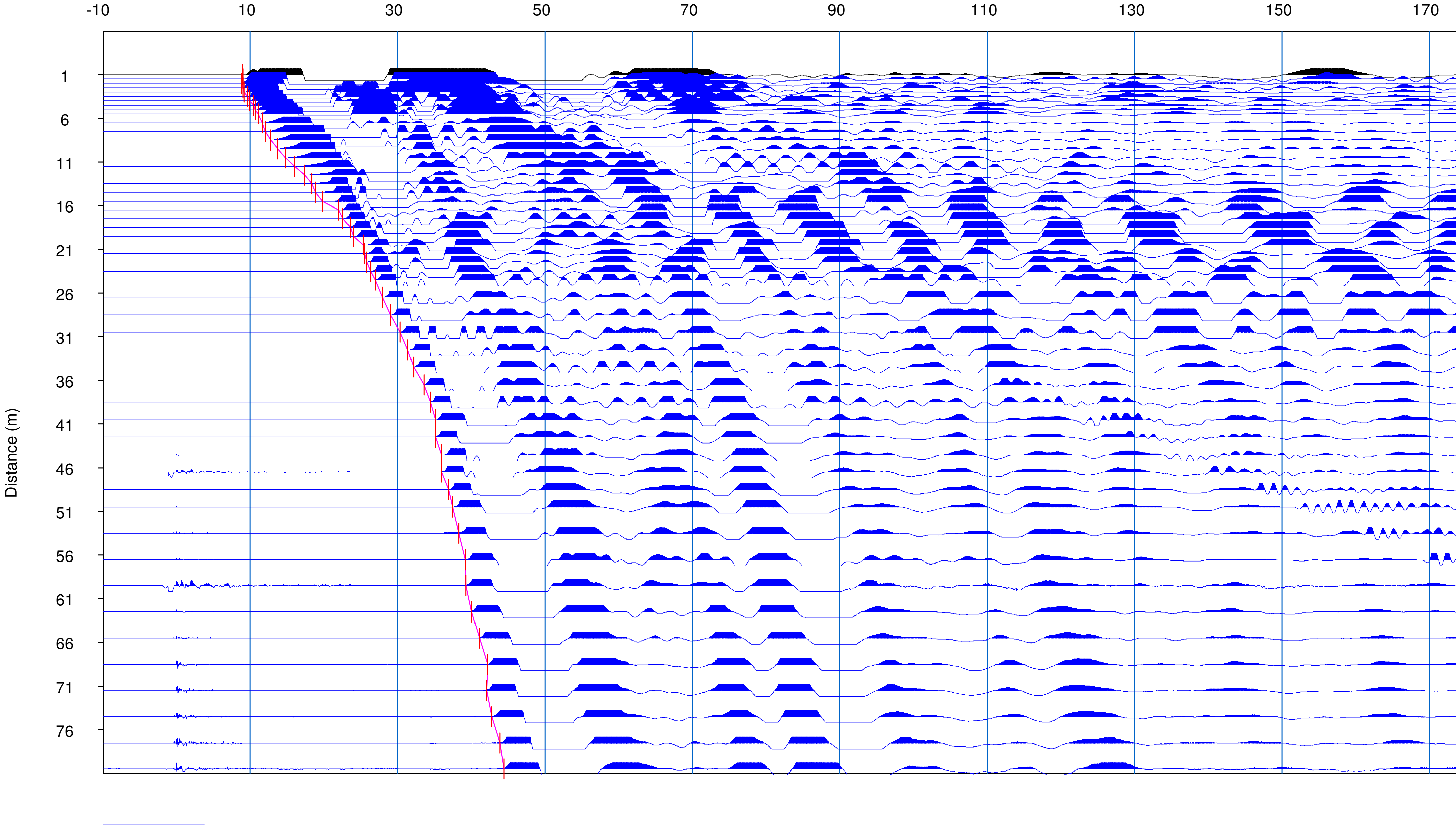


BH46_0.5-78.7m_Vertical_C1.dat

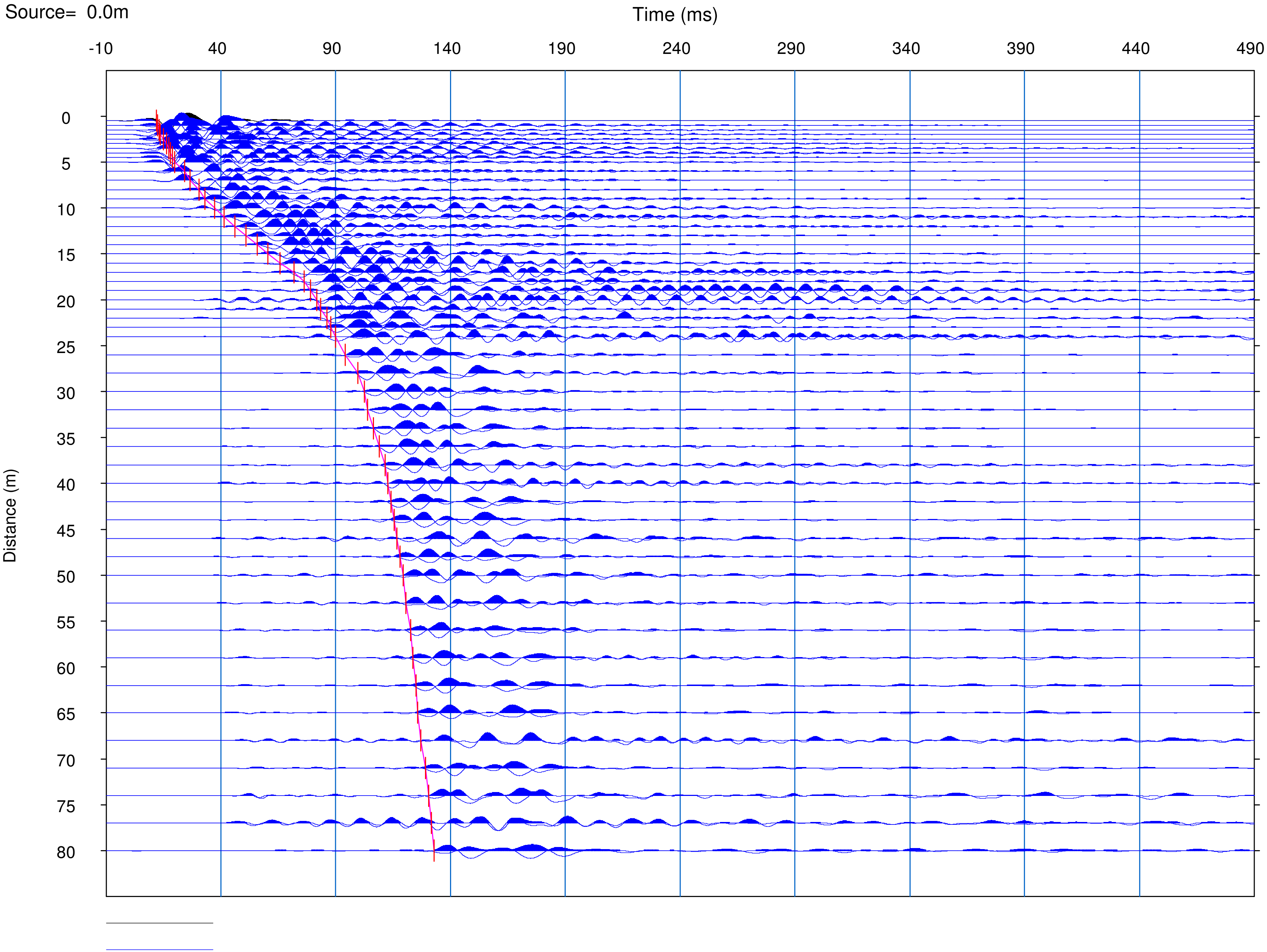


BH46 East+West Combined C2_filtered.dat

