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# ESTECH 2010
## Reno, Nevada
# Nanotechnology Seminar
## 5 May 2010

**Vibrations: Measured performance of newly designed and built nanoscale research facilities**

*How different structural designs and isolation schemes impact vibration characteristics of space*

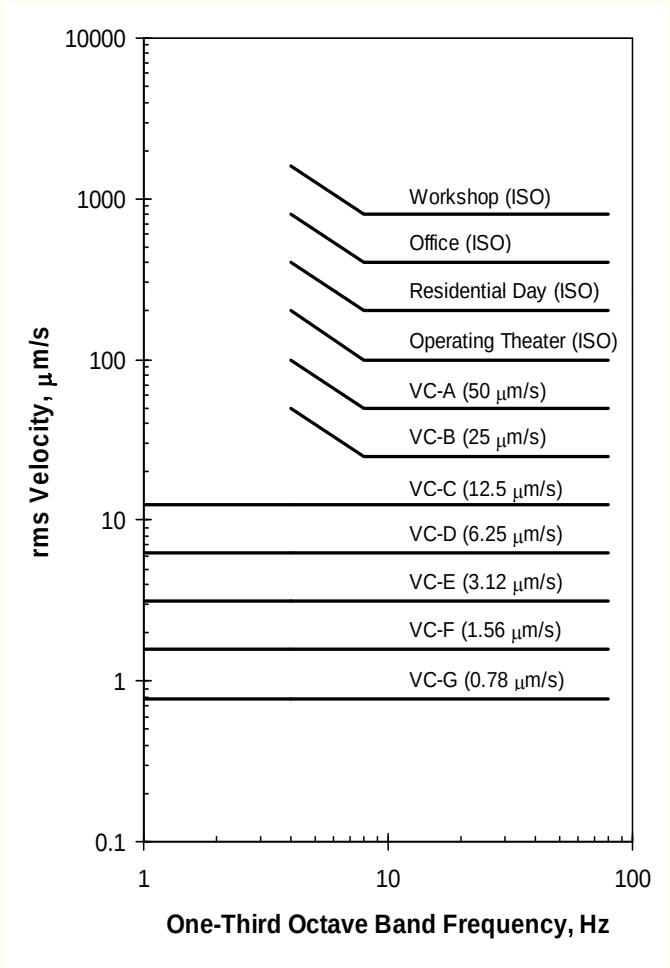
Hal Amick

# Overview

- Review of vibration criteria
- As-Built statistics of 23 recent facility designs
- Examine variables governing performance
  - Building Effect
  - Islands
  - Mechanical Systems
  - Depth

Amick: “Vibrations: Measured performance of newly designed and built nanoscale research facilities,” ESTECH 2010

# VC Curves: The Next Generation Published in IEST CC-RP012.2




| Criterion Curve | Amplitude[1] µm/s (µin/s) | Detail size[2] µm | Description of use |
|---|---|---|---|
| Workshop (ISO) | 800 (32 000) | N/A | Distinctly perceptible vibration. Appropriate to workshops and nonsensitive areas. |
| Office (ISO) | 400 (16 000) | N/A | Perceptible vibration. Appropriate to offices and nonsensitive areas. |
| Residential day (ISO) | 200 (8 000) | 75 | Barely perceptible vibration. Appropriate to sleep areas in most instances. Usually adequate for computer equipment, hospital recovery rooms, semiconductor probe test equipment, and microscopes less than 40x |
| Operating theatre (ISO) | 100 (4 000) | 25 | Vibration not perceptible. Suitable in most instances for surgical suites, microscopes to 100x and for other equipment of low sensitivity. |
| VC-A | 50 (2 000) | 8 | Adequate in most instances for optical microscopes to 400x, microbalances, optical balances, proximity and projection aligners, etc. |
| VC-B | 25 (1 000) | 3 | Appropriate for inspection and lithography equipment (including steppers) to 3 µm line widths. |
| VC-C | 12.5 (500) | 1 – 3 | Appropriate standard for optical microscopes to 1000x, lithography and inspection equipment (including moderately sensitive electron microscopes) to 1 µm detail size, TFT-LCD stepper/scanner processes. |
| VC-D | 6.25 (250) | 0.1 – 0.3 | Suitable in most instances for demanding equipment, including many electron microscopes (SEMs and TEMs) and E-Beam systems. |
| VC-E | 3.12 (125) | < 0.1 | A challenging criterion to achieve. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, E-Beam lithography systems working at nanometer scales, and other systems requiring extraordinary dynamic stability. |
| VC-F | 1.56 (62.5) | N/A | Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation. |
| VC-G | 0.78 (31.3) | N/A | Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation. |

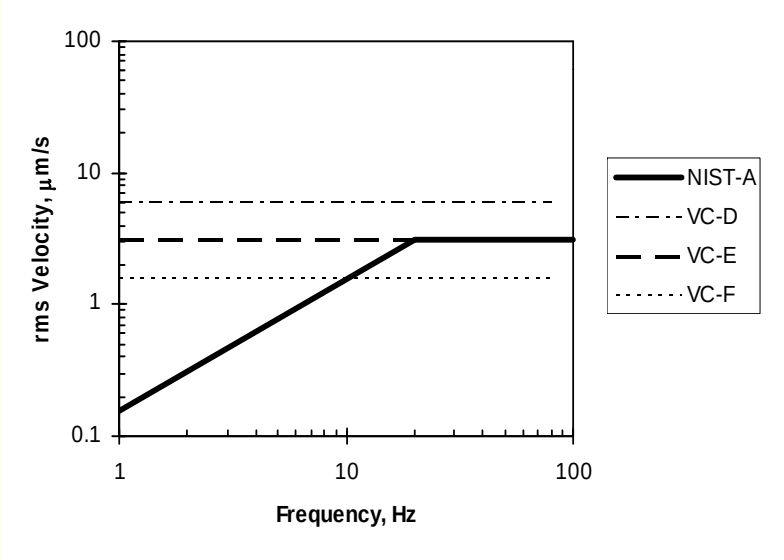
[1]As measured in one-third octave bands of frequency over the frequency range 8 to 80 Hz (VC-A and VC-B) or 1 to 80 Hz (VC-C through VC-G).

[2]The detail size refers to line width in the case of microelectronics fabrication, the particle (cell) size in the case of medical and pharmaceutical research, etc. It is not relevant to imaging associated with probe technologies, AFMs, and nanotechnology.

*The information given in this table is for guidance only. In most instances, it is recommended that the advice of someone knowledgeable about applications and vibration requirements of the equipment and processes be sought.*

H. Amick, M. Gendreau, T. Busch, and C. Gordon, "Evolving criteria for research facilities: vibration," *Proceedings of SPIE Conference 5933: Buildings for Nanoscale Research and Beyond*, San Diego, CA, 31 Jul 2005 to 1 Aug 2005

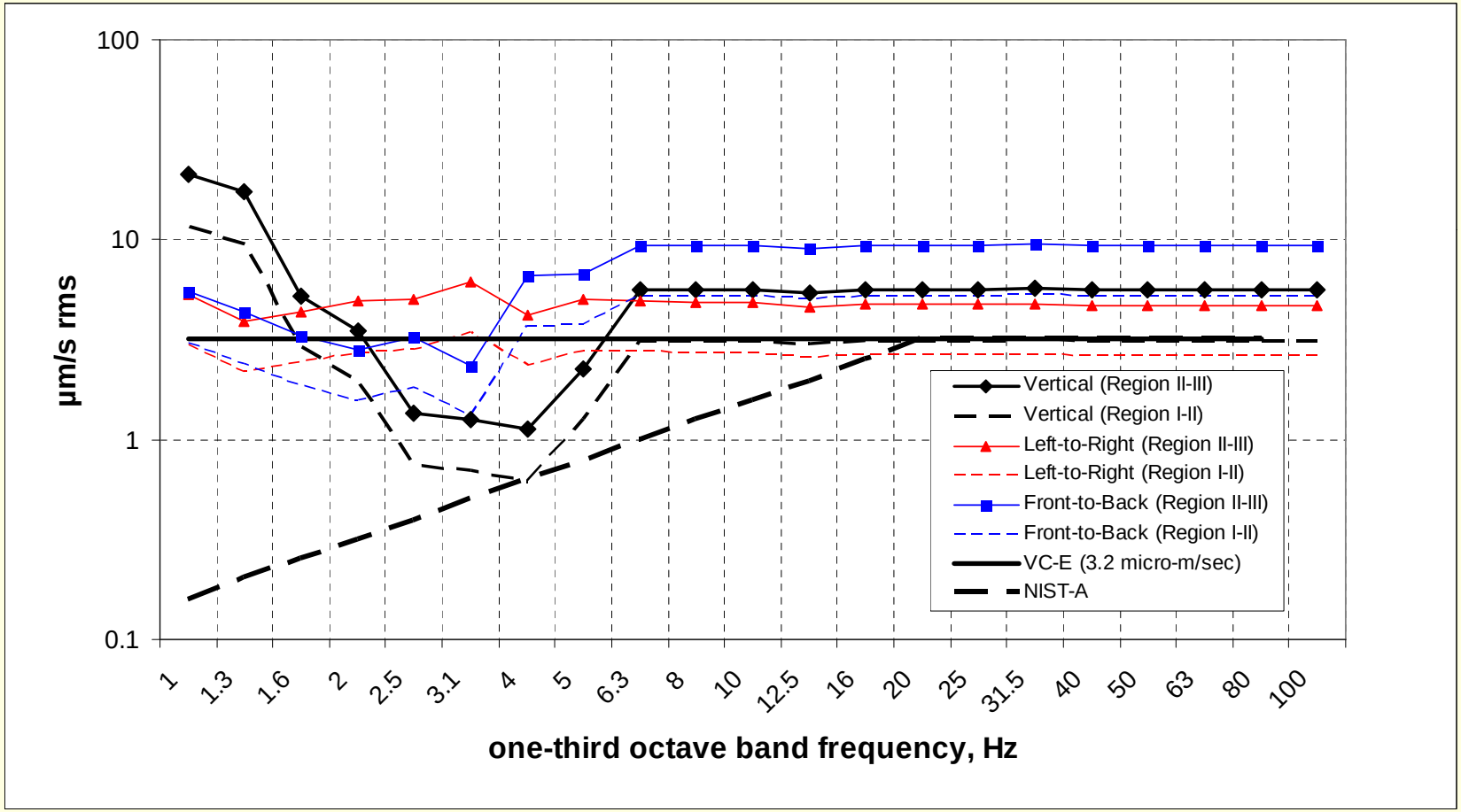
# Nanotechnology: NIST-A Criterion




- Developed as part of NIST AML design process
- Hybrid of 1 um rms (req'd by some NIST researchers) and VC-E (required by other researchers and "current practice"
- Much harder for a site to meet than VC-E

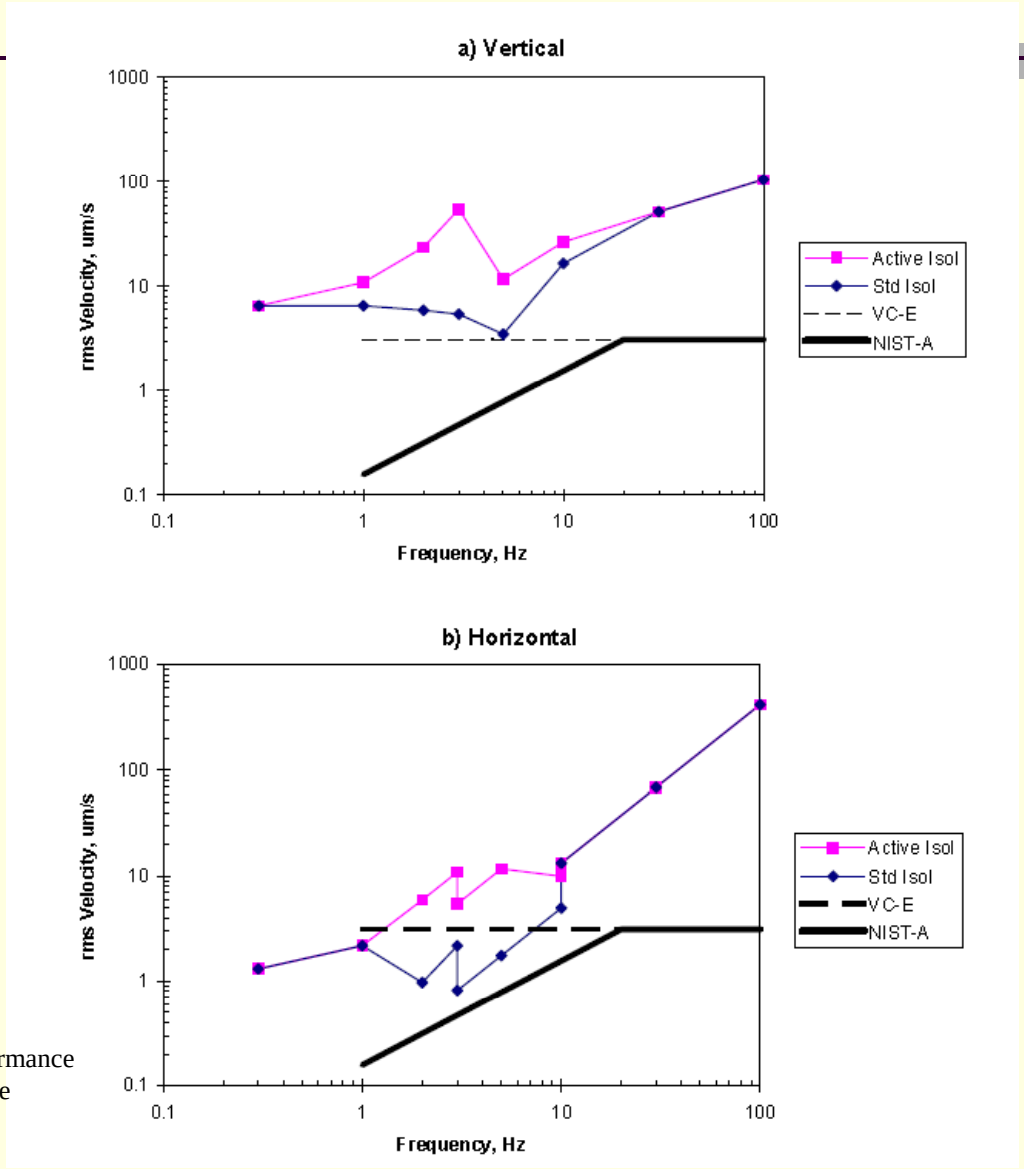
H. Amick, M. Gendreau, T. Busch, and C. Gordon, "Evolving criteria for research facilities: vibration," *Proceedings of SPIE Conference 5933: Buildings for Nanoscale Research and Beyond*, San Diego, CA, 31 Jul 2005 to 1 Aug 2005

# Relevant Specific Criteria: FEI Titan Vibration Specification expressed in Velocity Units




Amick: "Vibrations: Measured performance of newly designed and built nanoscale research facilities," ESTECH 2010

# JEOL 4000EX and 2010-F Vibration Specification expressed in Velocity Units

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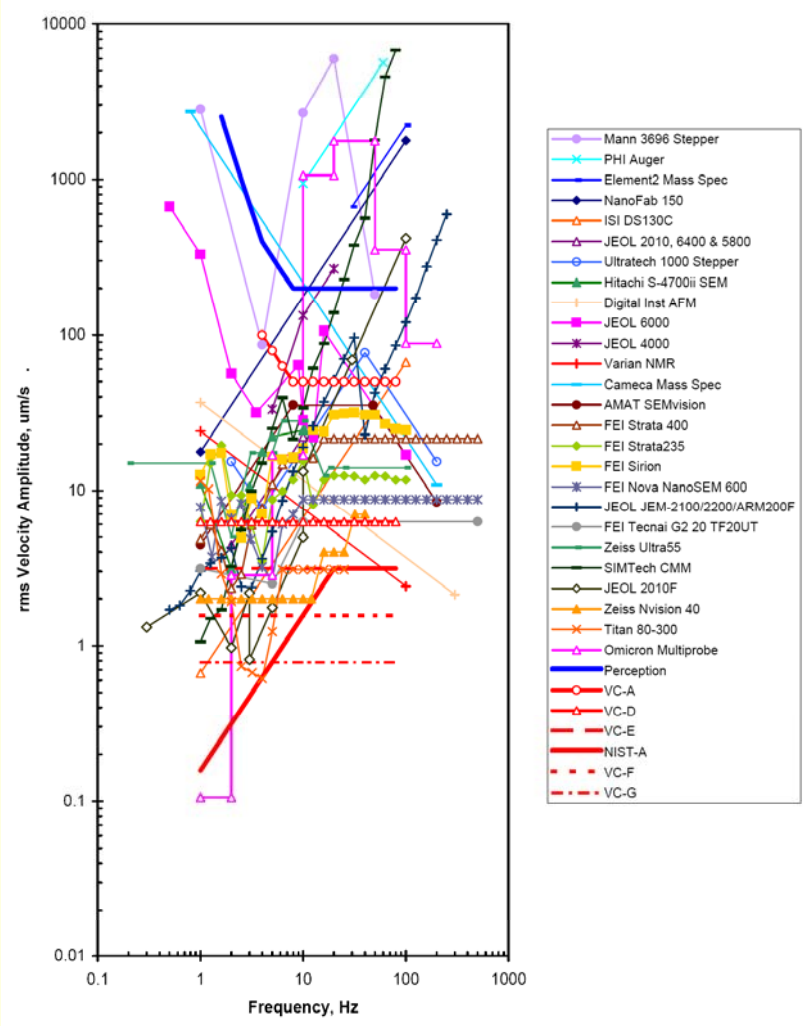
# Wide Range of Sensitivity in Nanotechnology




