SLS
Space Launch System

National Aeronautics and Space Administration

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Frequency-Based Spatial Correlation Assessments of the Ares I Subscale Acoustic Model Test Firings

164th Acoustical Society of America Meeting
Noise, Physical Acoustics, Structural Acoustics, and Vibration: Launch Vehicle Acoustics
Session 3aNS
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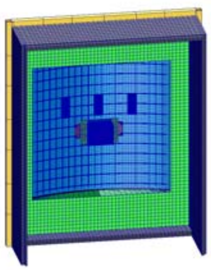
SLS Liftoff Acoustics – Spatial Definition

- **Launch vehicle liftoff acoustic environment defined by multiple sound sources and time-dependent vehicle / launch pad geometric relationships.**

- **Liftoff environment definition needed by vibration analysts to determine accurate hardware responses.**

- **Space Launch System (SLS) program vibration analysts have requested that the SLS liftoff acoustics environments include:**
  - Vehicle zone dependent acoustic spectra for entire liftoff timeframe
  - Vehicle zone dependent acoustic *spatial definition* for entire liftoff timeframe

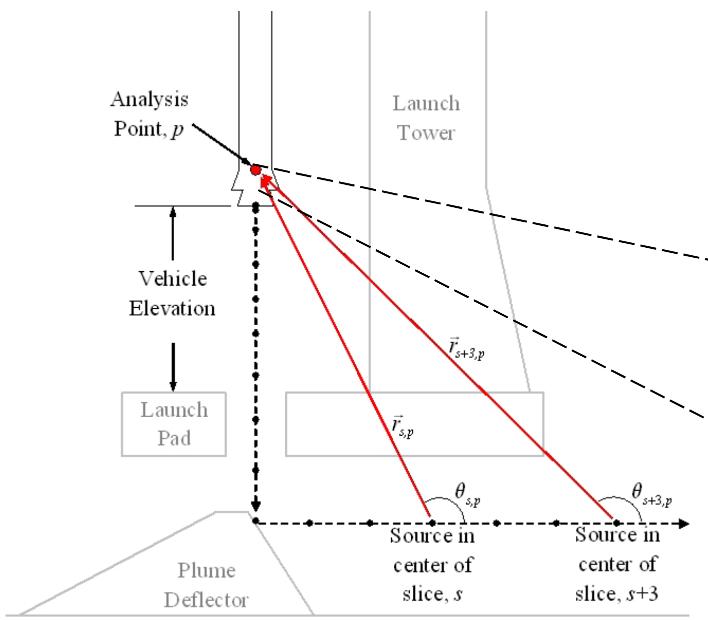


- **Spatial definition of fluctuating pressure environments are needed to better determine hardware responses to a given acoustic spectra.**
  - General process previously shown by Prock et al. "Recovering the Spatial Correlation of Liftoff Acoustics from the Ares I Scale Model Acoustics Test" (ASA-2011)

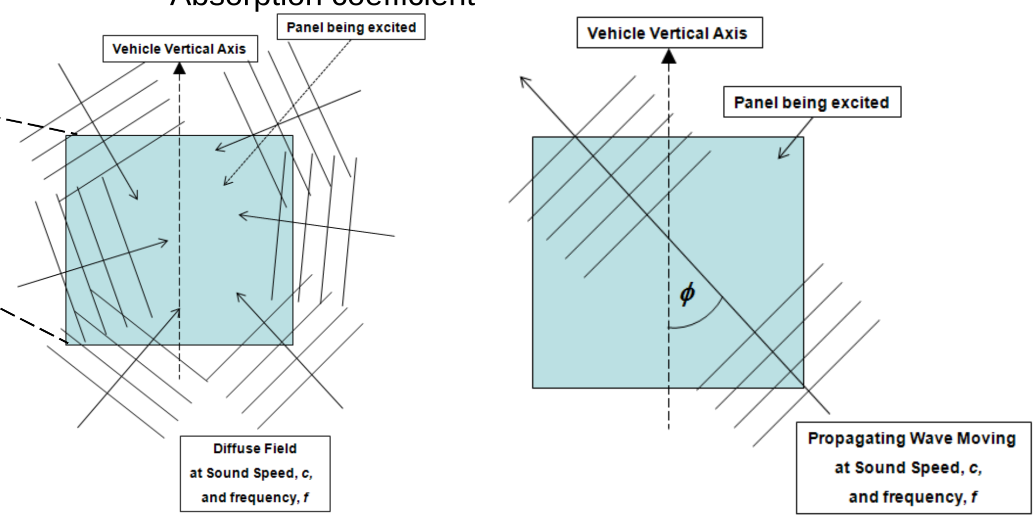
- **This presentation will review efforts by MSFC to establish a more rigorous process for acoustic spatial definitions for use in official SLS analyses.**
  - Ares I Scale Model Acoustics Test (ASMAT) data being leveraged to develop process