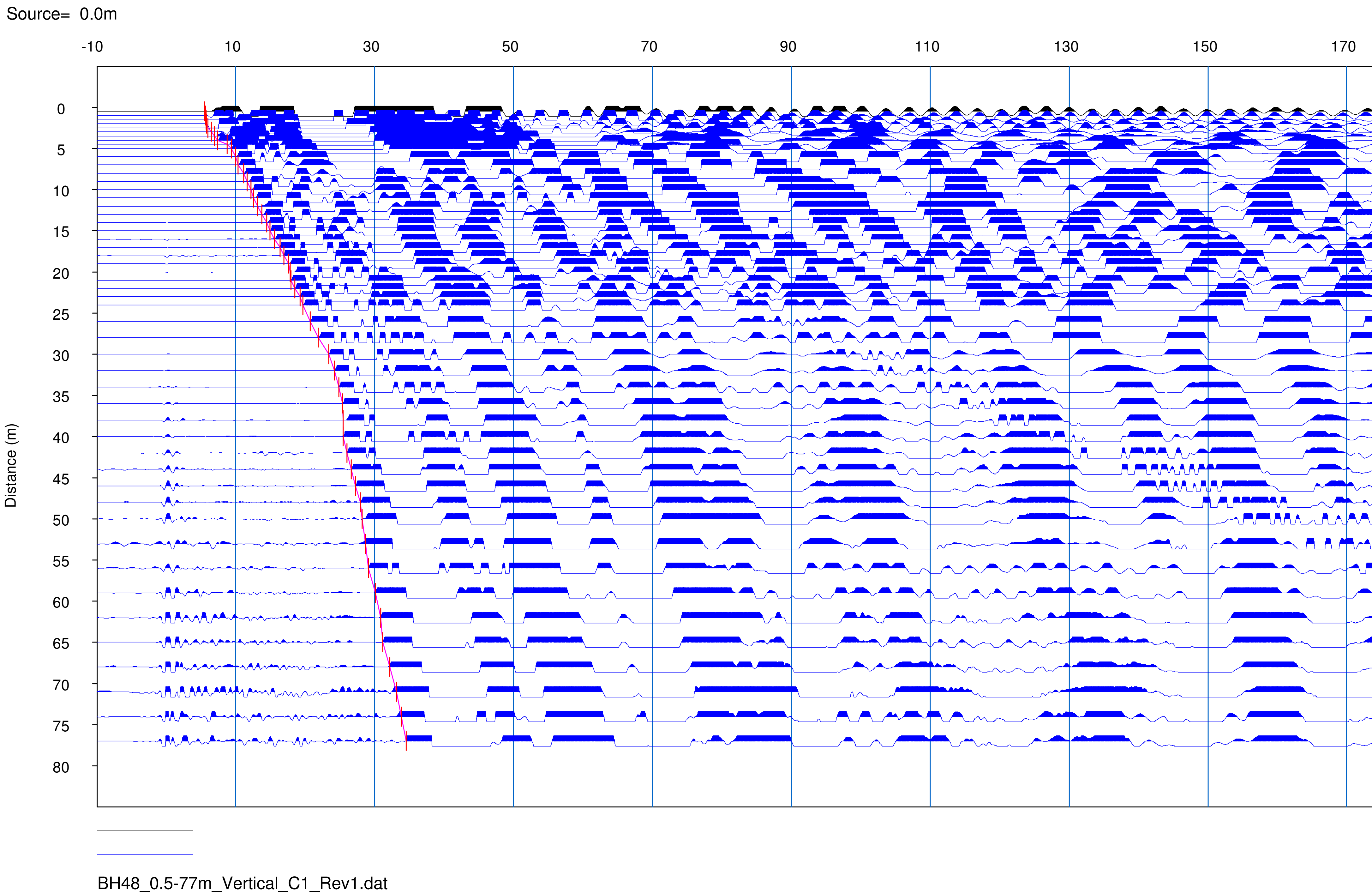
Source= 52.0m

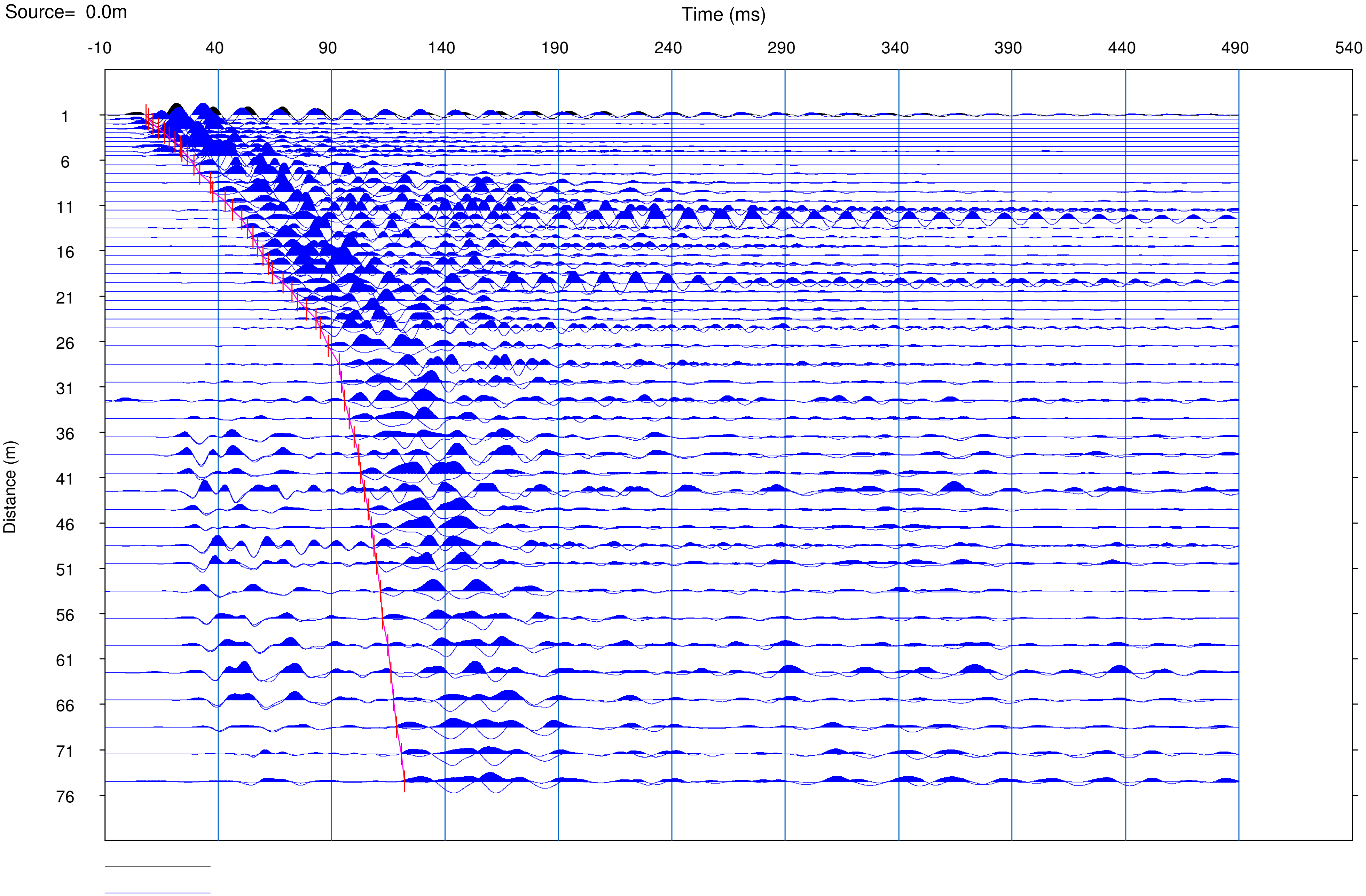


BH47_0.5-80m_Vertical_Ch1.dat



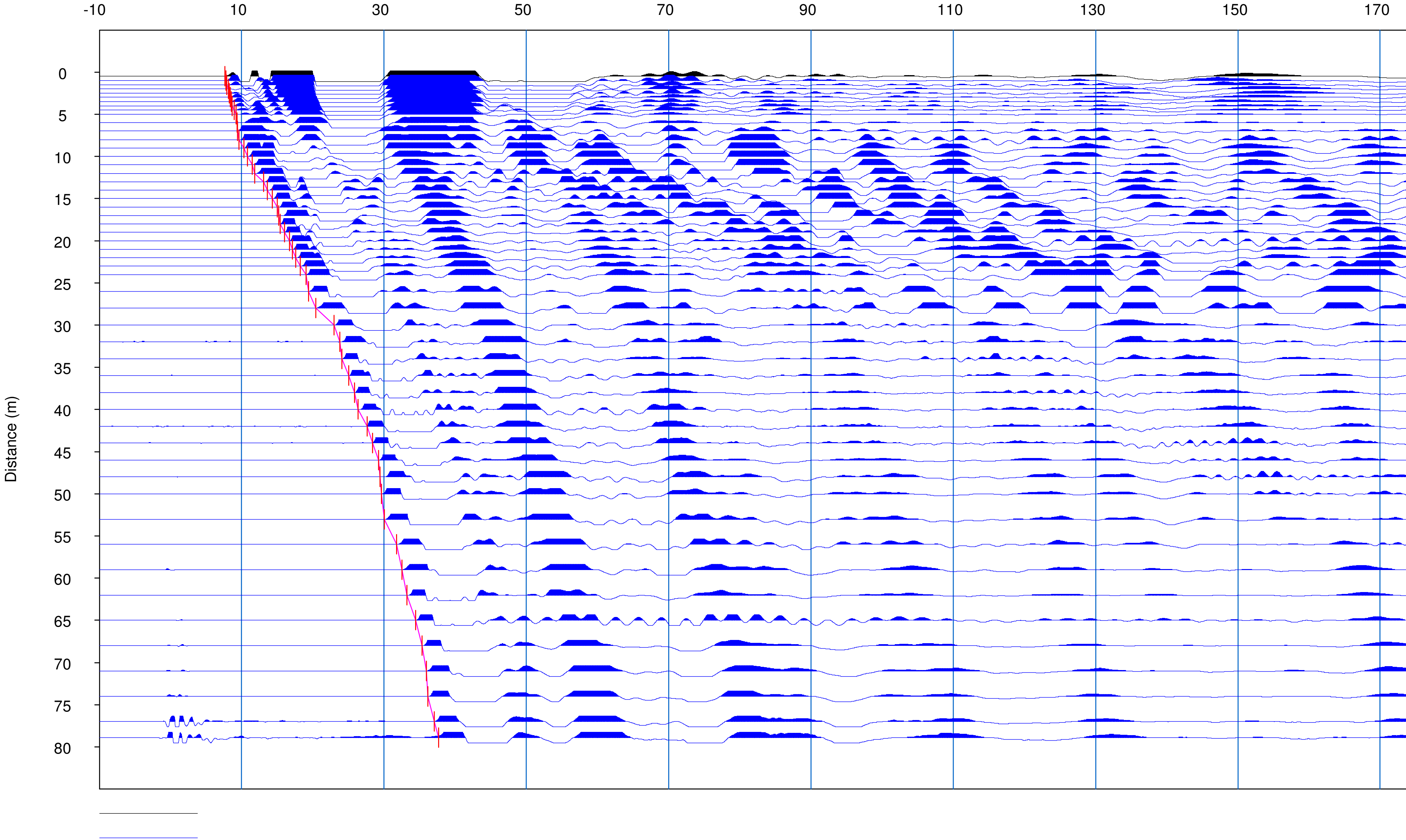
BH47_0.5-80m_East+West_Ch2_filtered.dat


Source= 0.0m
-10
10
30
50
70
90
110
130
150
170
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Distance (m)
BH48_0.5-77m_Vertical_C1_Rev1.dat