- Five orders of magnitude
- *Below* NIST-A to *above* threshold of perception

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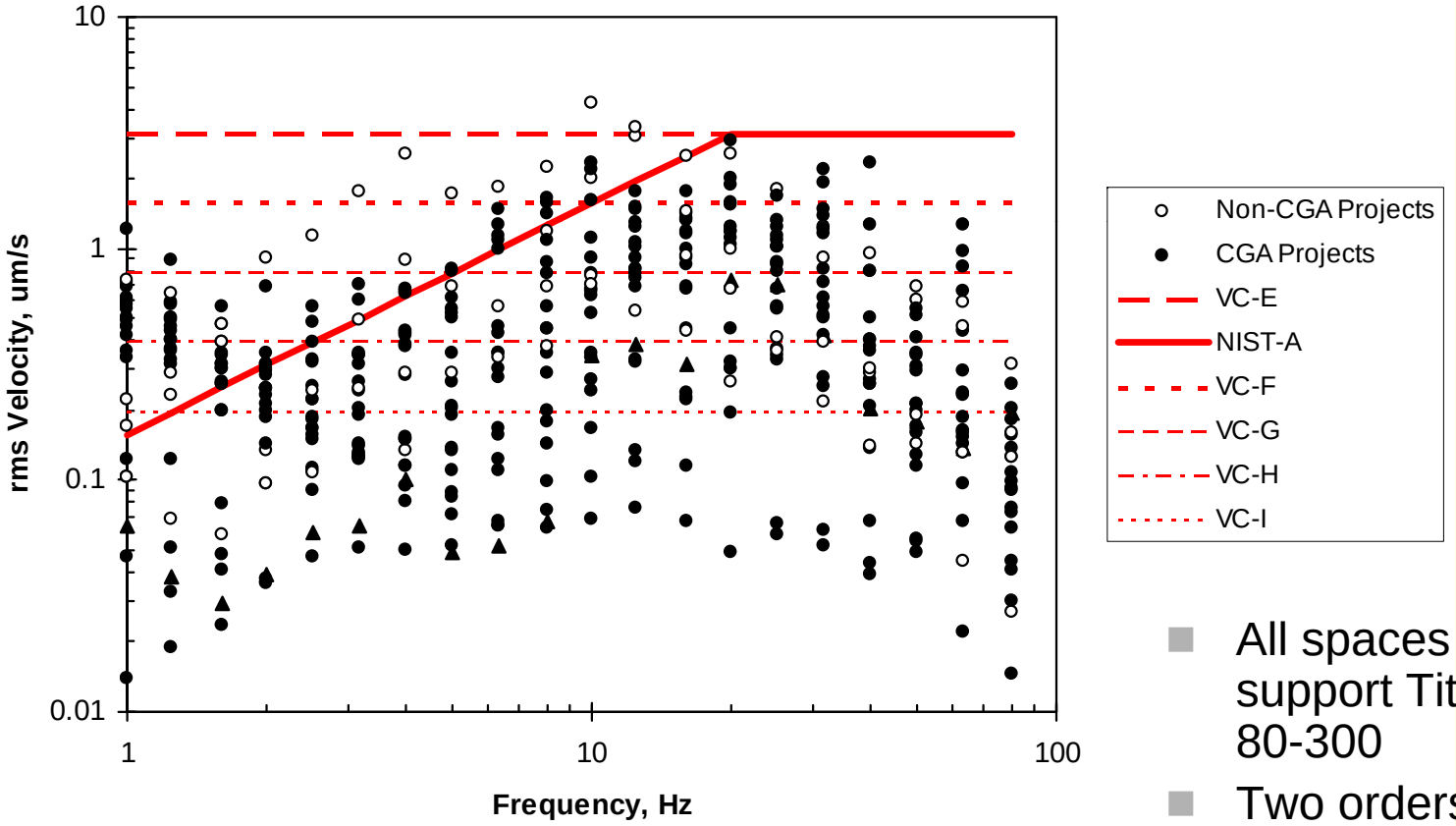
How is the “first wave” of facilities performing?

# Measured Data from 23 Recent Facility Designs

## Intended for nanoscale research or to house advanced imaging (e.g., Titan)




- All spaces can support Titan 80-300
- Two orders of magnitude variation

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# The 23 Recent Facility Designs Included …

- Duffield Hall Imaging Suite
- Birck Center
- NIST AML Instrumentation
- NIST AML Metrology
- ANL Center for Nanoscale Materials
- University of Florida NIMET
- NanoGUNE
- Belknap Research Center
- Stinson-Remick Hall, Notre Dame
- Several Facilities for Confidential Clients
- LBNL National Center for Electron Microscopy
- National Institute for Nanotechnology (NINT)
  - Slab on Grade
  - Island
  - Island on Piles
- Lorry Lokey Laboratory (ONAMI), University of Oregon
- Ion Beam Laboratory (Sandia)
- FEI Demonstration Facility

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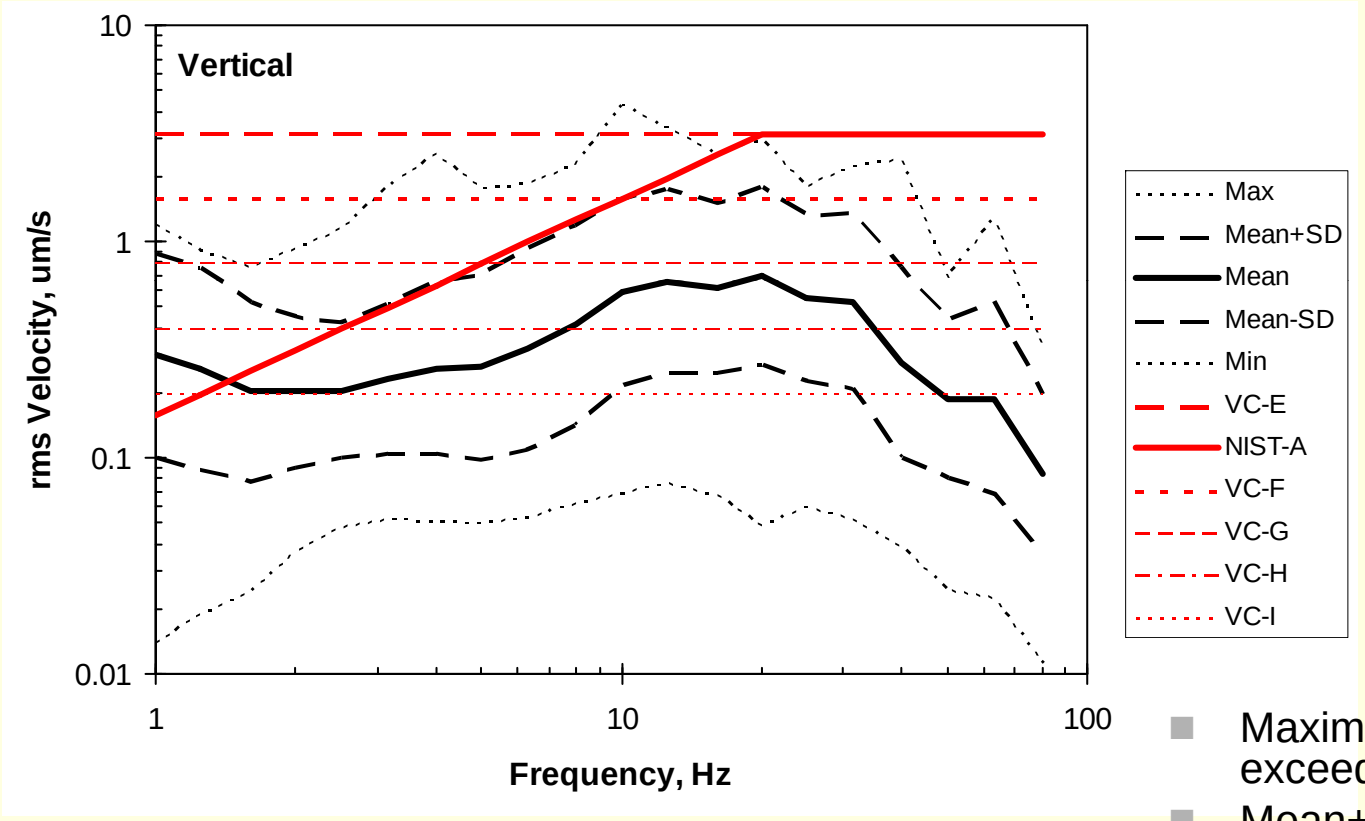
# Statistics of Performance of 23 Facility Designs




- Maximum slightly exceeds VC-E
- Mean+SD meets VC-F
- Mean meets VC-G
- Mean-SD meets VC-H

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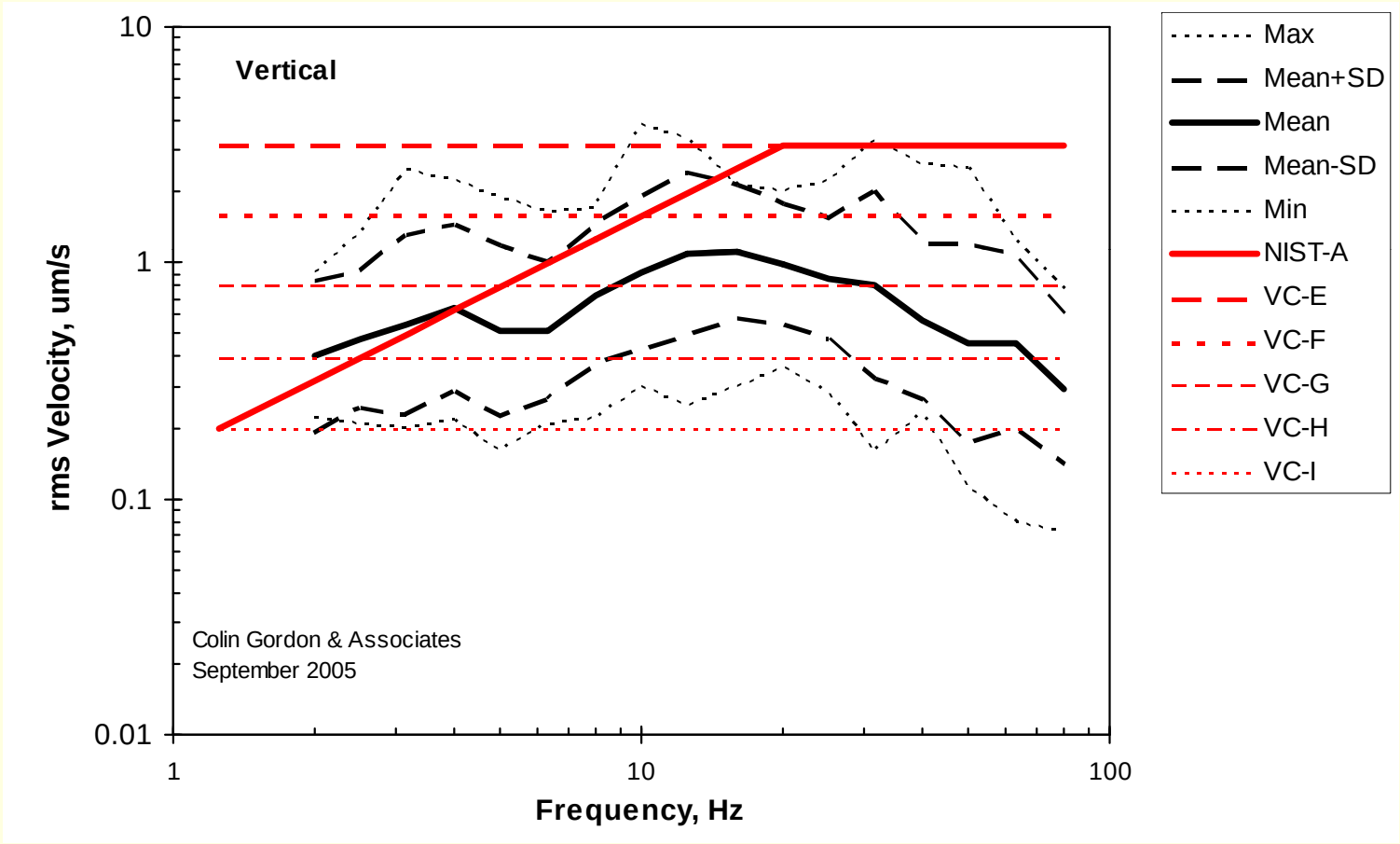
# Recall the Statistics of Site Surveys (2005)

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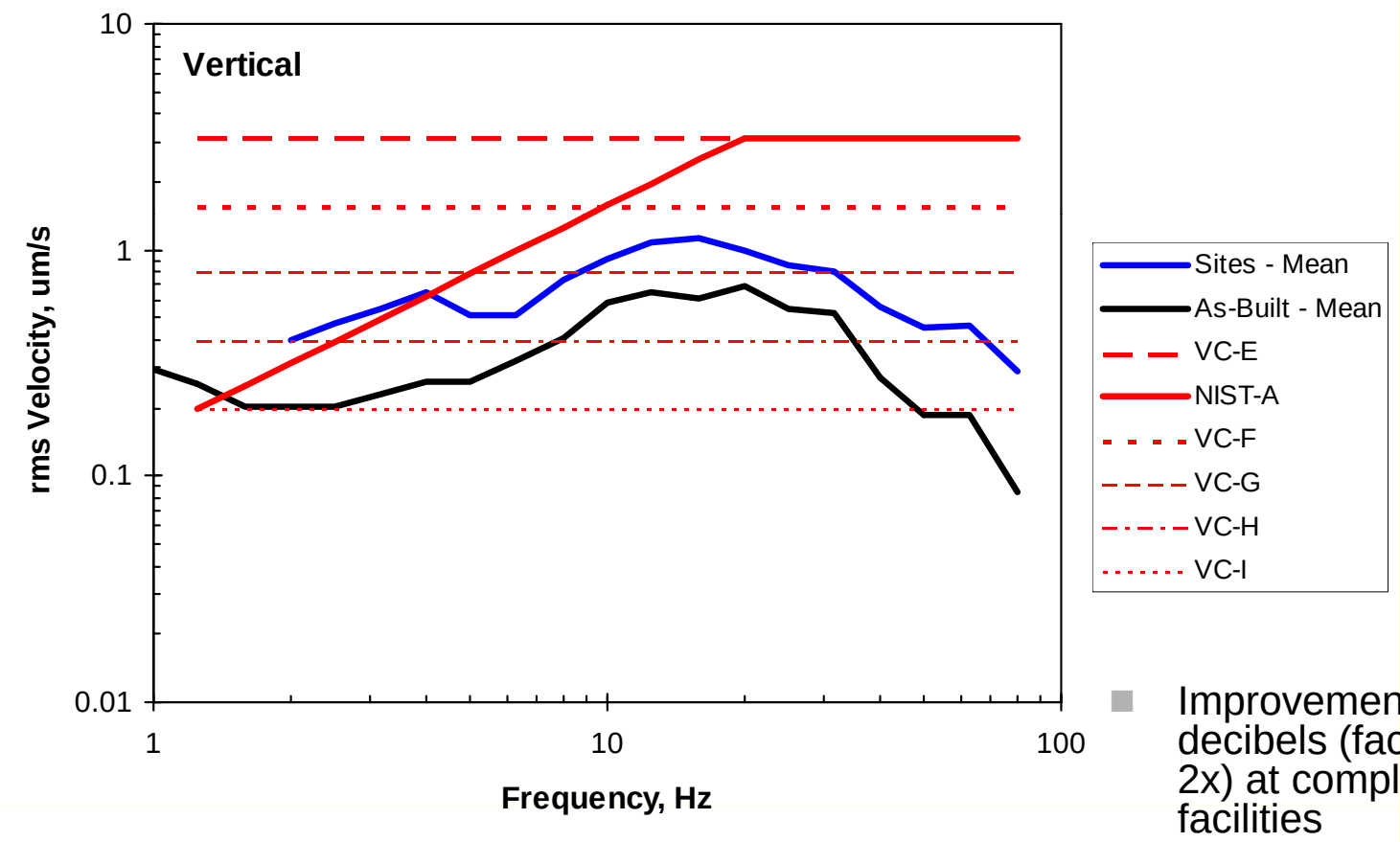
# Compare “Mean” Spectra of Each Group




- Improvement of 4-6 decibels (factor of up to 2x) at completed facilities
- About one VC class

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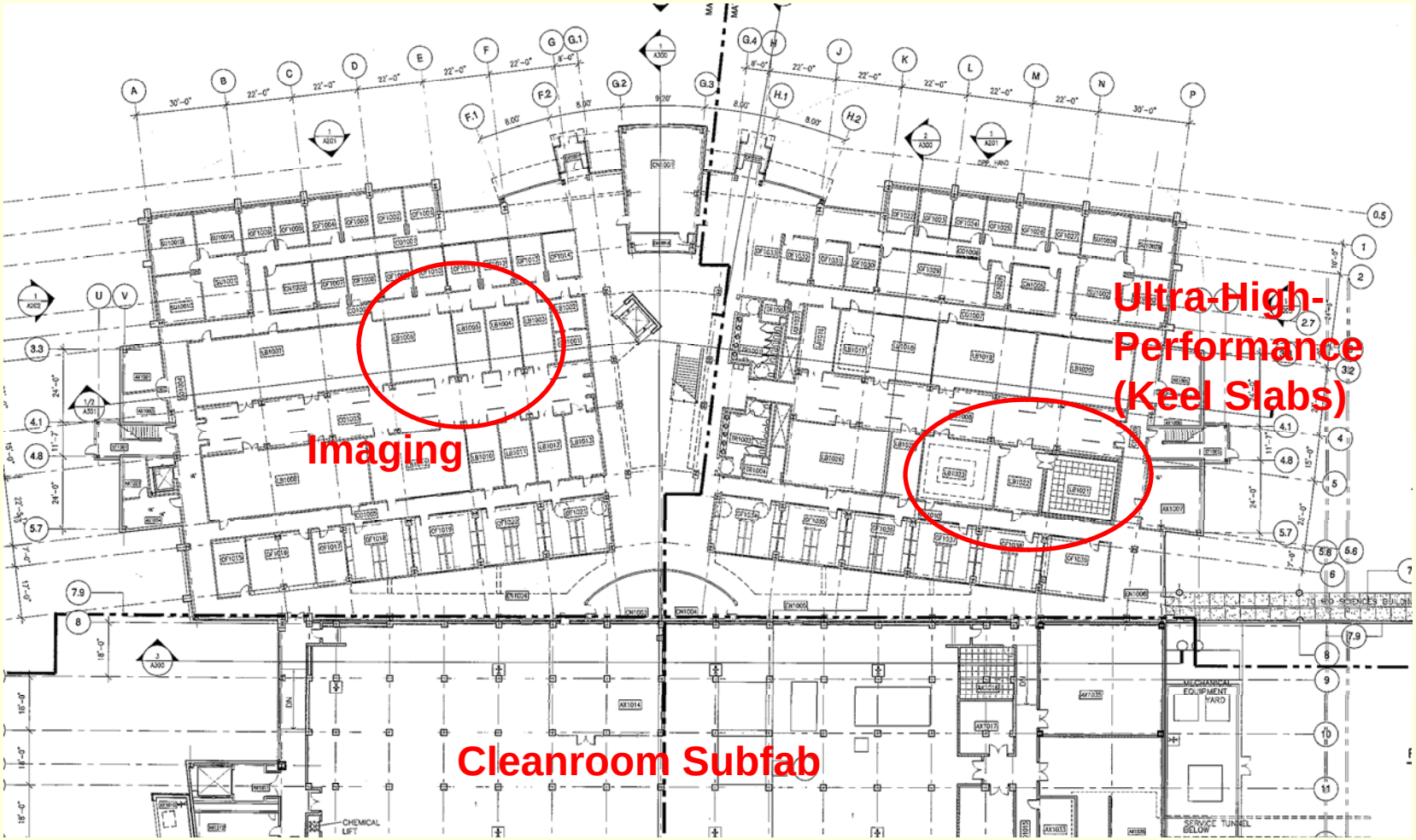
Birck Center for Nanotechnology

Purdue University, West Lafayette IN (USA)

# CASE STUDY

# Overall Plan – Ground Level

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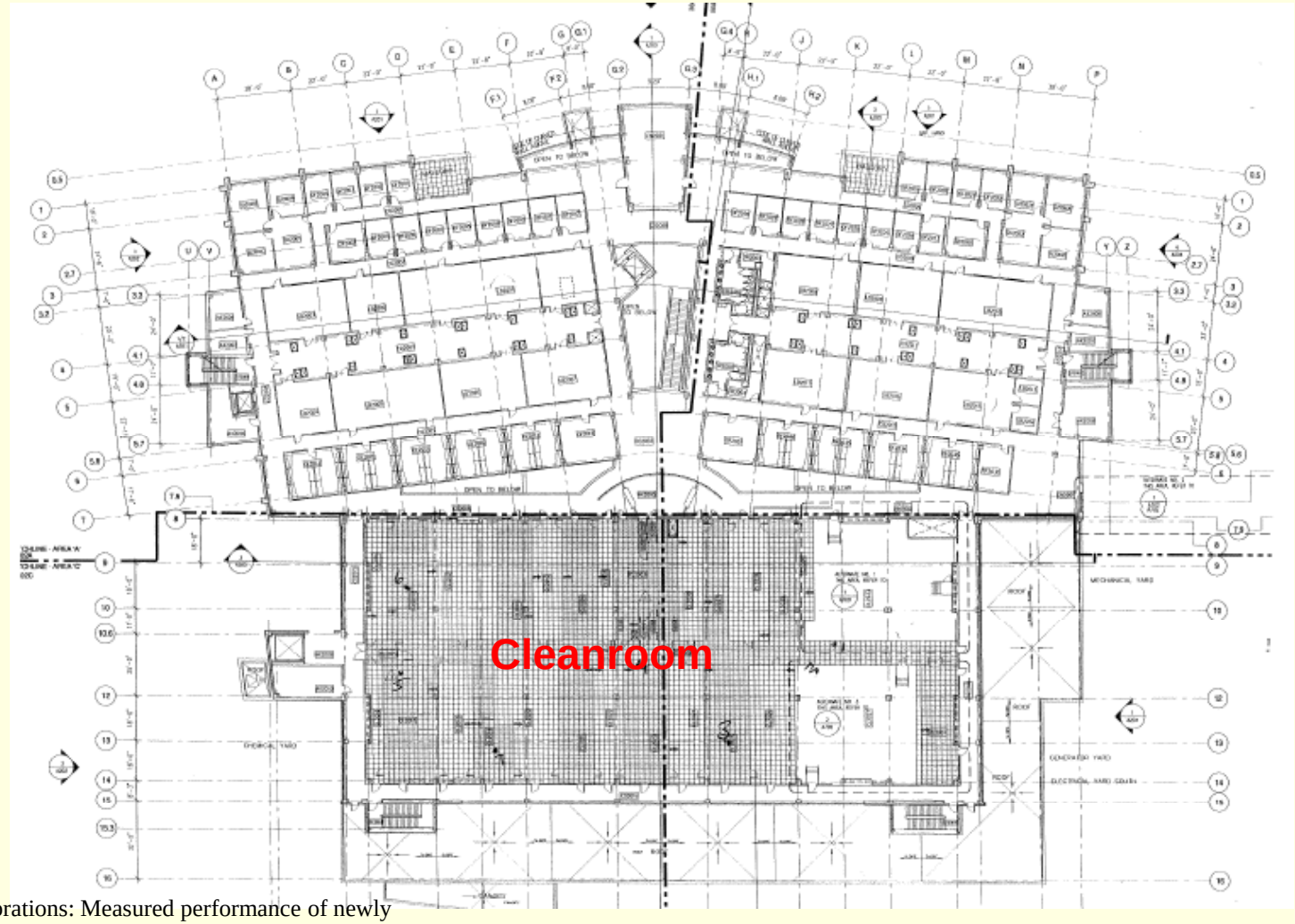
# Overall Plan – Cleanroom Level

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# Imaging Suite
## (Embedded at Center of Building)

Room for Case Study


Amick: “Vibrations: Measured performance of newly designed and built nanoscale research facilities,” ESTECH 2010

# Parameters

- Large Isolated Slab
  - 300mm thick
  - 40.9m x 18.9m
  - 12 lab modules plus common service chase
  - Interior columns penetrate slab to spread footings
- Stud walls
- Vibration meets VC-G
- Acoustics meets NC-27
- Meets Titan requirements

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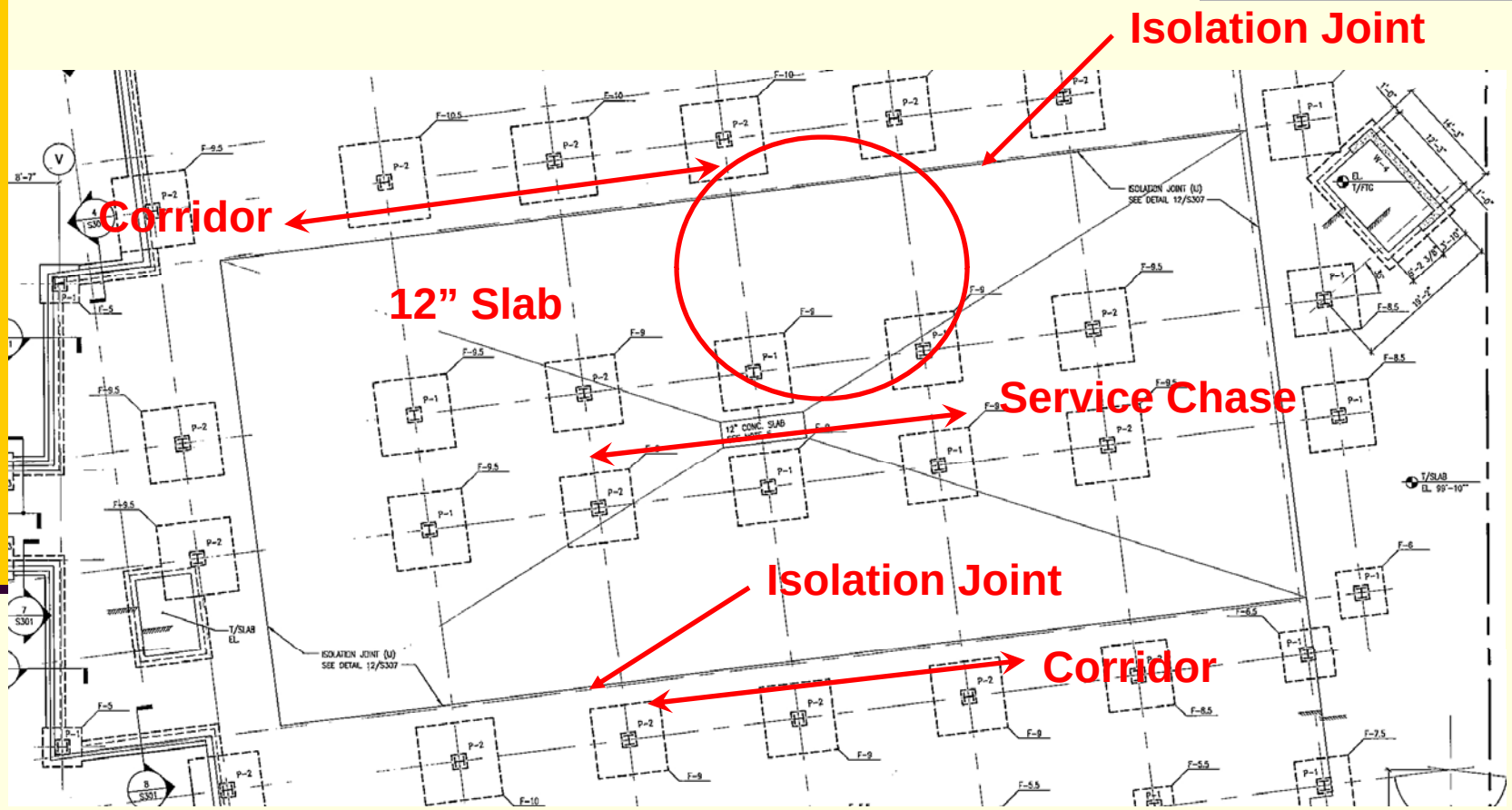
# Foundation – Imaging Area

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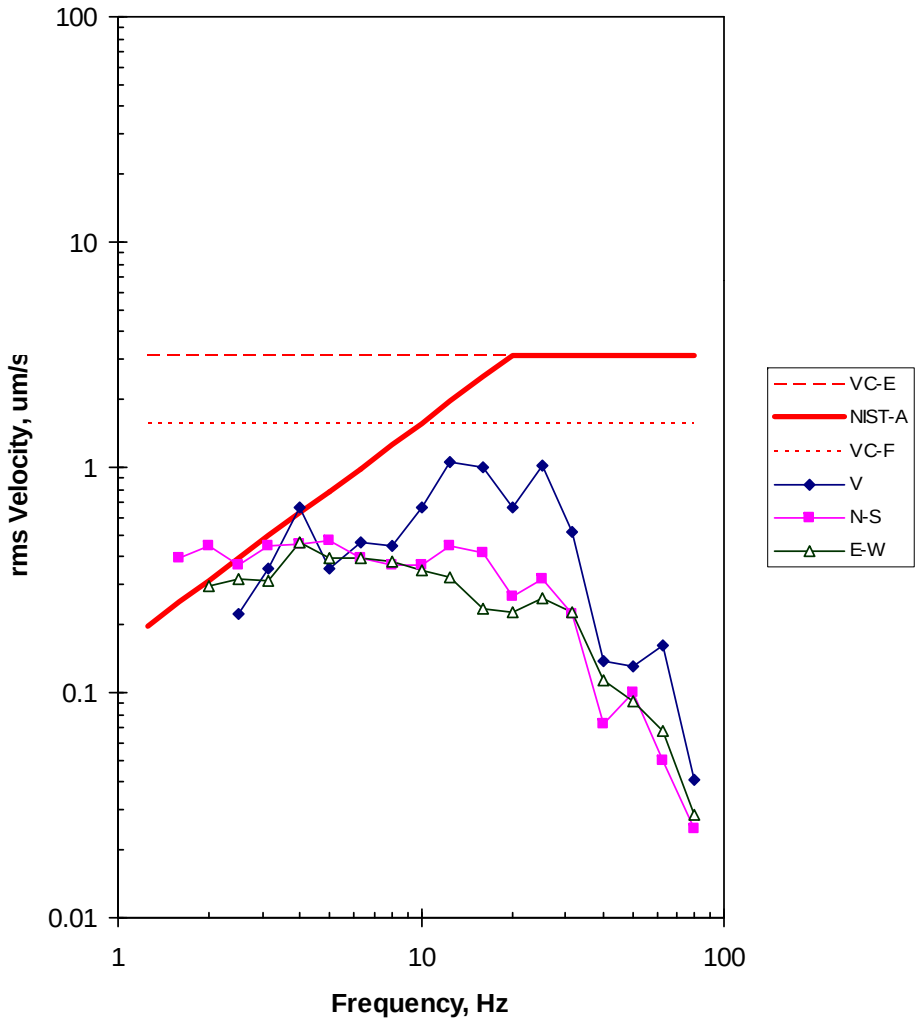
# Performance when Completed




- Meets VC-E
  - (also VC-F)
- Meets NIST-A at f > 2 Hz
- Meets Titan requirements (see following pages)

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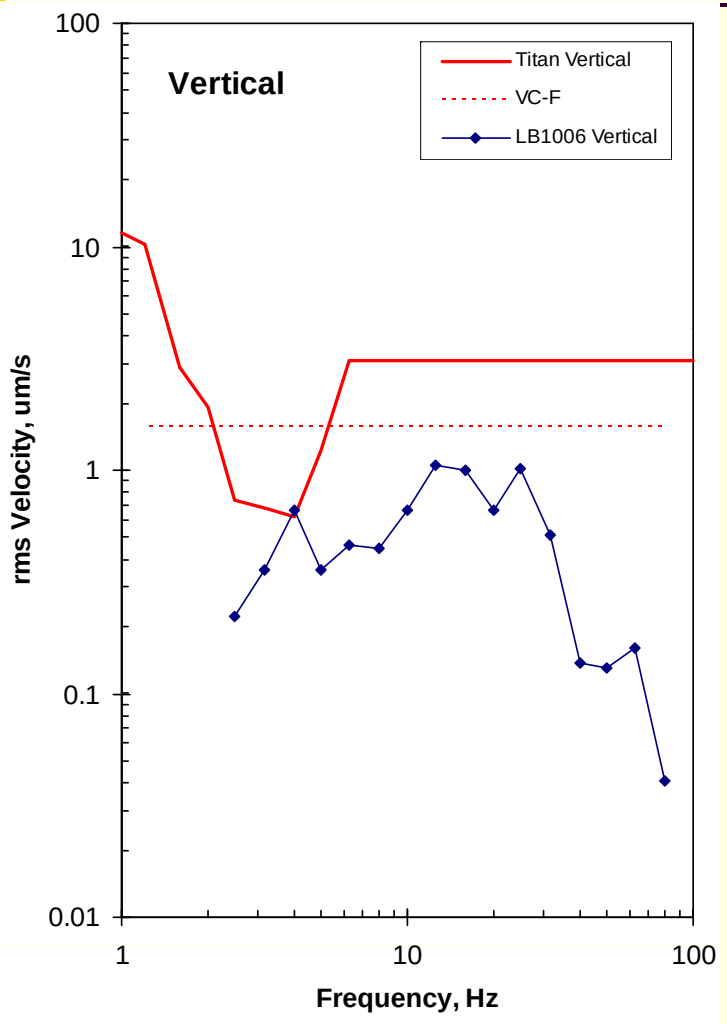
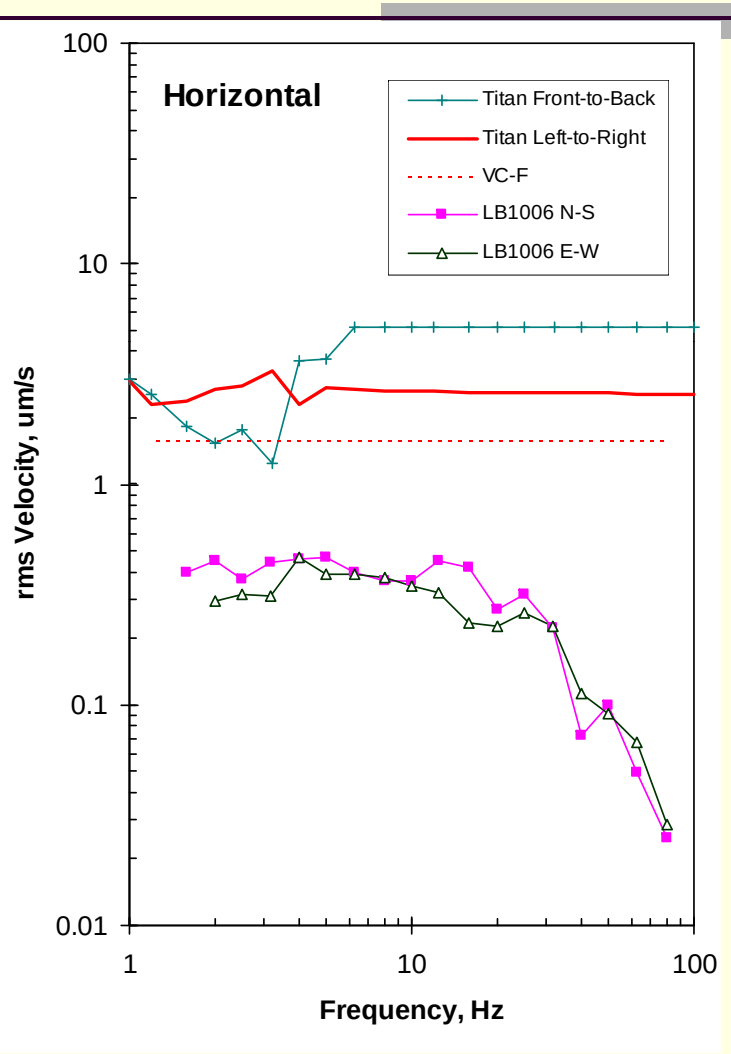
# Meets Titan Requirements (Vibration)