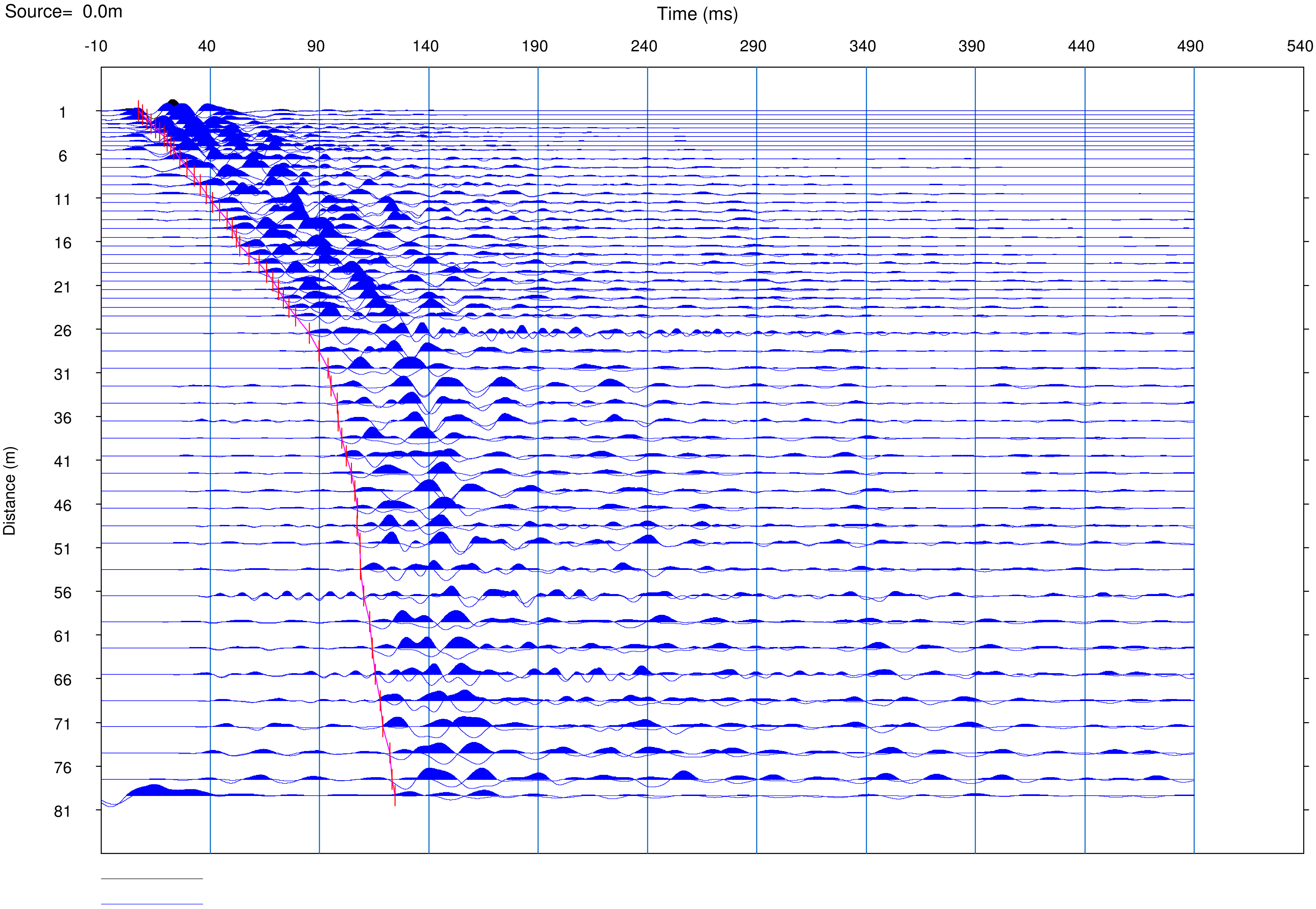


BH48_0.5-77m_East+West_Ch3_filtered.dat

Source= 0.0m

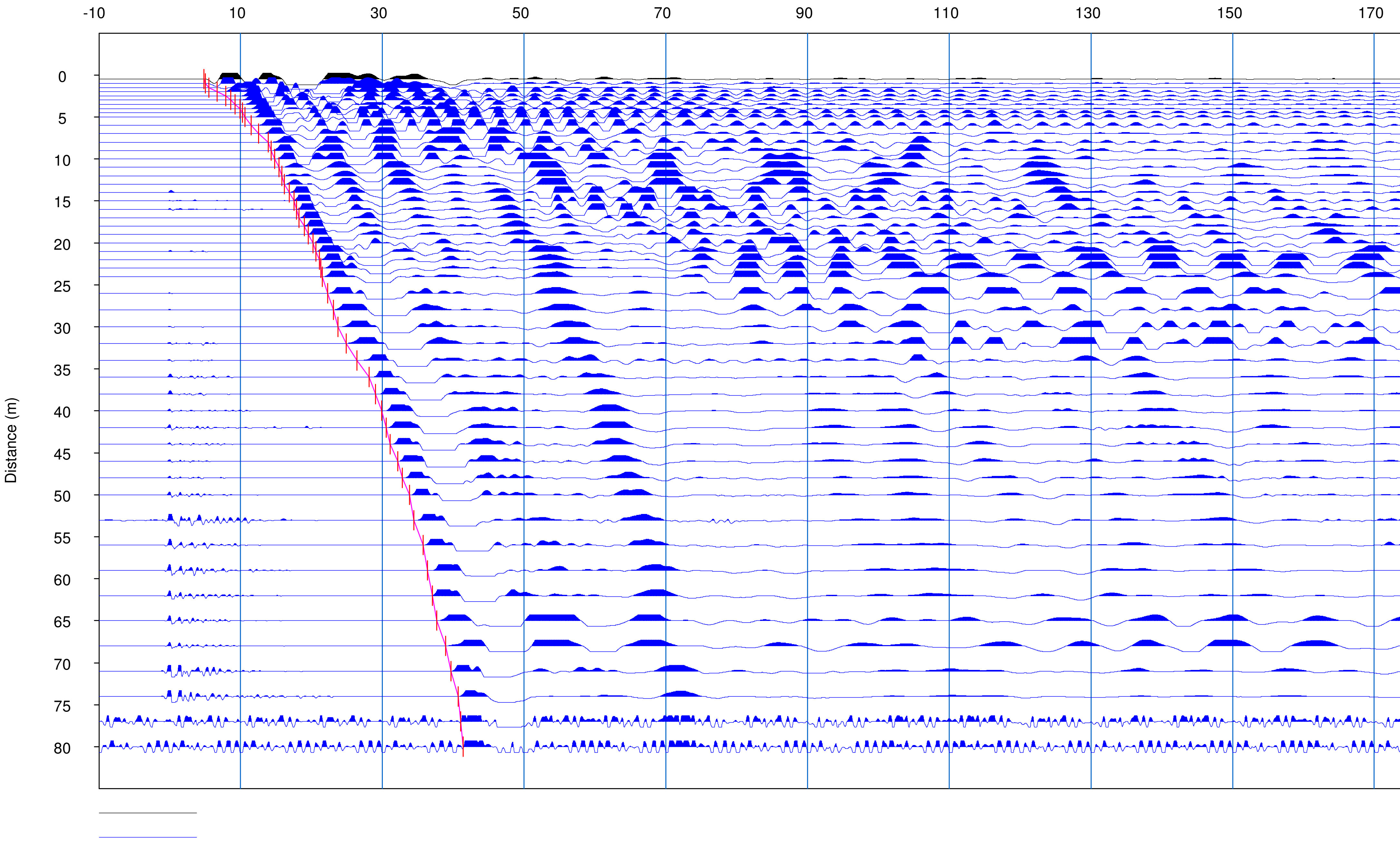


BH49_0.5-78.9m_Vertical_Ch1.dat