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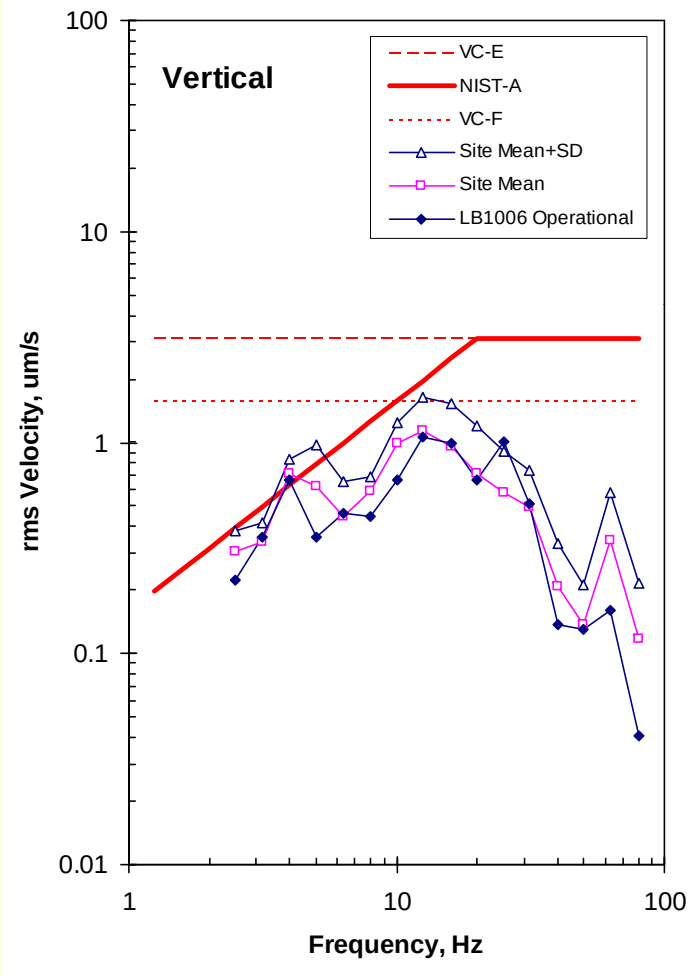
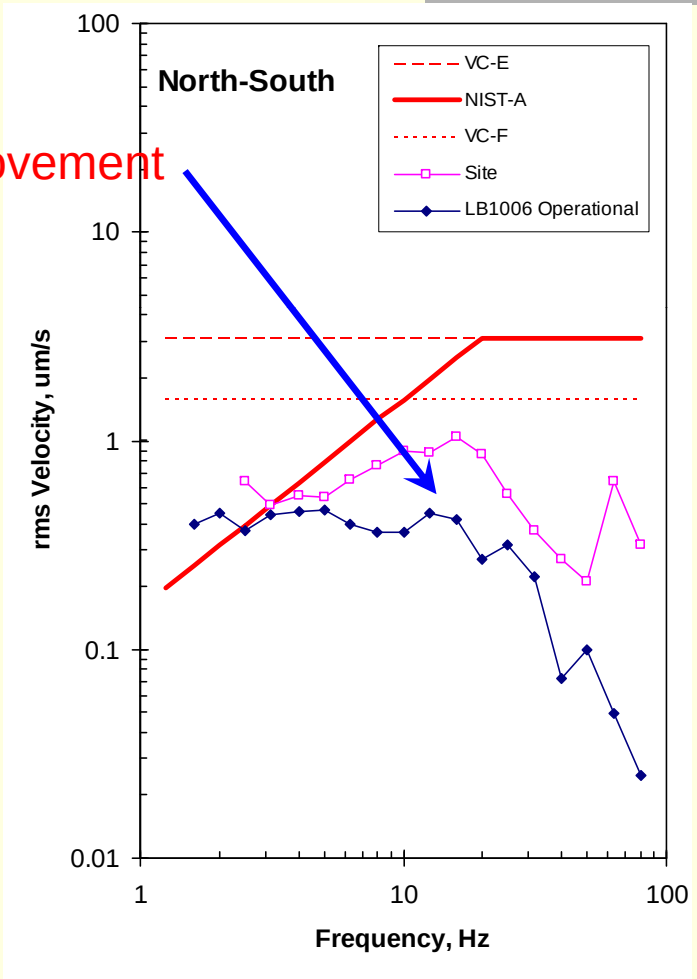
# Compare with Original Site




Improvement

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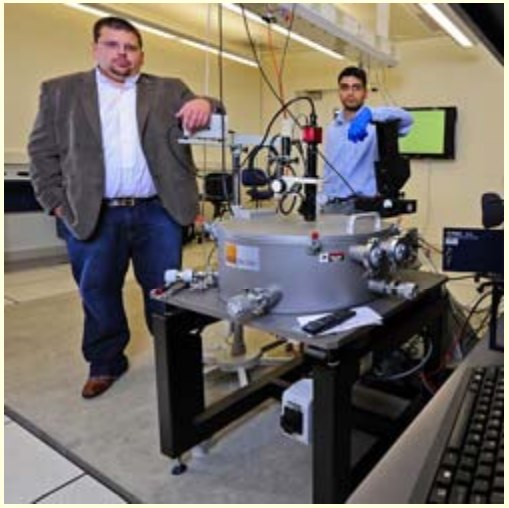
# Two Rooms with Keel Slabs and Shielding

- One used for probe development (Reifenberger, shown left)
- Other used for MEMS bandpass filter (Rhodes, below left)



| Units | | Vertical | North-South | East-West |
|---|---|---|---|---|
| Velocity, μm/s | f ≥ 2 Hz | 0.40 | 0.21 | 0.28 |
| | f ≥ 5 Hz | 0.126 | 0.075 | 0.072 |
| Acceleration, μg | f ≥ 2 Hz | 0.52 | 1.03 | 0.48 |
| | f ≥ 5 Hz | 0.52 | 1.03 | 0.48 |
| Displacement, nm | f ≥ 2 Hz | 31.5 | 17.0 | 22.4 |
| | f ≥ 5 Hz | 3.2 | 2.4 | 2.3 |

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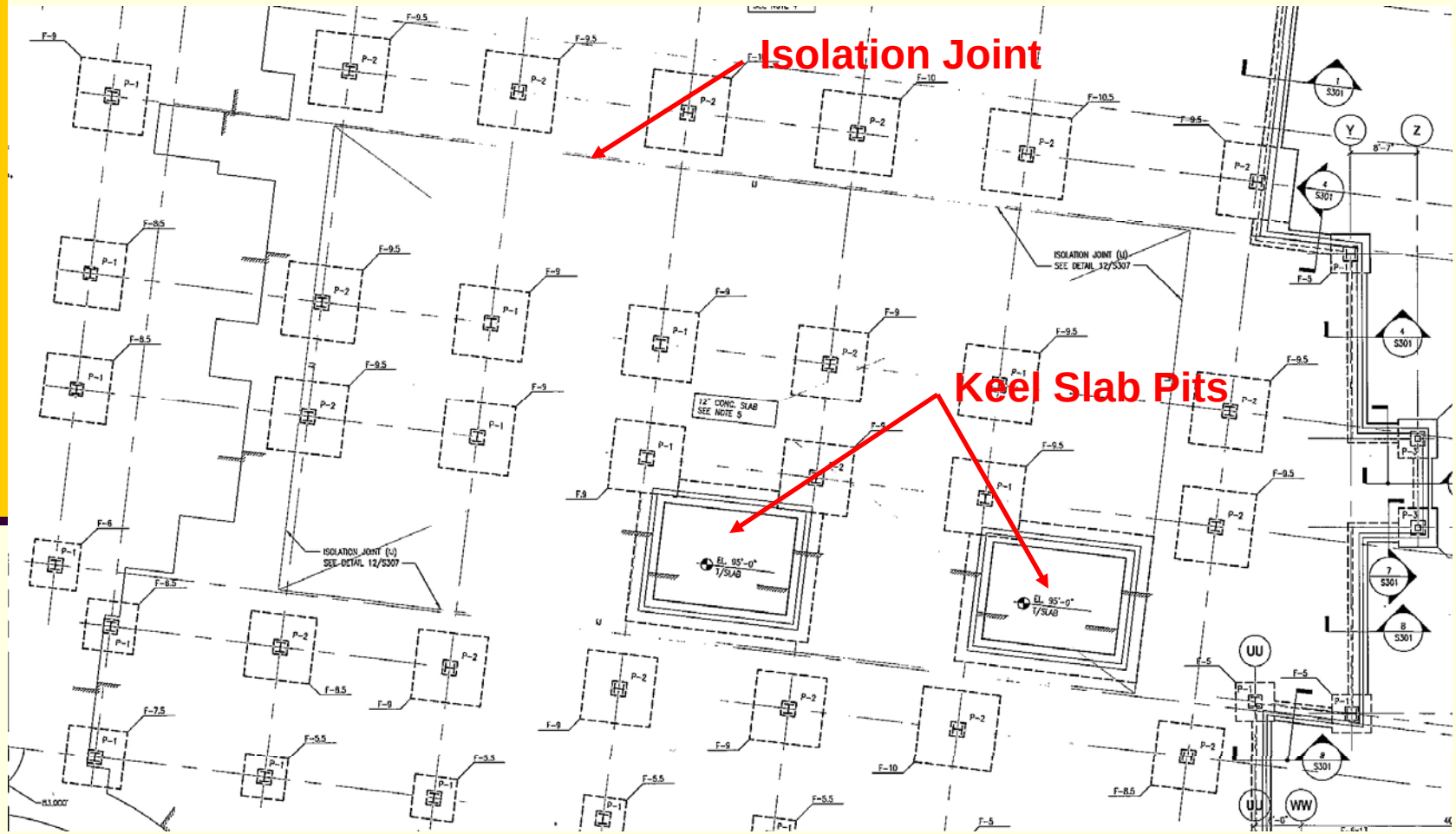
# Foundation – Ultra-High-Performance Area

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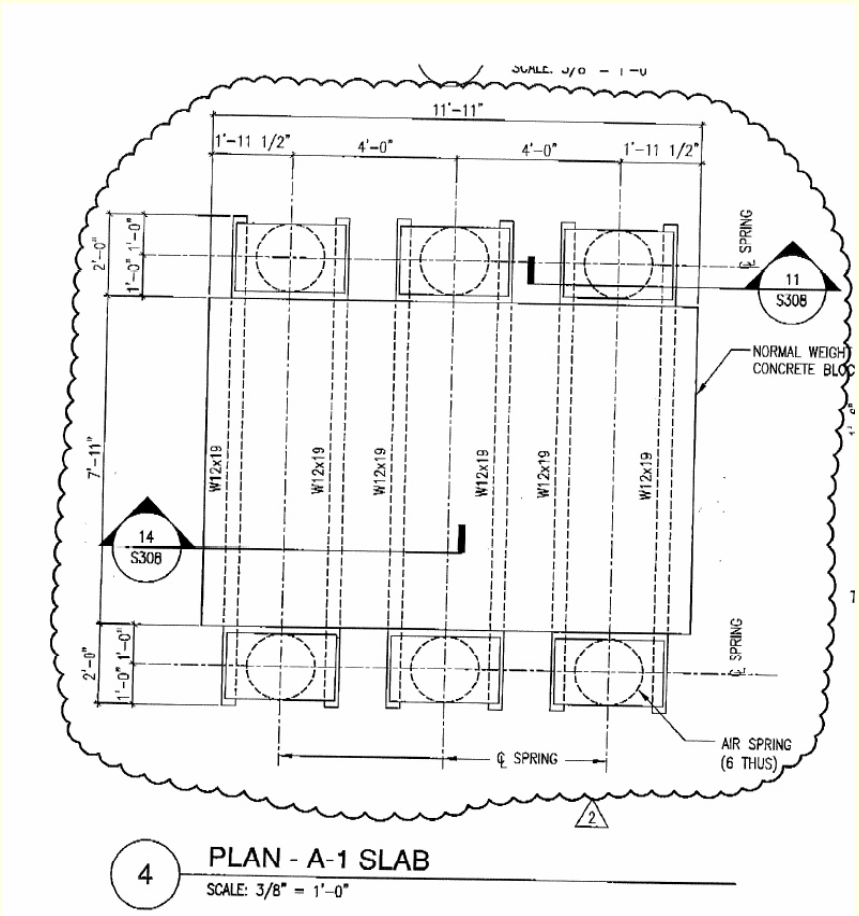
# Plan of Keel




- 2.5m x 3.7m x 1.45m (8 ft x 12 ft x 4’-8”)
- 30,600 kg (67,200 lb)
- Normal concrete plus ConcreDamp
- 200 Hz fundamental internal resonance

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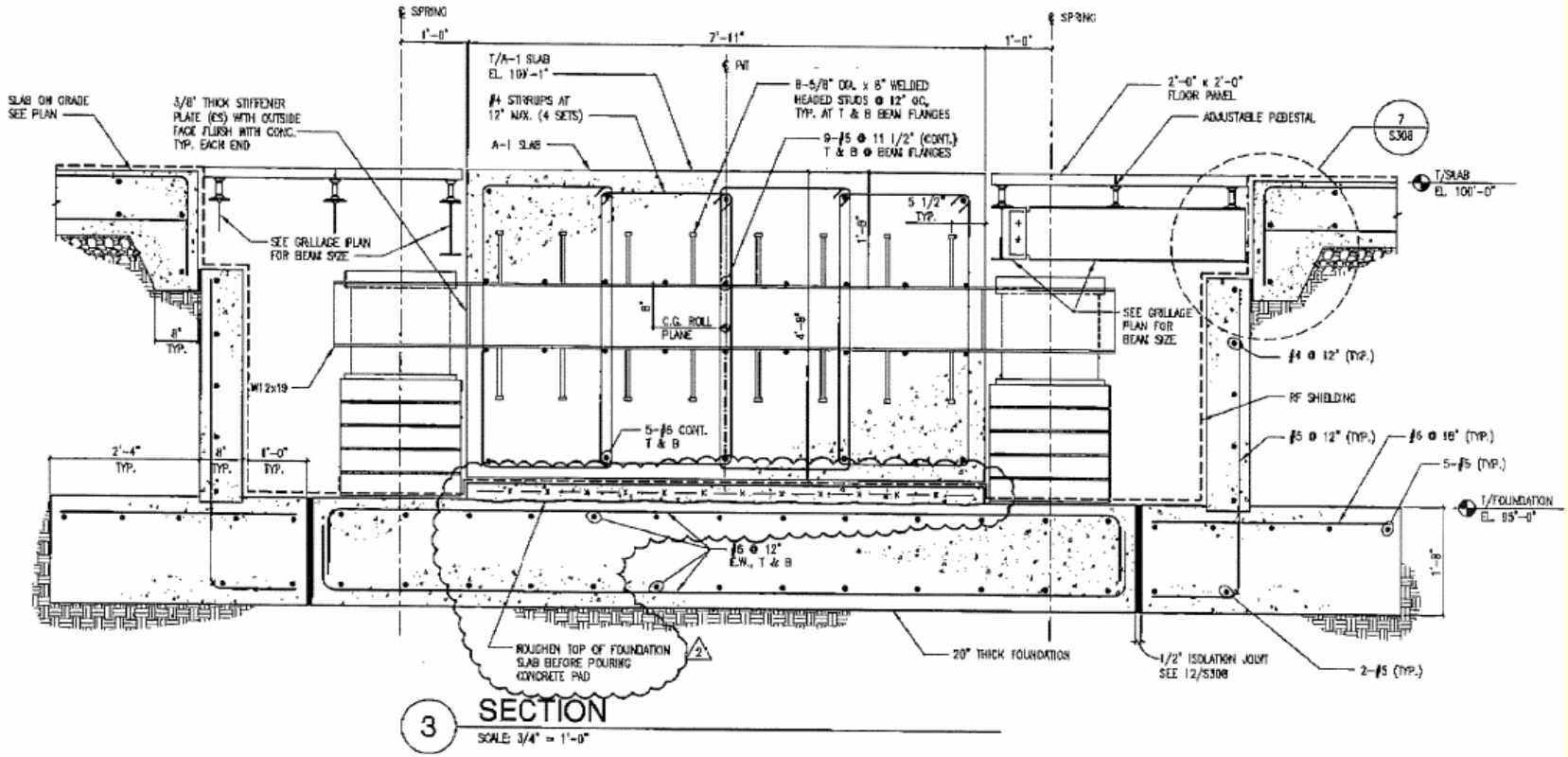
# Section through Keel

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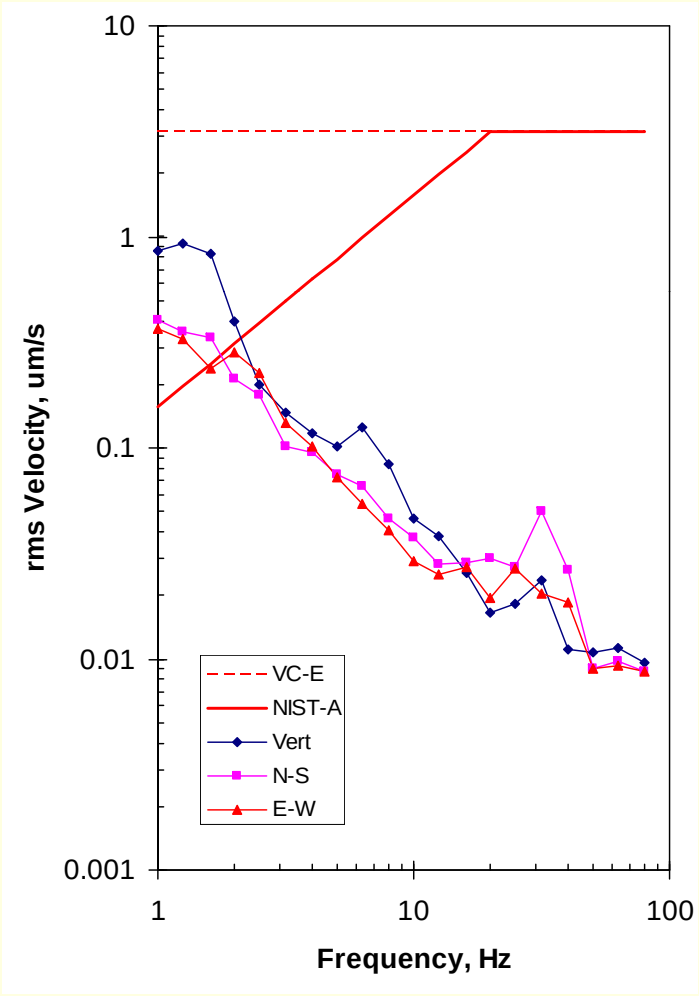
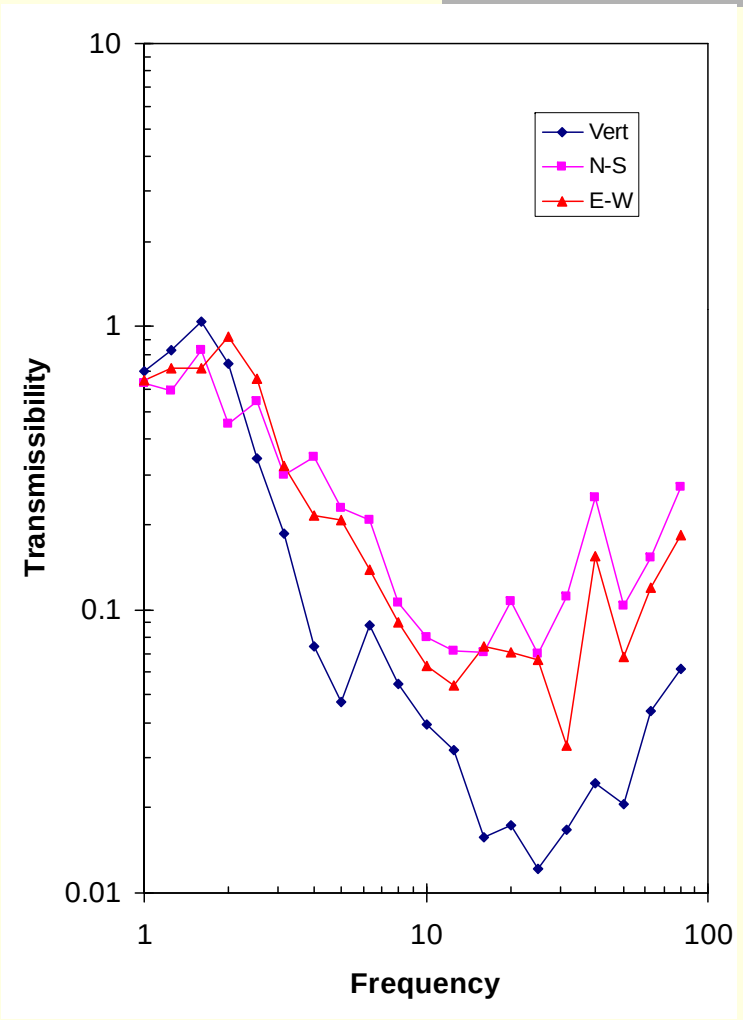
# Performance at Center of Slab

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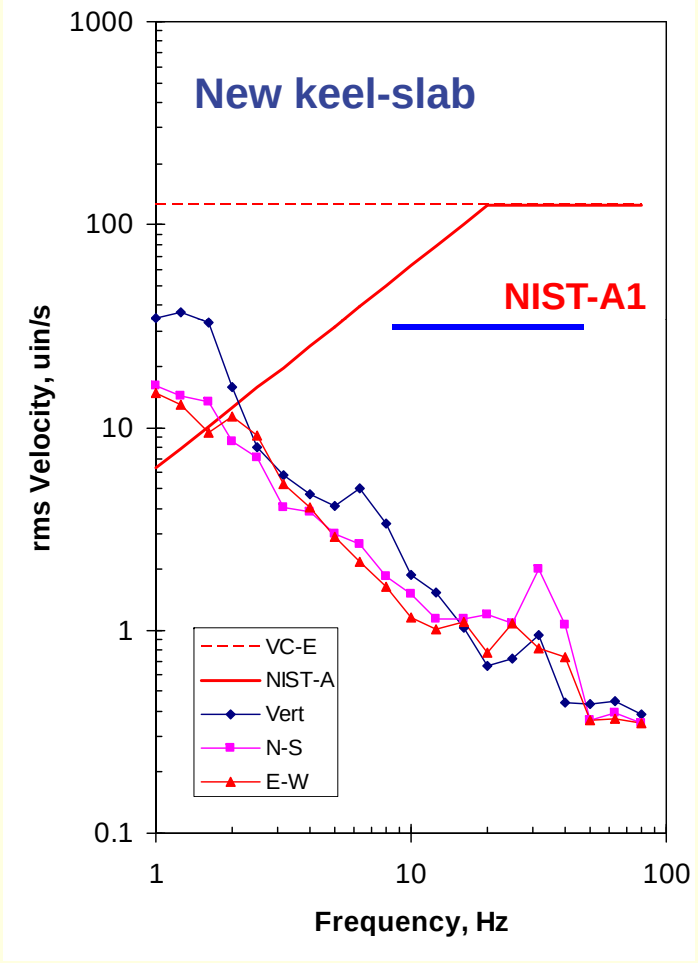
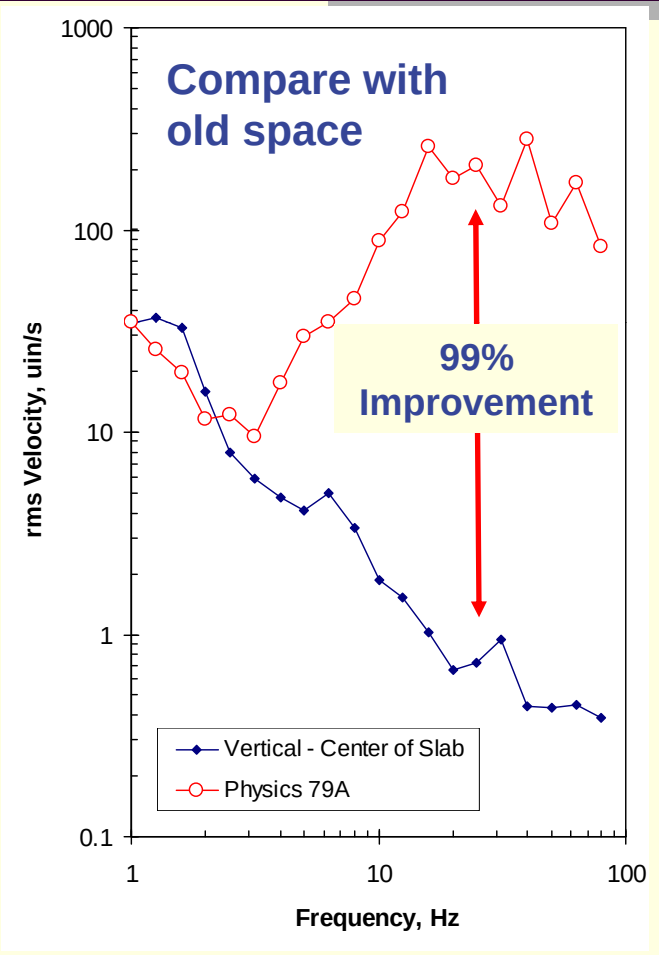
# Performance at Center of Slab

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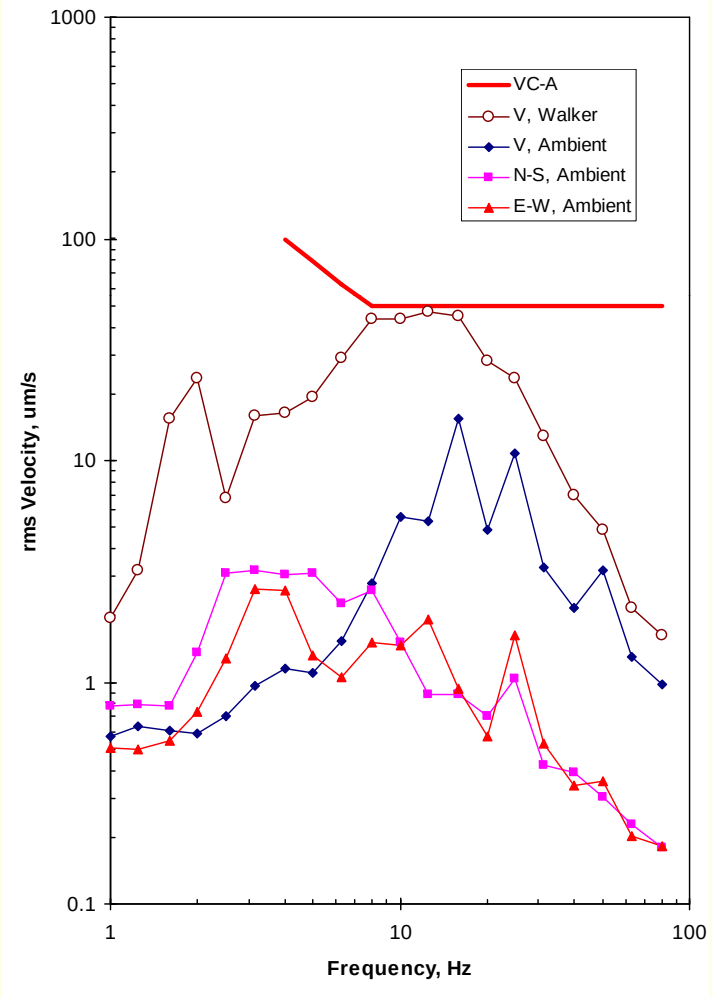
# Second-Floor Performance

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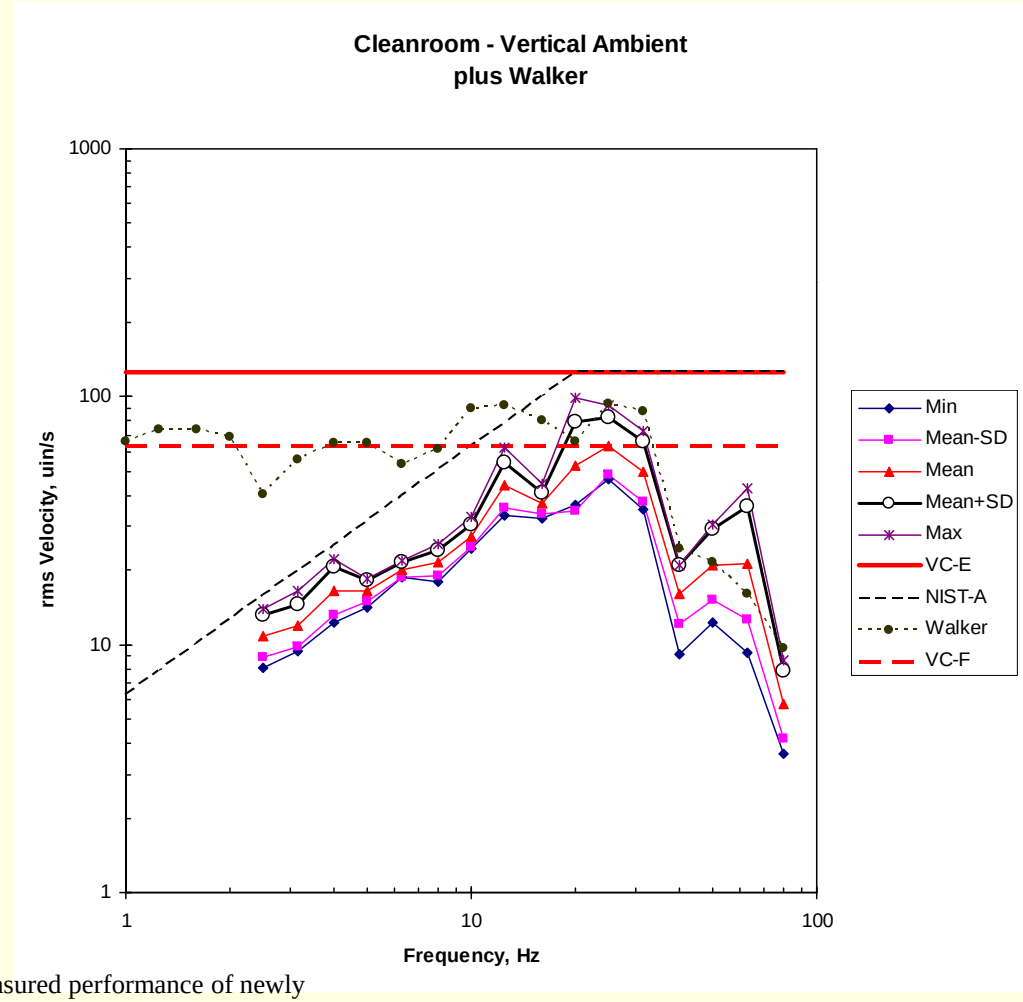
# Cleanroom – Vertical

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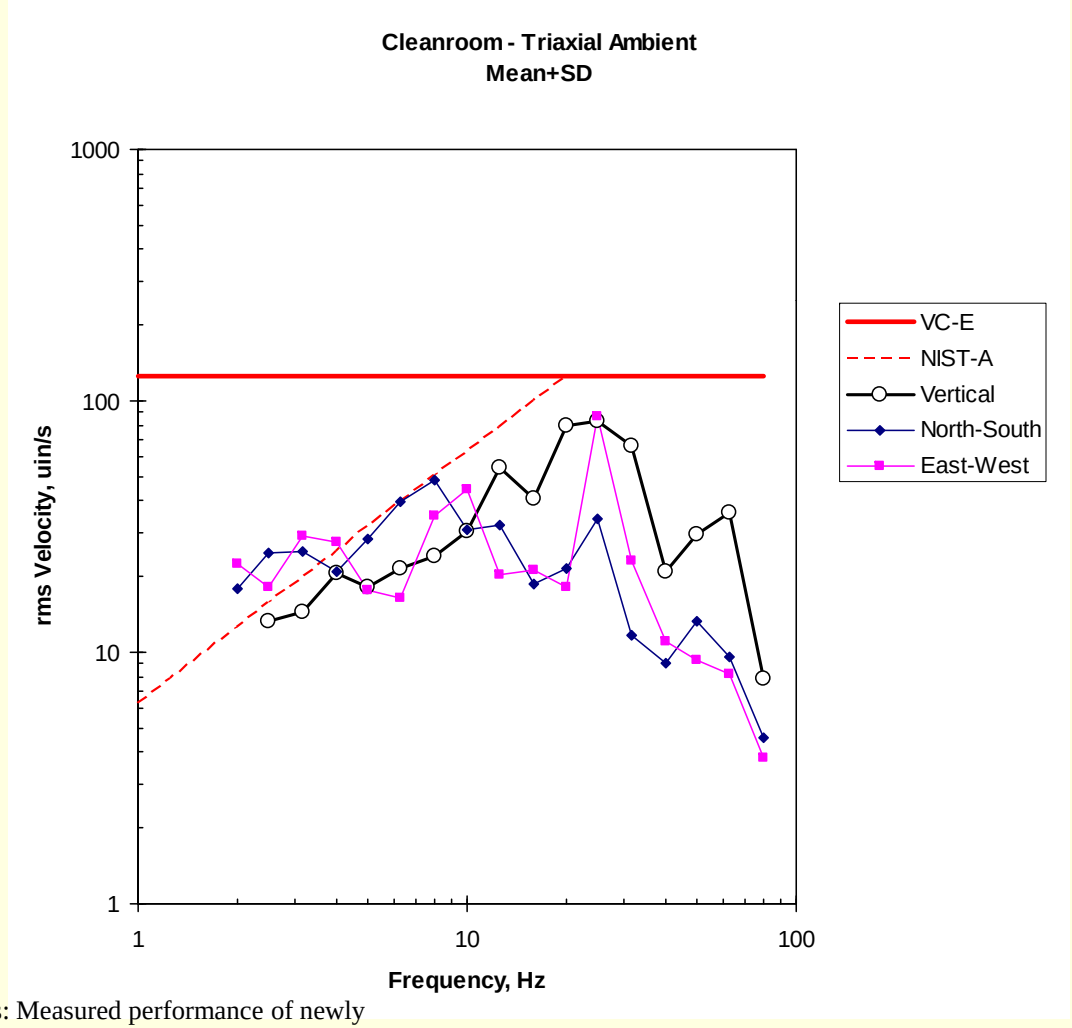
# Cleanroom - Triaxial

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# What is Happening?