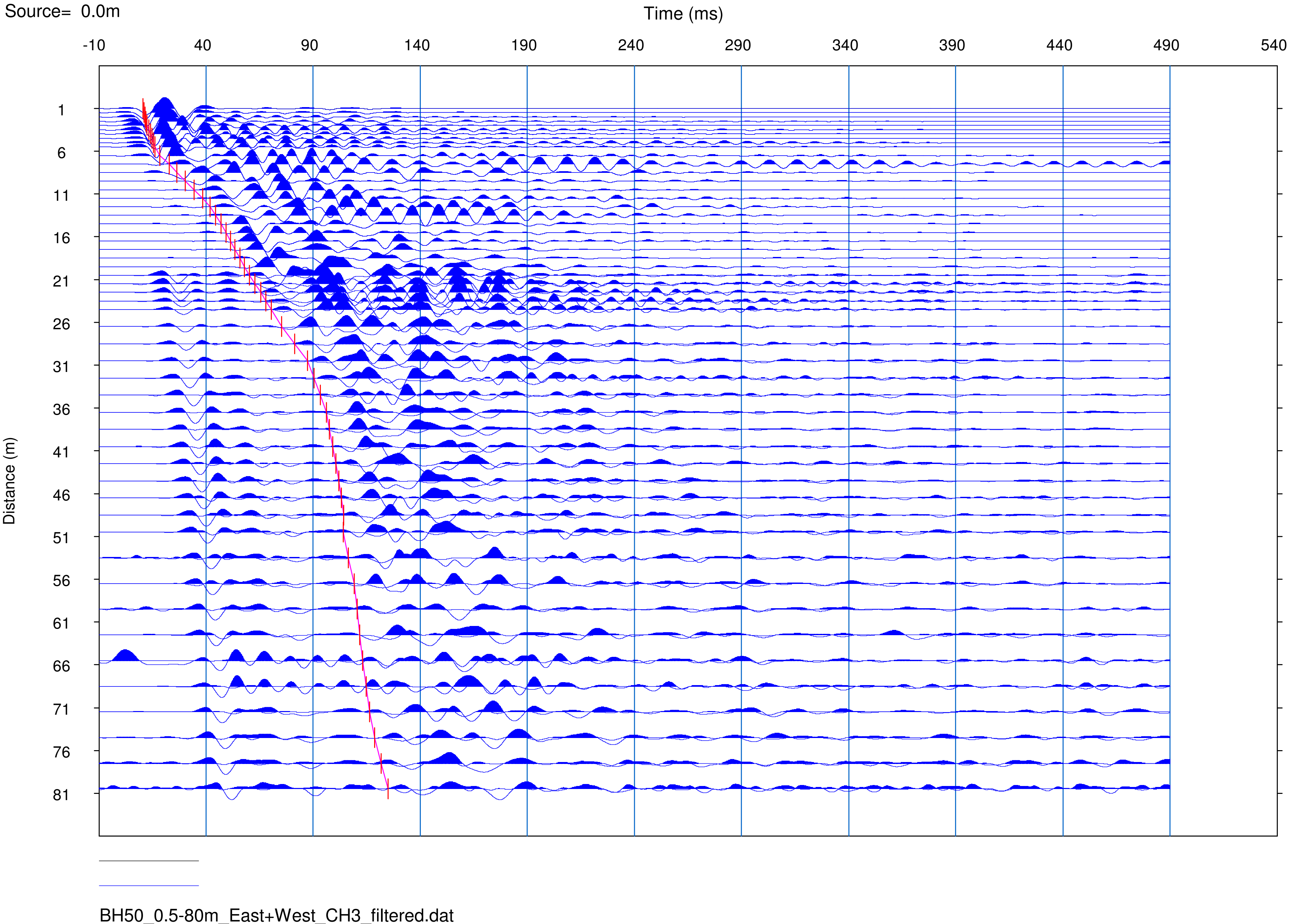


BH49_0.5-78.9m_North+South_CH3_Filtered.dat

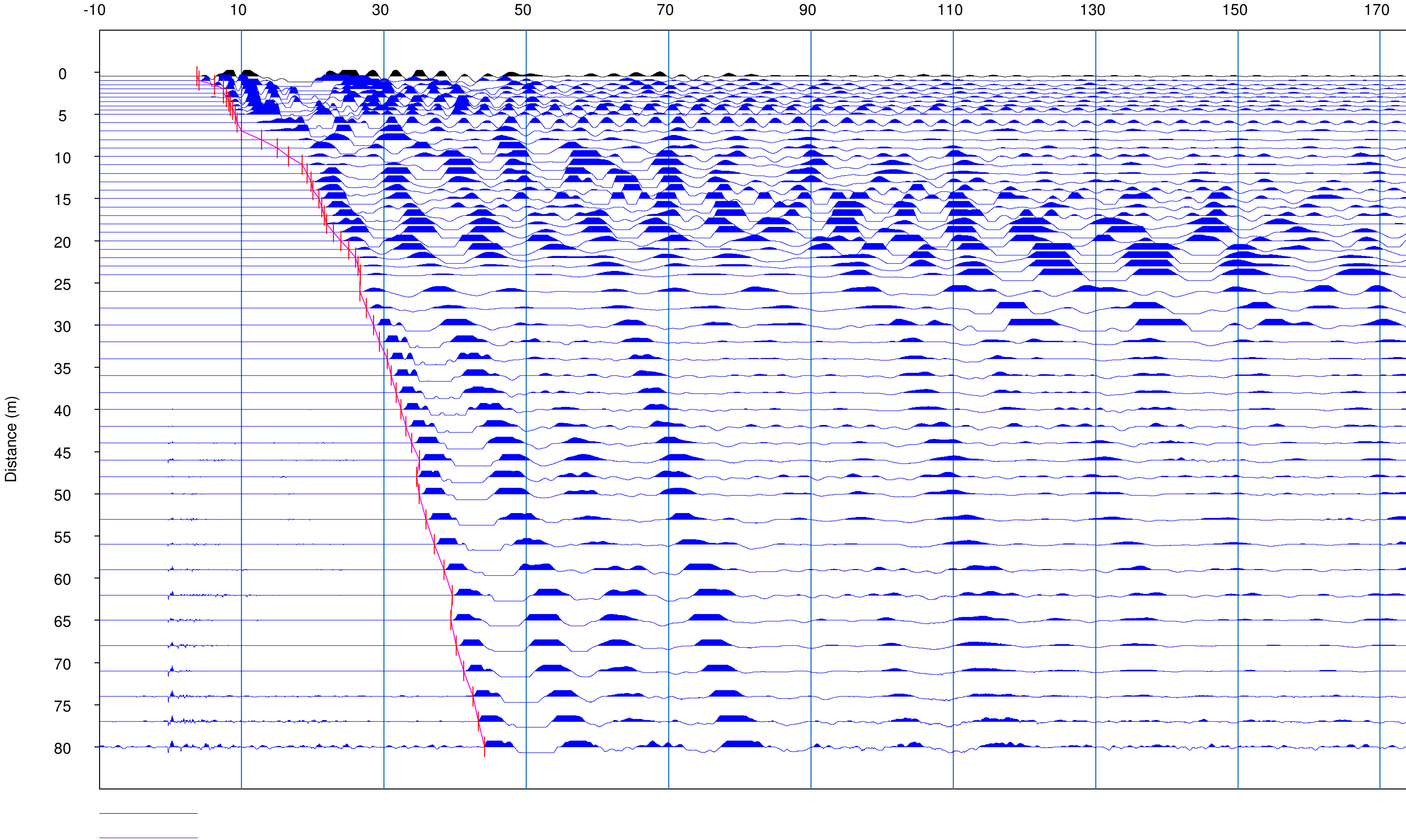
Source= 0.0m



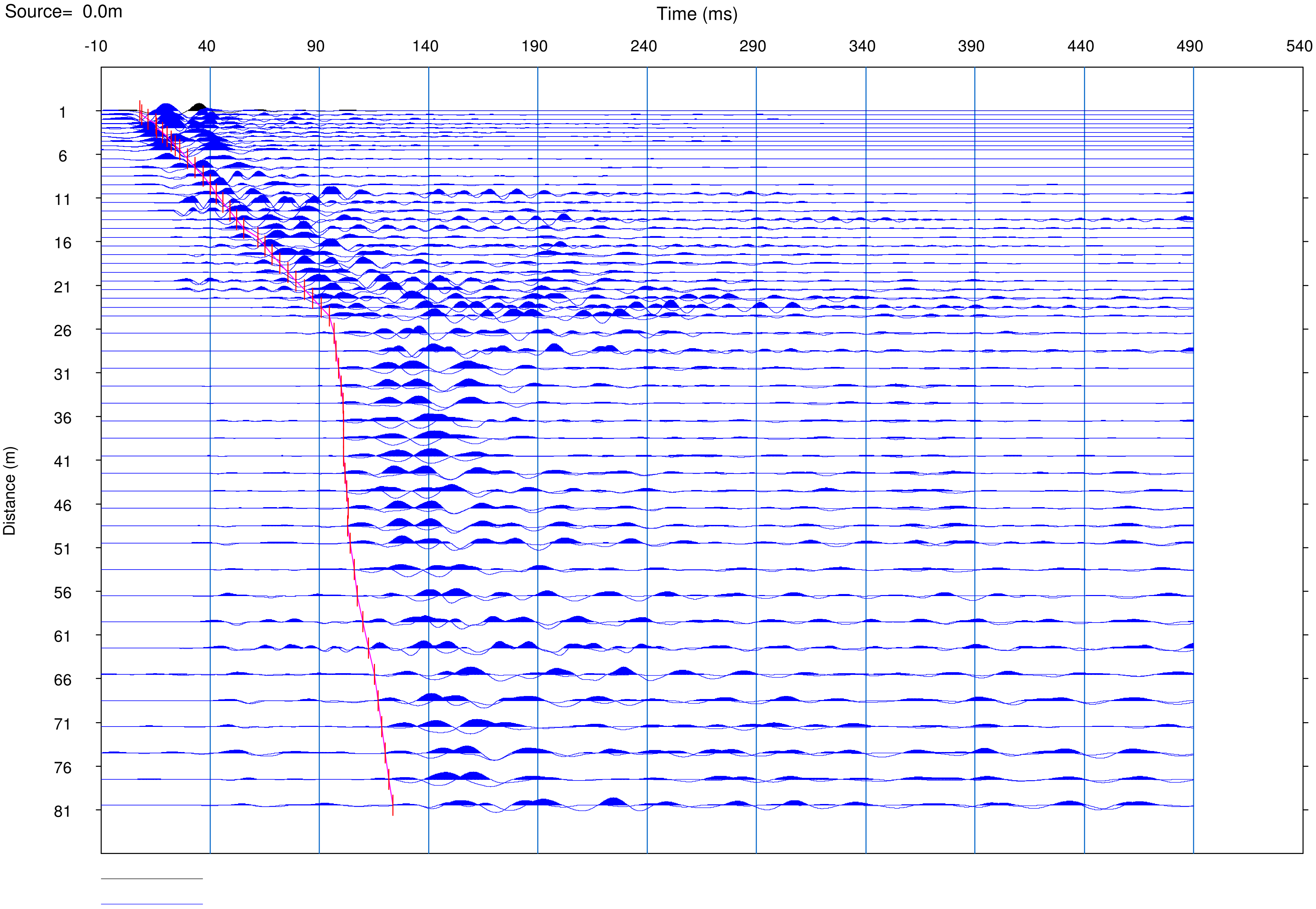
BH50_0.5-80m_Vertical_C1.dat


Source= 0.0m
Time (ms)
-10
40
90
140
190
240
290
340
390
440
490
540
Distance (m)
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
BH50_0.5-80m_East+West_CH3_filtered.dat