- Ongoing study is examining several variables
  - Building Effect
    - The presence of the building “modifies” the site ambient environment
  - Depth
    - Basement or below-grade … how much does it help ?
  - Islands
    - “Islands” involve a concrete block with a surrounding isolation break, separating it from the surrounding slab, foundation and building
    - Do they work as believed ?
  - Mechanical Systems
    - Is it “adequate” to design vibration isolation as we currently do?

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# Building Effect

- The presence of a building can “modify” site vibrations
- Well documented in seismic engineering
- Several papers in the literature regarding low-amplitude and low-frequency effects
- In a nutshell …
  - The presence of a building affects site vibration
    - Impedance change, reflections
    - Stiffening of surface layer
    - Suppresses waves with wavelengths shorter than the size of the building or building component

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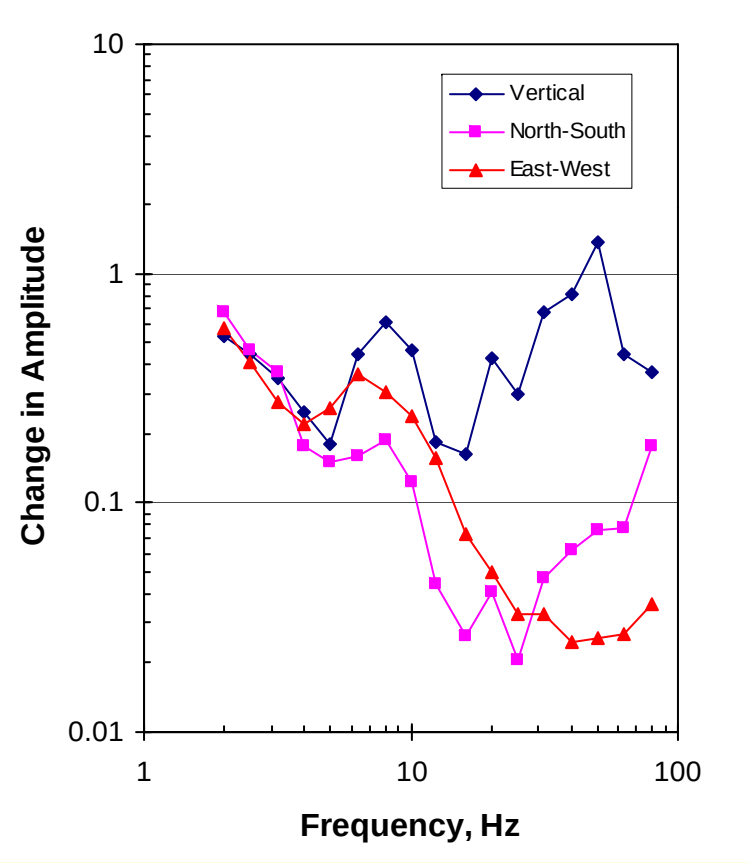
# Building Effect (1)
# LBNL Molecular Foundry

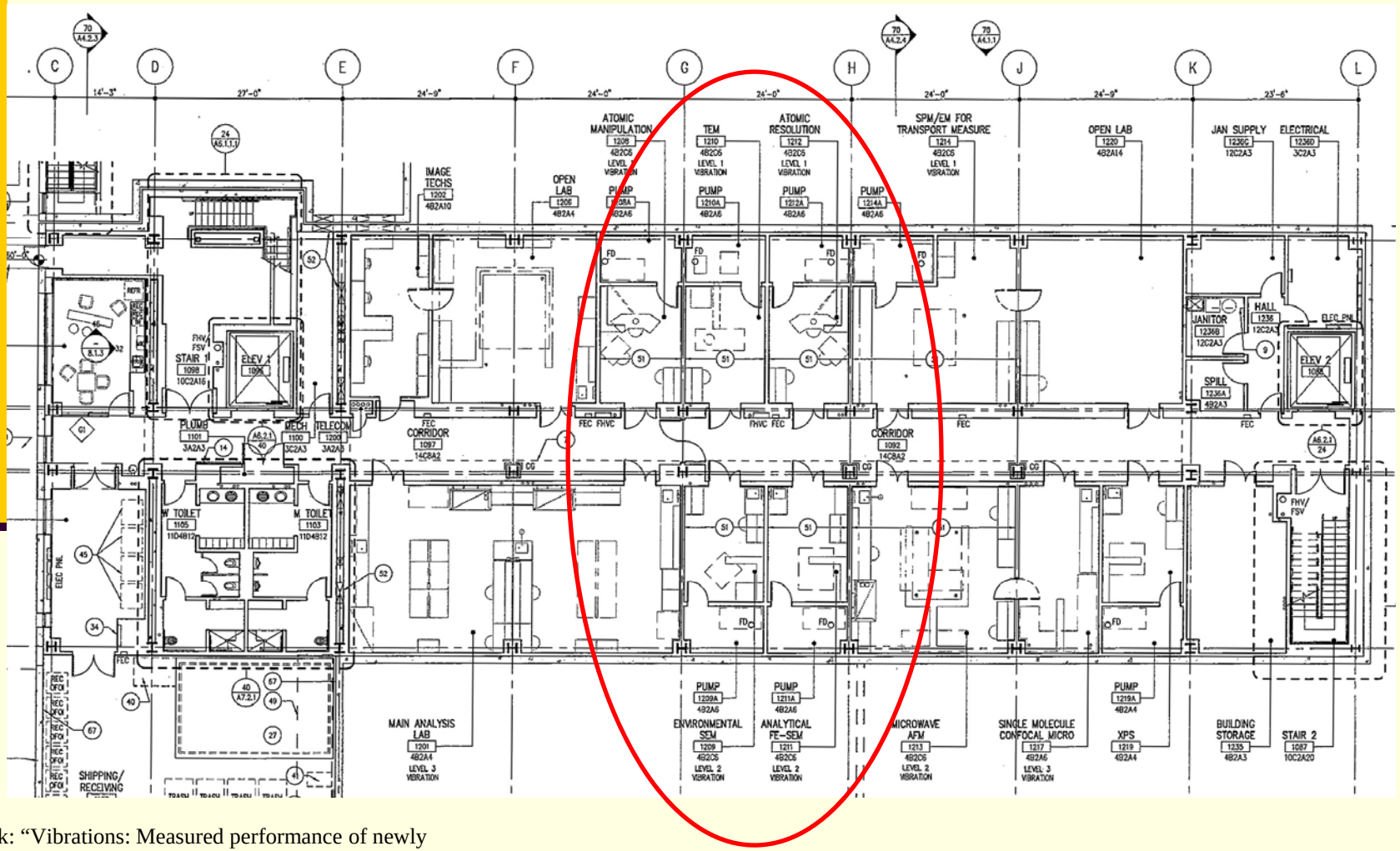



- Single large slab without joints, with integral grade beams
  - 200 mm thick (8 in)
  - 22 lab modules plus central corridor
  - Interior columns penetrate slab to pile caps footings

Amick: "Vibrations: Measured performance of newly designed and built nanoscale research facilities," ESTECH 2010

# Overall Plan – Ground Level - Molecular Foundry

**(Imaging Embedded at Center of Building)**

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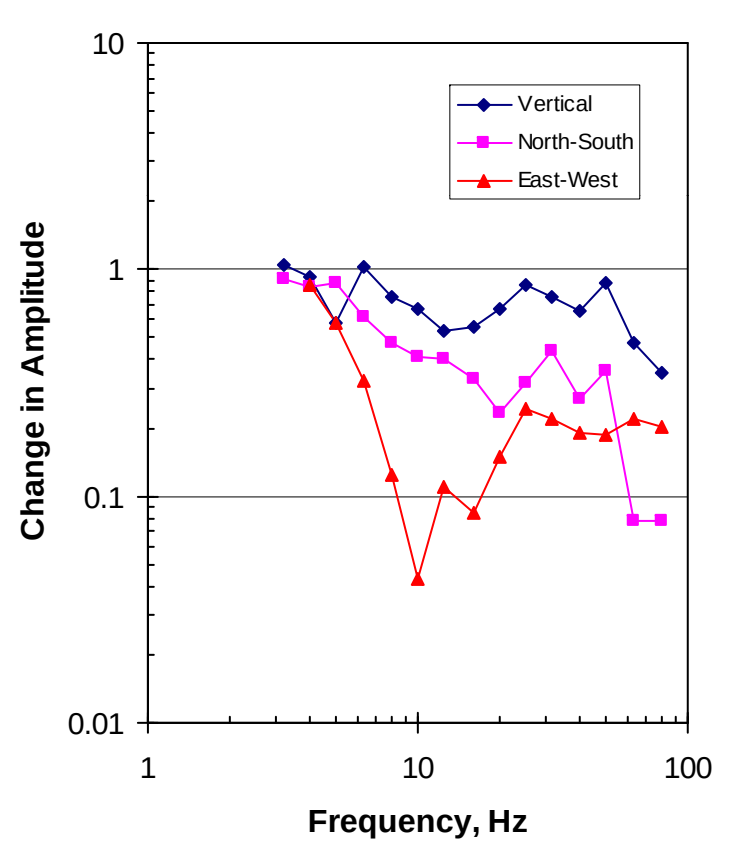
# Building Effect (2)
# Purdue's Birck Nanotechnology Center




- Large Isolated Slab
  - 300 mm thick (12 in)
  - 40.9 m x 18.9m (132 ft x 61 ft)
  - 12 lab modules plus common service chase
  - Interior columns penetrate slab to spread footings

Amick: "Vibrations: Measured performance of newly designed and built nanoscale research facilities," ESTECH 2010

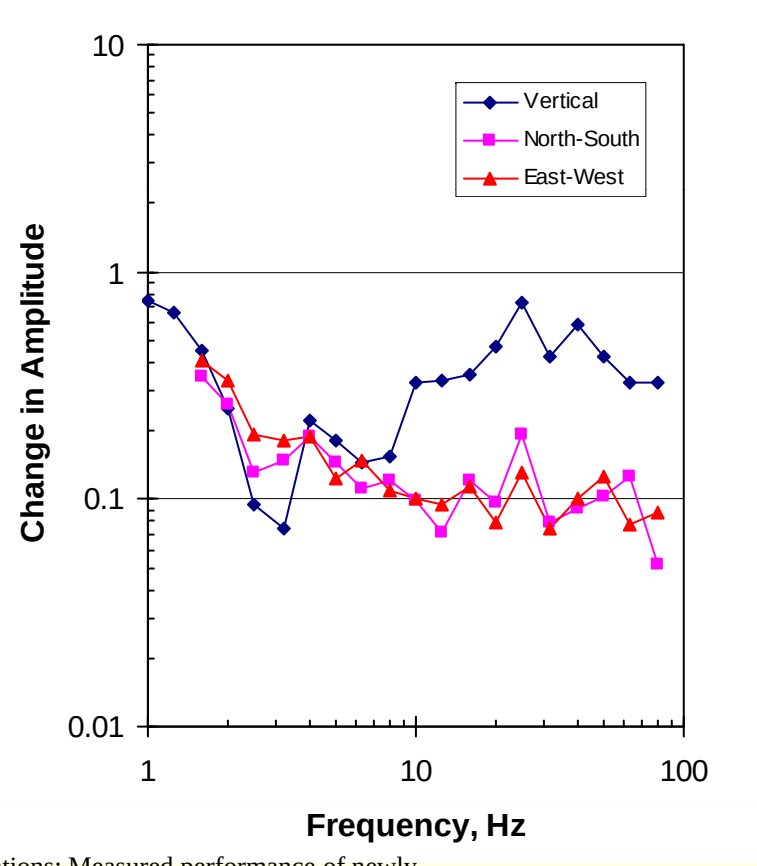
# Imaging Suite – Birck Center

**(Embedded at Center of Building)**

Room for Case Study


Amick: “Vibrations: Measured performance of newly designed and built nanoscale research facilities,” ESTECH 2010

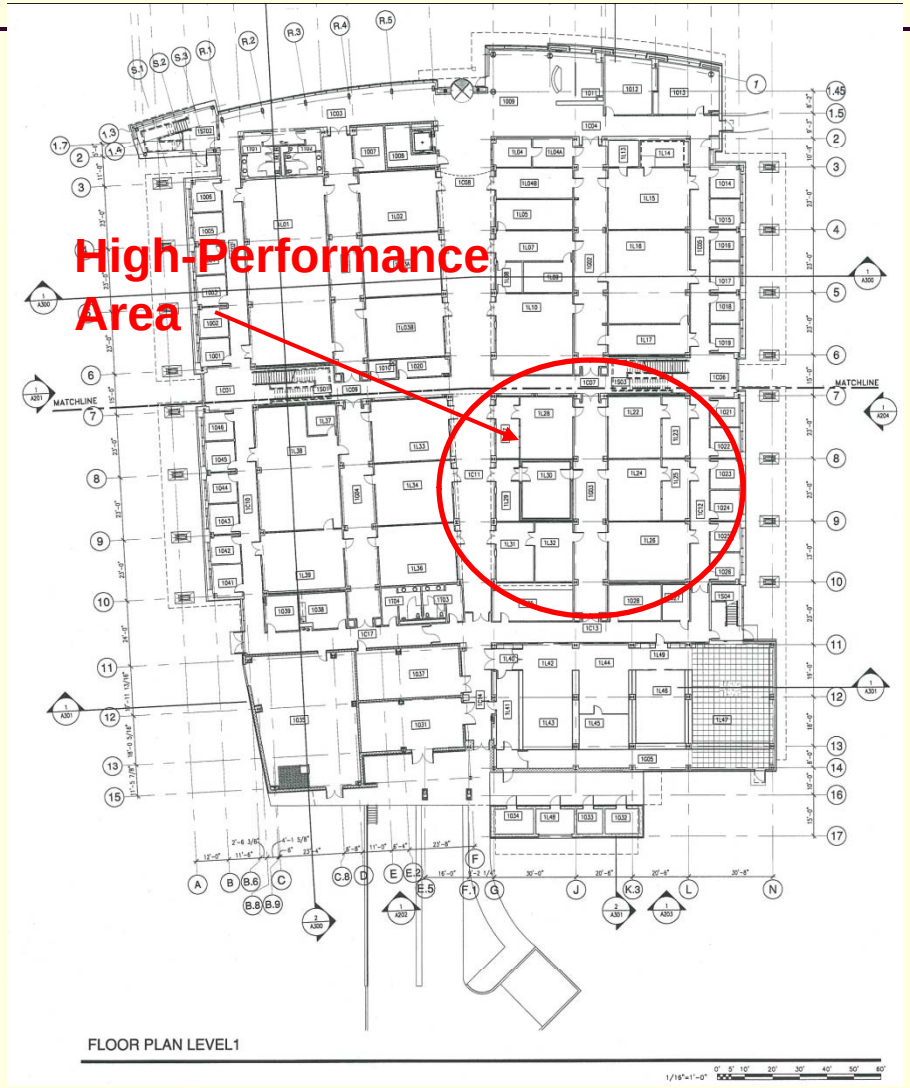
# Building Effect (3)
# BNL Center for Functional Nanomaterials (CFN)




Amick: "Vibrations: Measured performance of newly designed and built nanoscale research facilities," ESTECH 2010

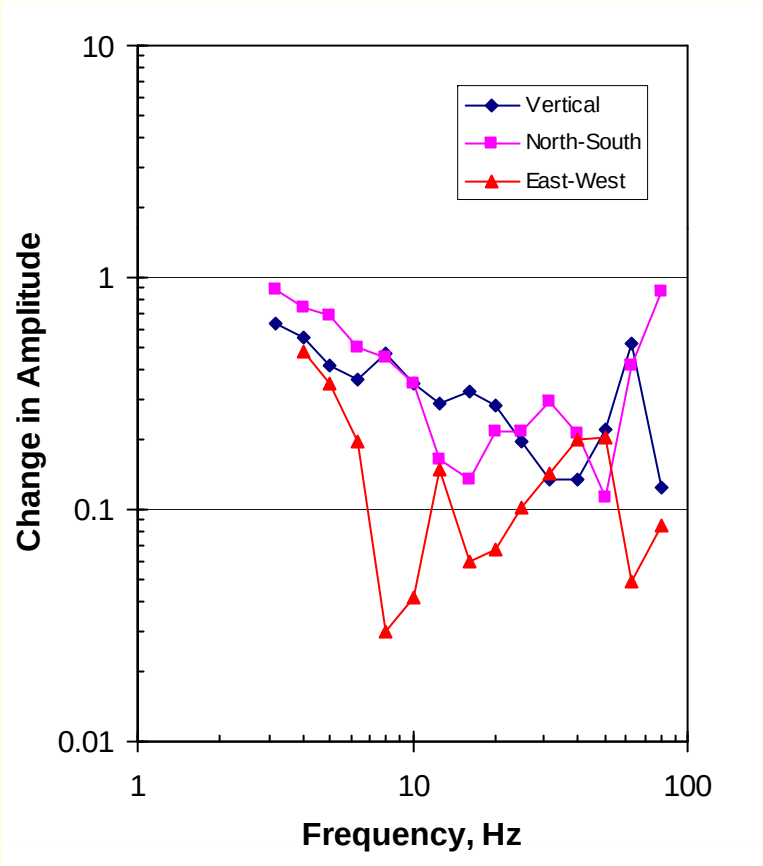
- Large Isolated Slabs beneath Two or Three Lab Modules
  - 600 mm thick (24 in)
  - 14.2m x 9.3m (46 ft x 30 ft) or 21.4m x 9.3m (69 ft x 30 ft)
  - 7 lab modules plus common service chases
  - Interior columns do not penetrate slab

# Overall Plan – Ground Level – Brookhaven CFN

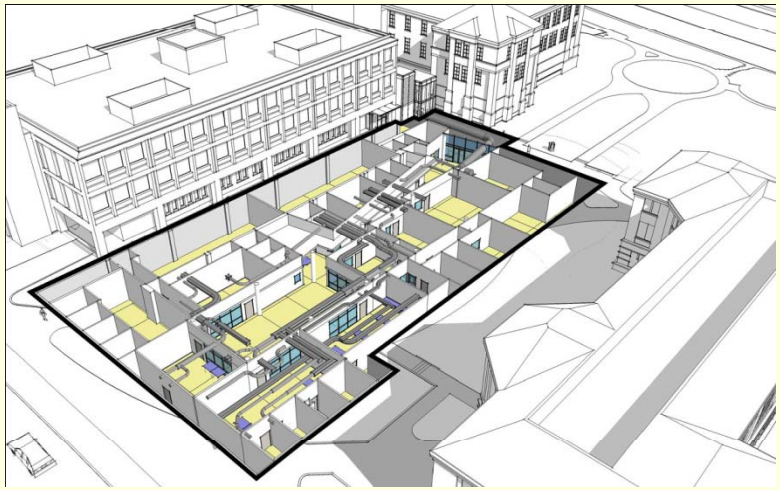



Amick: "Vibrations: Measured performance of newly designed and built nanoscale research facilities," ESTECH 2010

# Building Effect (4)
# Lorry Lokey Laboratory (ONAMI), University of Oregon




- Below-Grade Building
  - 8 in Slab on Grade
  - Slab attached to rock formation



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# Below Grade or Underground

- Special case of building effect
- 70% of ground vibrations are Rayleigh (surface) waves
- Rayleigh waves diminish with depth

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# Case Study 1: Experiment at ASU Site

- Drilling a 6m deep hole, equivalent to the planned depth of the future lab basement, at the shortest distance between that basement and a utility plant
- Accelerometers were placed both on the asphalt at the surface near the top of the hole, and on the packed sand at the base of the hole.
- Vibration data were measured simultaneously at these locations during ambient conditions and while the equipment in a nearby utility building was operated under different conditions
- At the time of the study, there was normal traffic on the nearby roadways, including automobiles, buses, and trucks
- Present discussion involves the ambient measurements.

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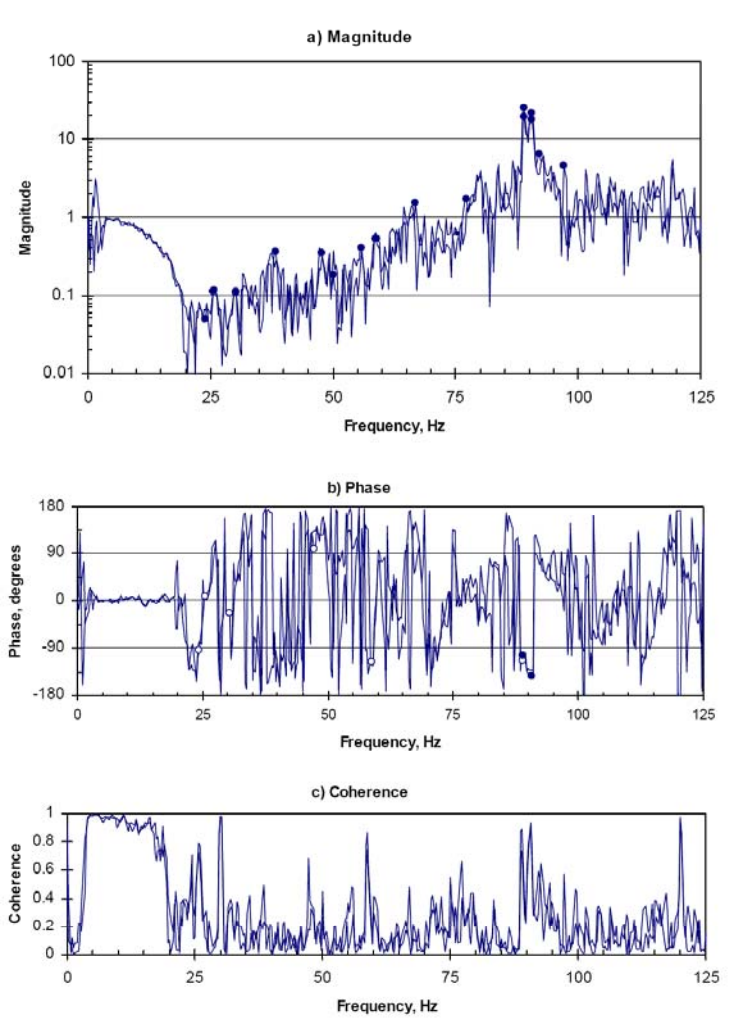
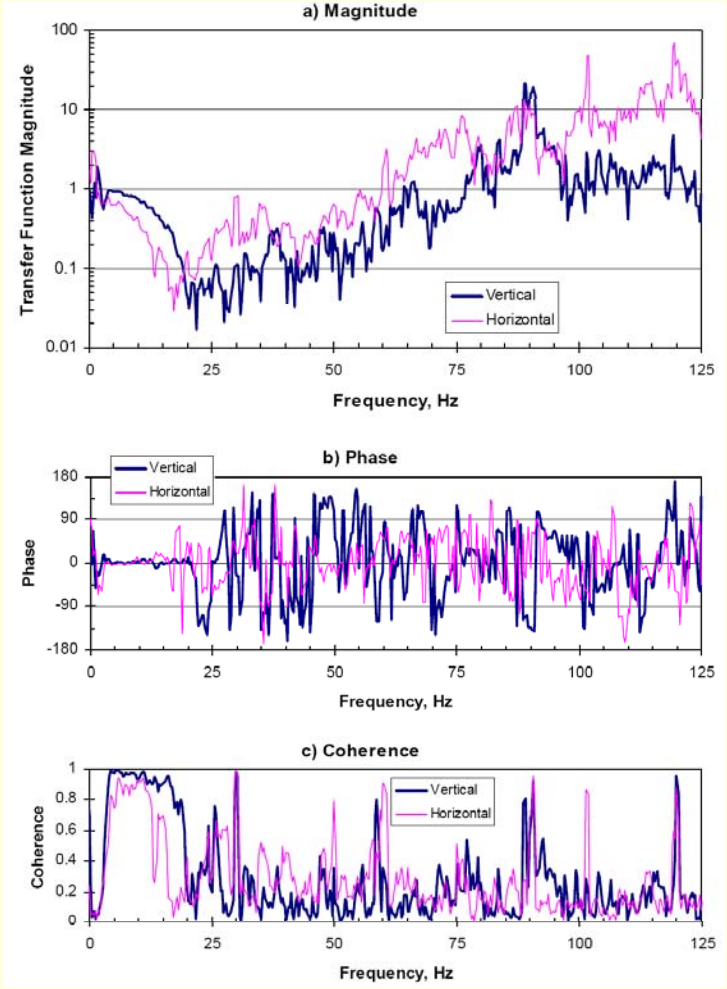
# Frequency Response Functions - Vertical




- Two distinct frequency zones, separated by the "dip" or cutoff frequency, $f_0$, at approximately 20 Hz
  - At $f < f_0$,
    - the spectra are relatively smooth between about 4 Hz and f0.
    - the magnitude approaches a value of 1 as frequency approaches zero, reaches its minimum near $f = f_0$.
    - the coherence stays between 0.9 and 1 and the phase remains close to zero.
  - At $f > f_0$,
    - spectra become less smooth
    - phase varies erratically
    - coherence is quite low, except for a few isolated frequencies

Amick, Gendreau, Xiong, and Simos, "Effects of frequency and depth on attenuation of ambient ground vibration," Proceedings NOISE-CON 2010, Baltimore, MD, April 19-21, 2010.

# Compare Horizontal and Vertical FRFs




- Horizontal also exhibits two distinct frequency zones, but the cutoff frequency is at approximately 17 Hz instead of 20 Hz
- Less pronounced dip in the magnitude and coherence spectra at approximately 13.5 Hz.

Amick, Gendreau, Xiong, and Simos, "Effects of frequency and depth on attenuation of ambient ground vibration," Proceedings NOISE-CON 2010, Baltimore, MD, April 19-21, 2010.

# Potential difference

- At low frequencies
  - the horizontal FRF lies almost entirely below the vertical FRF;
- At almost all frequencies above the crossover at 19 Hz, the horizontal FRF lies almost entirely above the vertical.
- This may suggest that at low frequencies, horizontal vibrations are more attenuated at depth than vertical vibrations, but that the reverse is true at frequencies above $f_0$.

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# Case 2: Experiment at Brookhaven Nat'l Lab

- Required quantitative information regarding improvement at depth
  - (Cost-benefit study for below-grade lab space)
- Three different manhole pits near building site
  - 1.5 m (4.8 ft)
  - 2.8 m (9 ft)
  - 5.3 m (17 ft)
- Accelerometers were placed both on the asphalt at the surface near the top of the hole, and on the concrete at the base of the hole.
- At the time of the study, there was normal traffic on the nearby roadways, including automobiles, buses, and trucks. Intermittent construction activity
- Present discussion involves the ambient measurements.
- Vertical only, due to time constraints in the field



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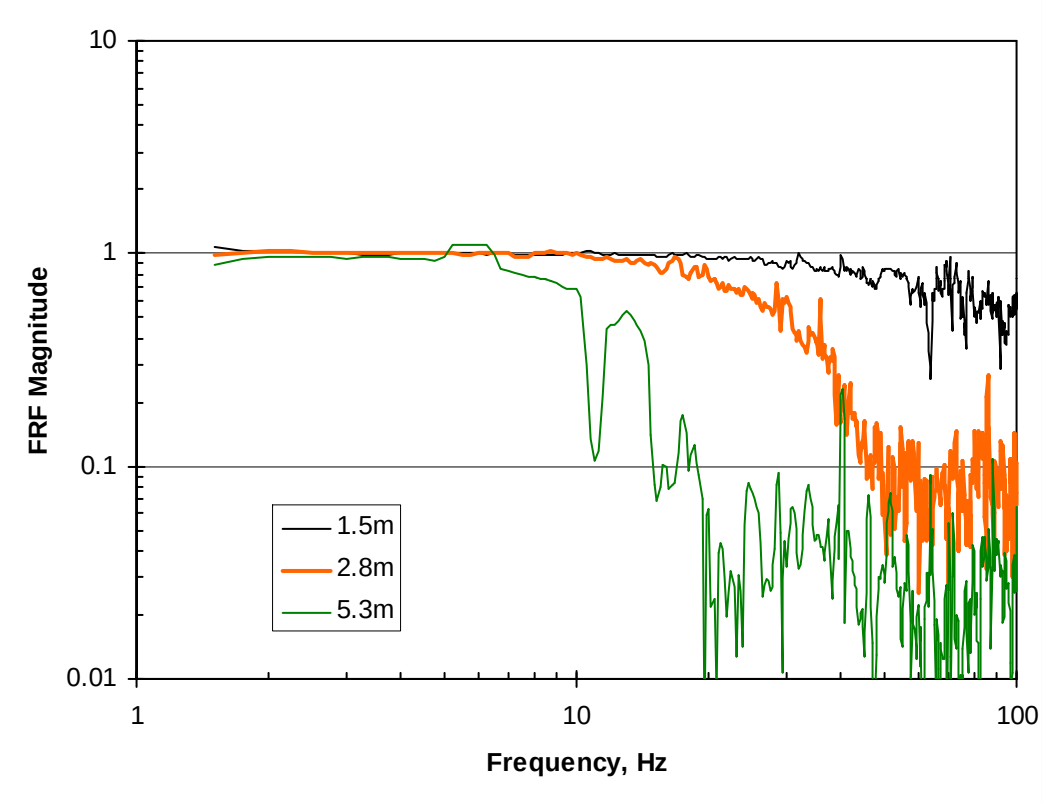
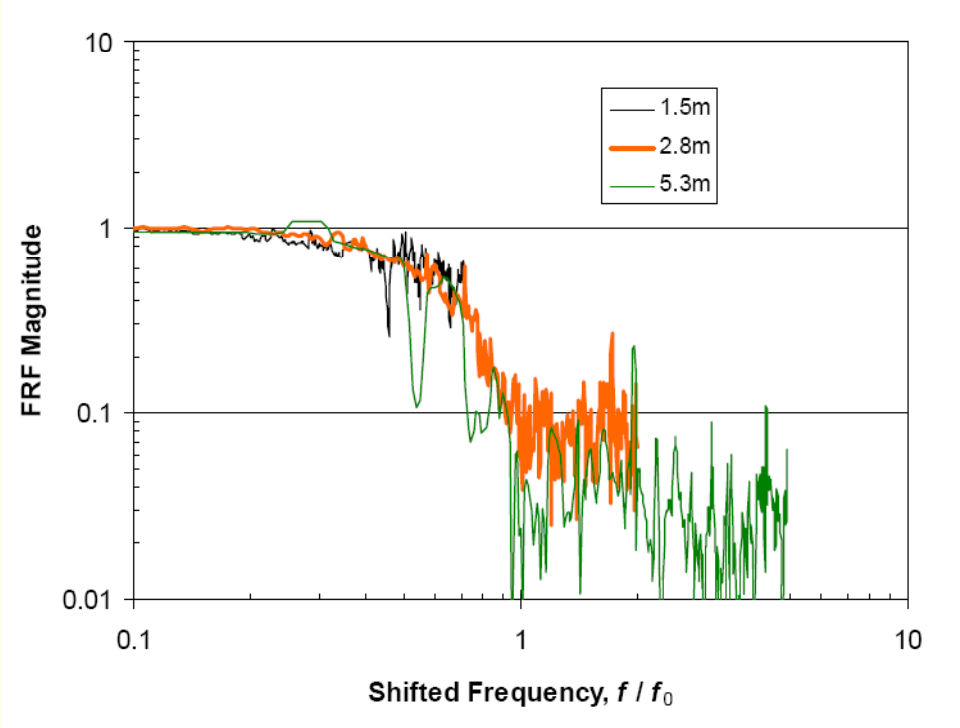
# Experiment by Simos at Brookhaven




- Measured attenuation at three depths
- Attenuation increases with depth for a given frequency
- Curves “shift to the left” with depth

Amick, Gendreau, Xiong, and Simos, “Effects of frequency and depth on attenuation of ambient ground vibration,” Proceedings NOISE-CON 2010, Baltimore, MD, April 19-21, 2010.