Source= 0.0m

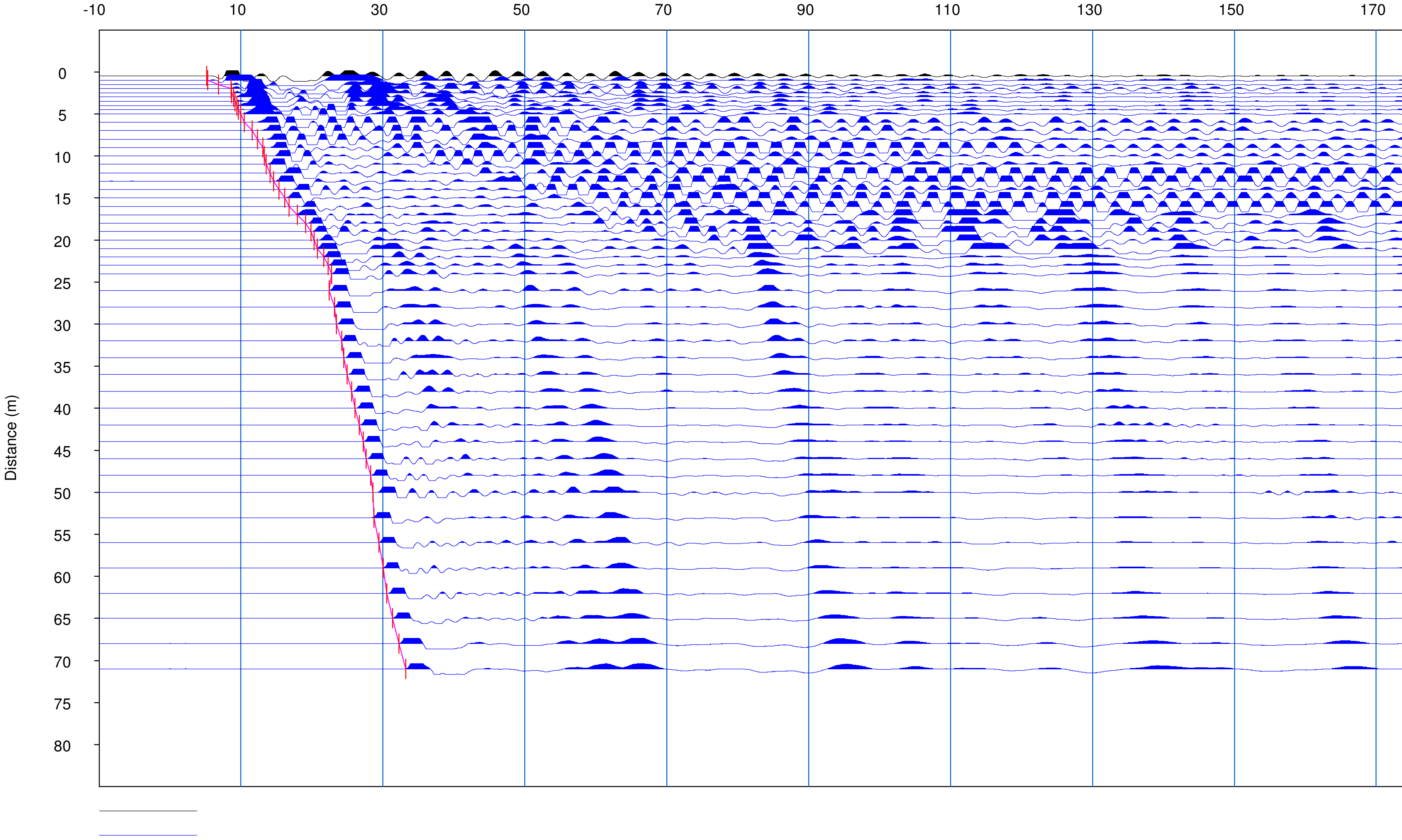


BH51_0.5-80m_Vertical_C1.dat

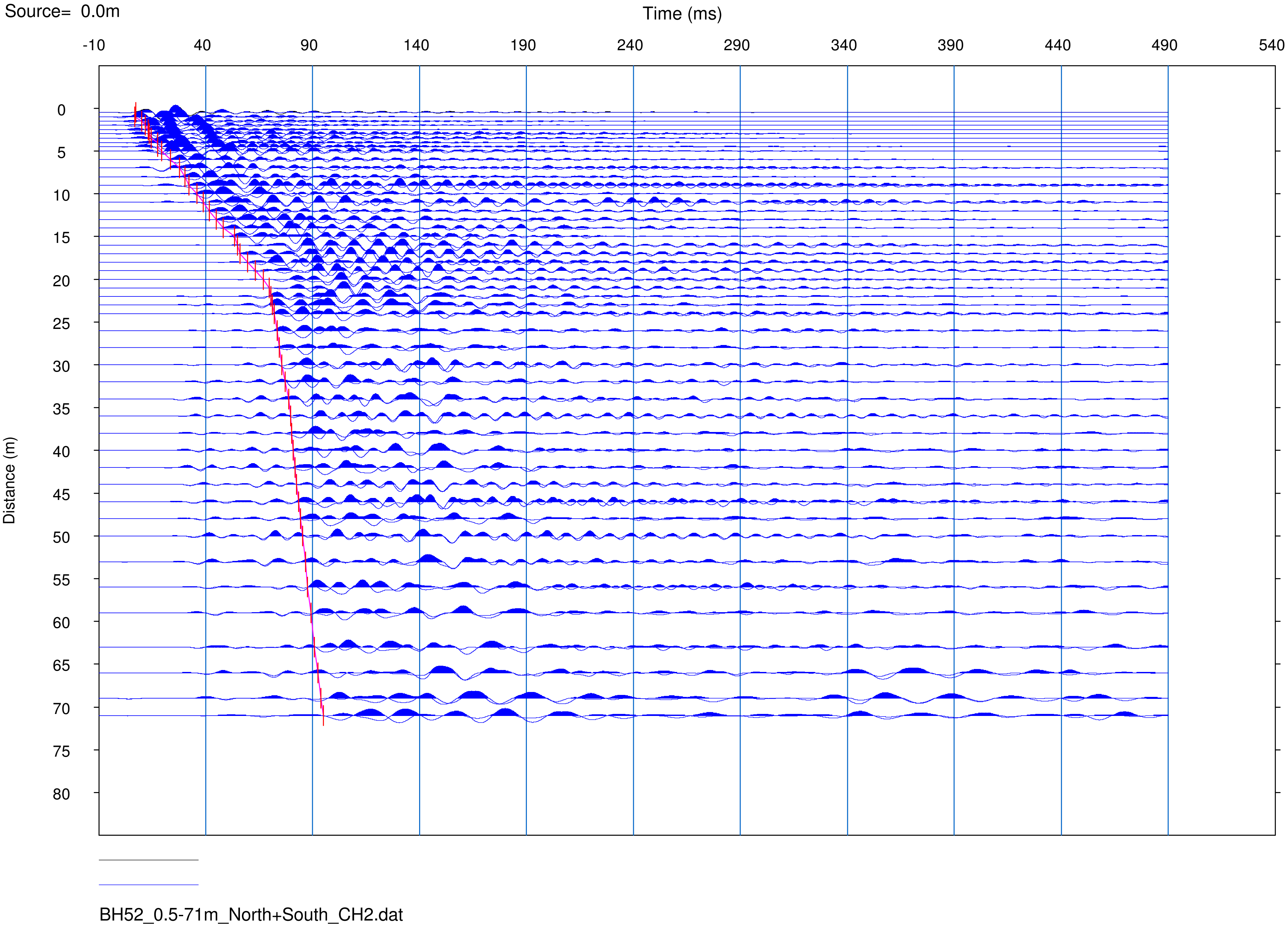


BH51_0.5-80m_North+South_CH3_Filtered.dat

Source= 0.0m

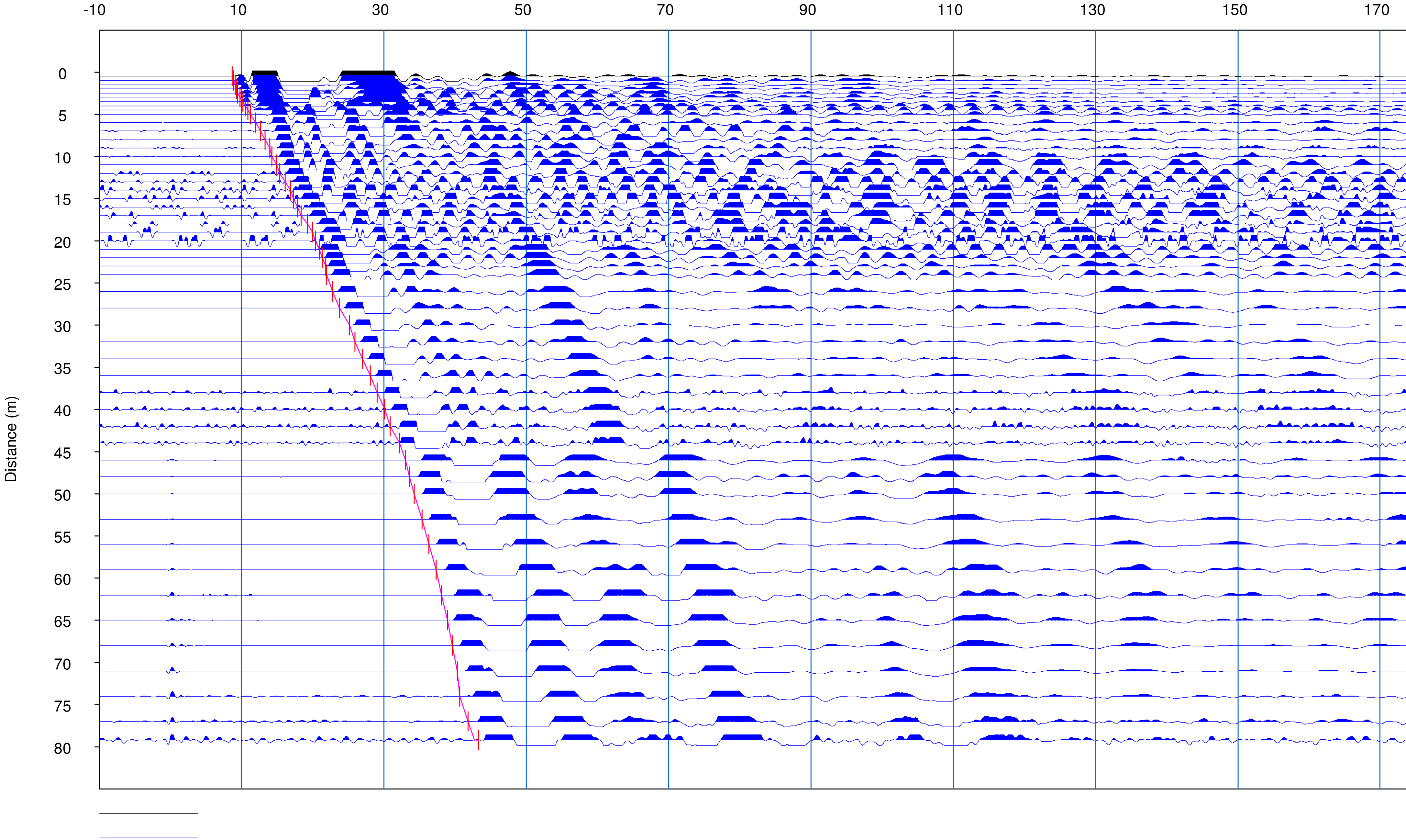


BH52_0.5-71m_Vertical_C1.dat

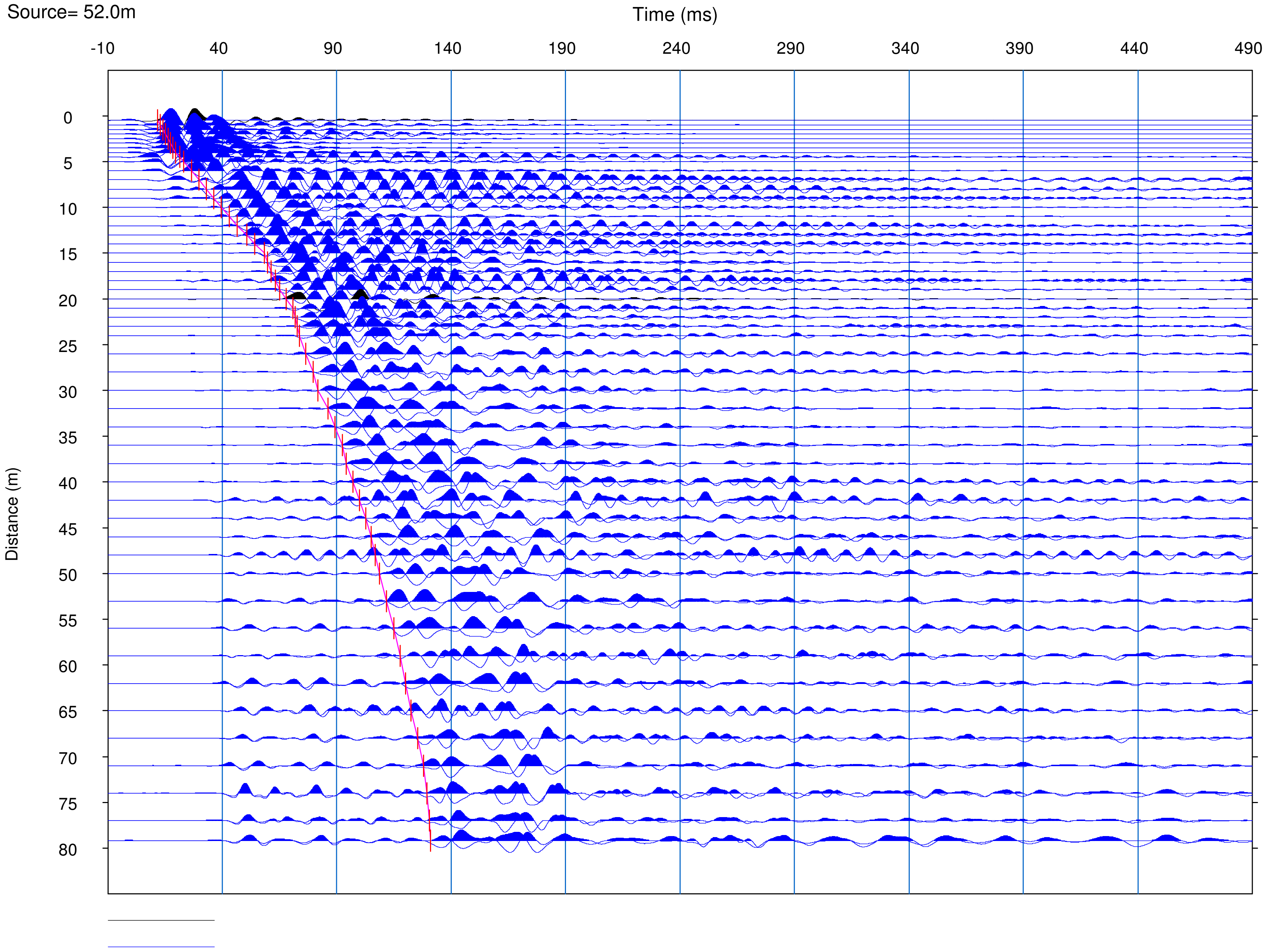


Source= 0.0m
Time (ms)
-10
40
90
140
190
240
290
340
390
440
490
540
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
BH52_0.5-71m_North+South_CH2.dat

Source= 52.0m



BH53_0.5-79.2m_Vertical_C1.dat



BH53_0.5-79.2m_East+West_CH3_filtered.dat