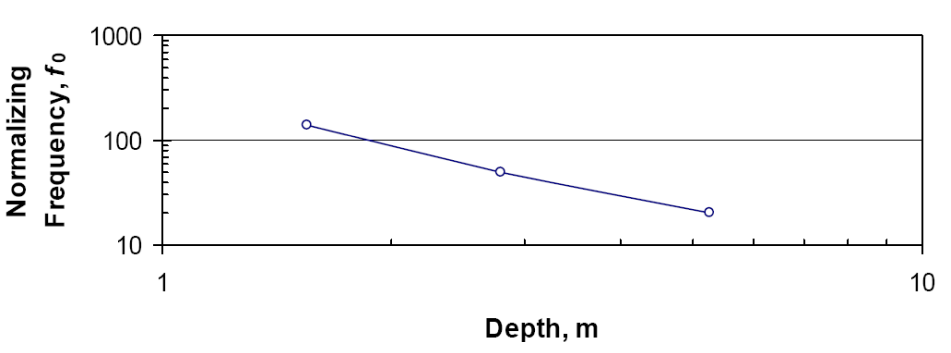
# Shift spectra (visually) to get overlap




- Shifted spectra are shown
- frequency axis of each spectrum has been divided by the apparent $f_0$ for each FRF
- curve-fitting suggests an approximation:
  - a portion of a cosine curve at shifted frequency < 1, and
  - an FRF magnitude of 0.1 at shifted frequency > 1

Amick, Gendreau, Xiong, and Simos, "Effects of frequency and depth on attenuation of ambient ground vibration," Proceedings NOISE-CON 2010, Baltimore, MD, April 19-21, 2010.

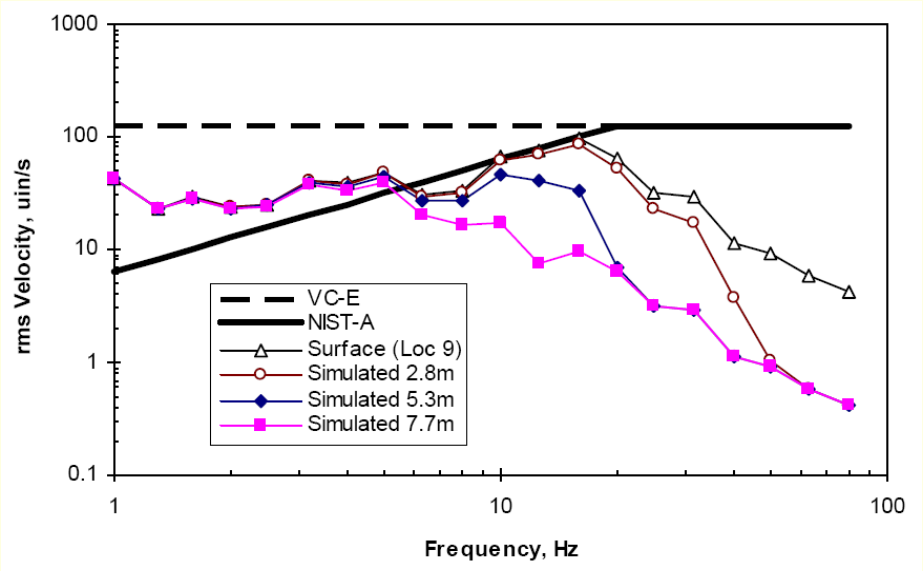
# Variation of shift frequency ($f_0$) with depth




- The shift function may be used for interpolation to other depths and a limited amount of extrapolation
- Use the collapsed shape and the shift function together to estimate spectra at a variety of depths, using measurements made at the surface.

Amick, Gendreau, Xiong, and Simos, “Effects of frequency and depth on attenuation of ambient ground vibration,” Proceedings NOISE-CON 2010, Baltimore, MD, April 19-21, 2010.

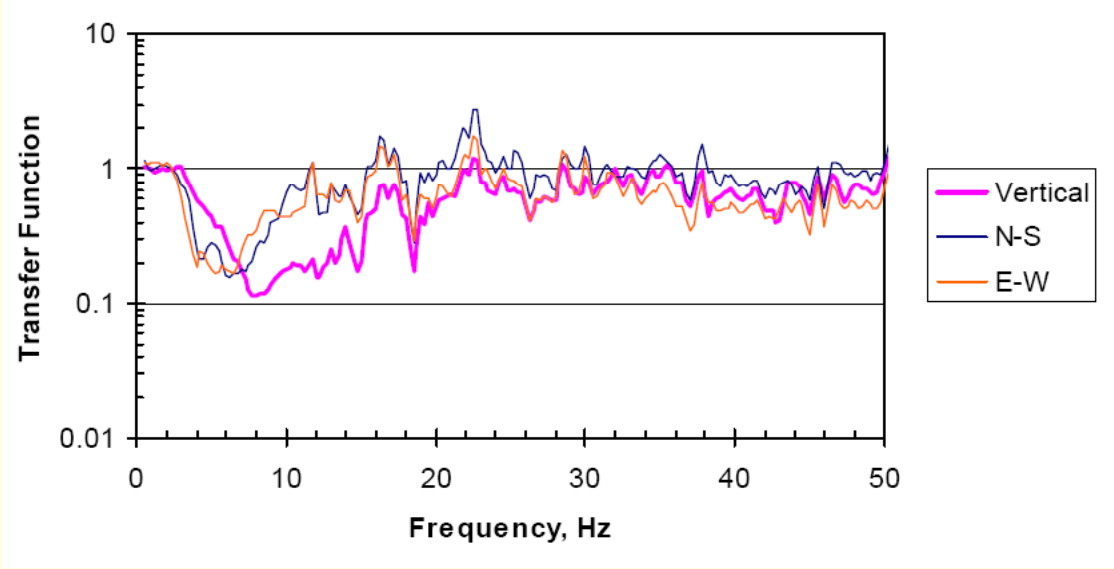
# Simulated spectra at depth




- Use spectrum measured at surface
- Predict spectrum at two depths with measured shift factors and synthesized shifted FRF
- Predict spectrum using extrapolated shift factor

Amick, Gendreau, Xiong, and Simos, "Effects of frequency and depth on attenuation of ambient ground vibration," Proceedings NOISE-CON 2010, Baltimore, MD, April 19-21, 2010.

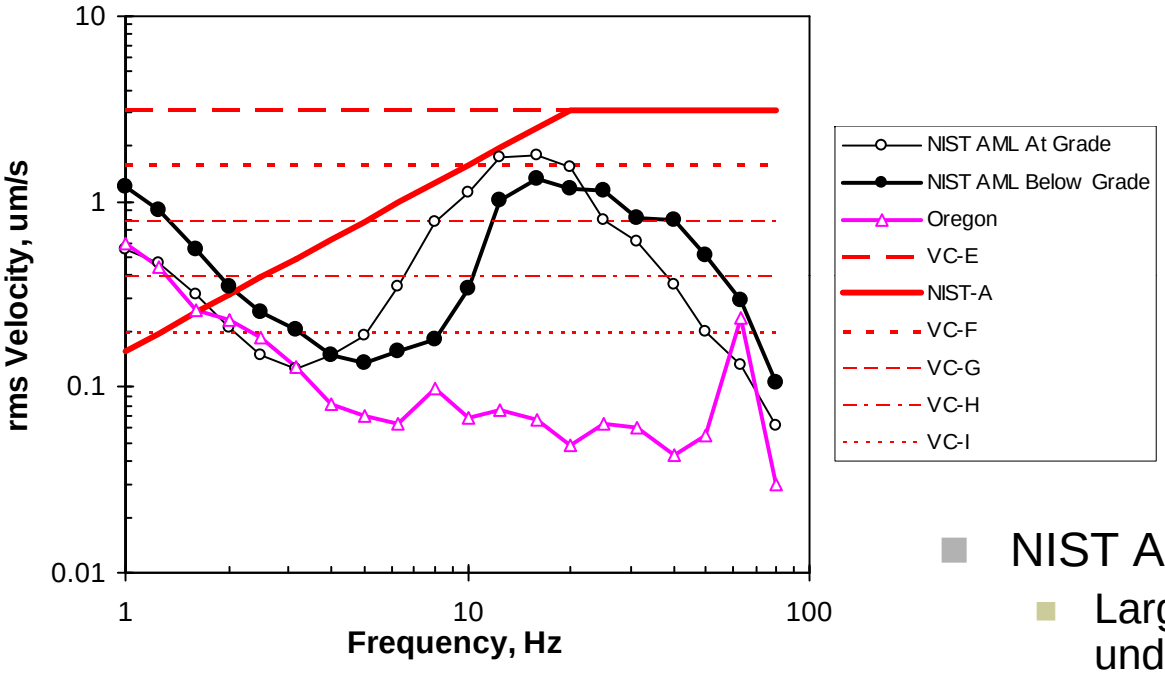
# Case 3: Actual Facility – NIST AML




- NIST Advanced Measurement Lab
  - 5 wings
    - 2 are at grade
    - 2 are 14 m below grade
    - 1 above grade
  - Soil identical
  - Foundations and slab identical
  - Facility operational
  - Measurements when operational

Can we make this concept any better … ?

# Two Examples – Underground Space




- NIST AML
  - Large at-grade and underground wings at same site
- Lokey Laboratory, U of Oregon
  - Mid-size building entirely below grade, affixed to quiet rock formation

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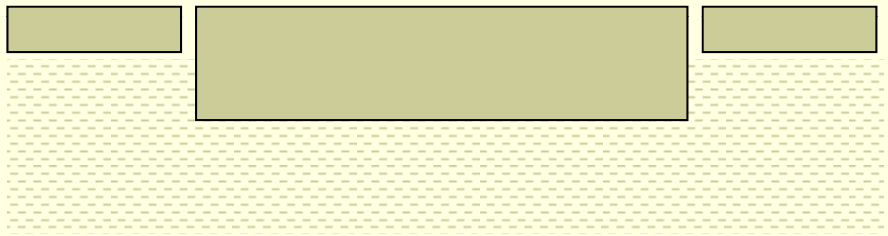
# Effects of Islands

- An island is a solid block of concrete with a surrounding joint
- Prevailing wisdom says that this improves environment
  - Does it?



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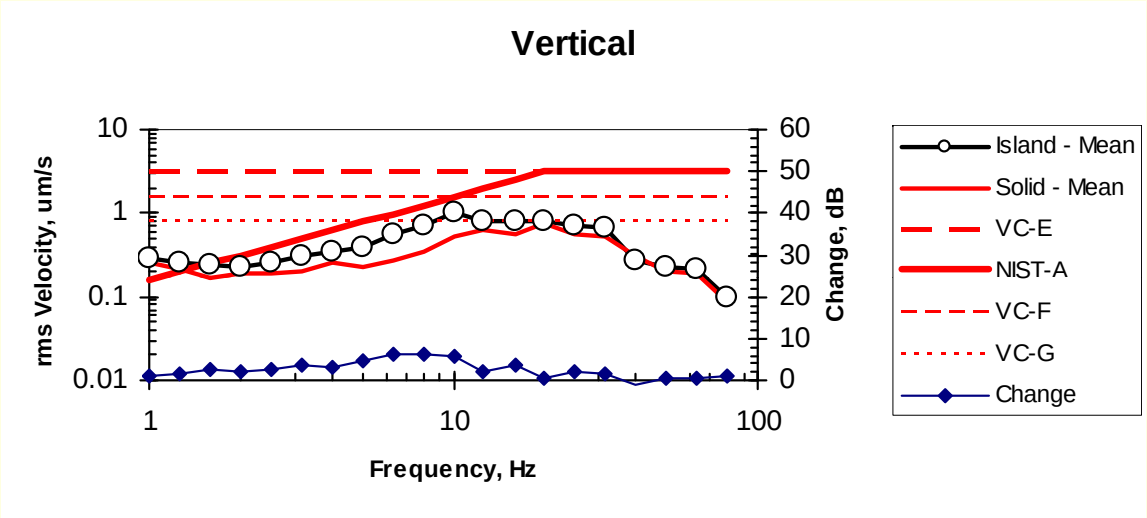
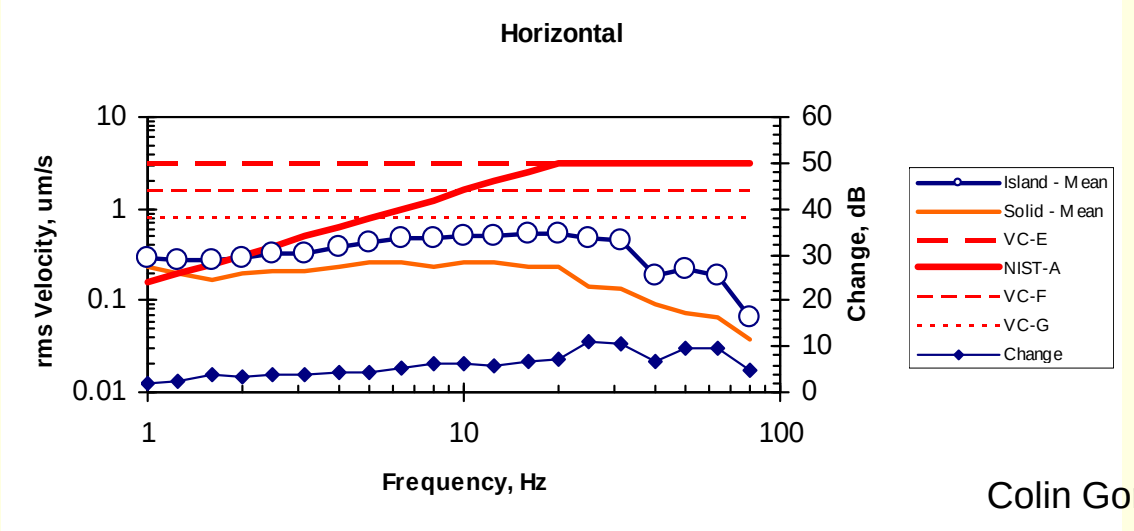
# Compare data from study facilities




Solid is lower in all cases

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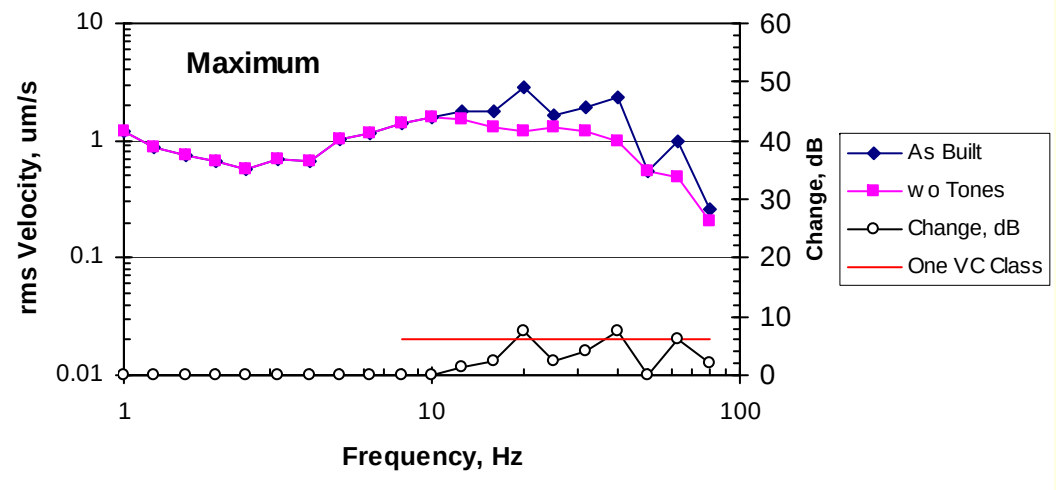
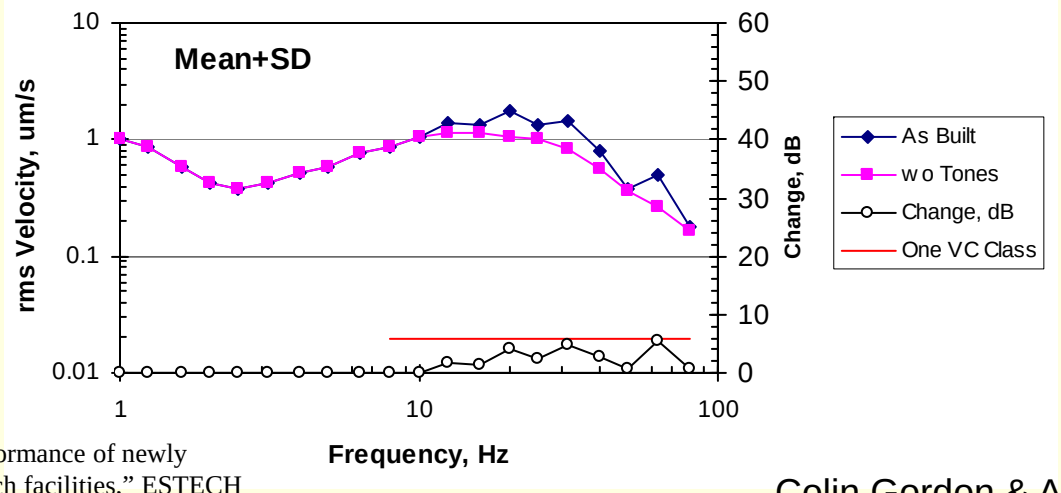
Colin Gordon & Associates Inc.

# Is there room to improve performance by more aggressive vibration isolation on mechanical equipment?

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# How Can we Make Things BETTER?

- Building Effect
  - Exploit it where possible
- Islands
  - Don’t use them
  - There are other ways to combat local perturbations
- Mechanical Systems
  - Isolation philosophy for VC-E is not adequate
- Depth
  - Put sensitive areas in basement or below ground
  - Consider attachment to bedrock

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