Acoustics – Spatial Characteristics

- **What field type does rocket / liftoff noise produce?**
  - SP-8072 models assume point sources -> propagating?
  - But, multiple sources exist at a given frequency and cross-interfere-> diffusive?



- **SLS acoustic environment classified as a mixture of two field types per frequency band:**
  - Diffuse field – uniform acoustic energy from all directions referenced to a given evaluation point
    - Acoustic spectra
  - Propagating field – acoustic energy from a particular orientation referenced to a given evaluation point
    - Acoustic spectra
    - Angle of incidence (or trace velocity)
    - Decay coefficient
      - Geometric decay (planar, cylindrical, or spherical?)
      - Absorption coefficient



- **MSFC needs to identify a process to define the mixed field parameters**
  - Will use spatial correlation plates on upcoming Scale Model Acoustic Test (SMAT)

Empirical Identification of Spatial Characteristics

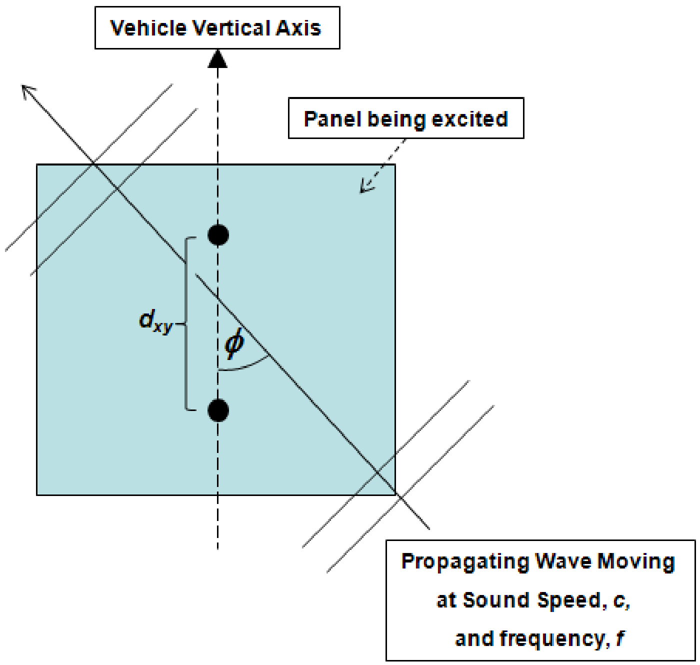
- **Traditional approaches use an acoustic pressure measurement pair to characterize the cross-spectral relationships ('spatial correlation') between individual locations ('x' and 'y') within the acoustic field**
  - Measurement pairs located 'close' to each other and to other measurement pairs to increase fitted parameter confidence -> multiple measurement pairs mounted on spatial correlation 'plate'
  - Referenced in Bendat & Piersol: *Engineering Applications of Correlation and Spectral Analysis*

- **Linear coherence between locations ('x' and 'y')**

$$|\gamma_{xy}(f)| = \frac{\left(\frac{r_x}{r_x + d_{xy}}\right)^{n_{xy}} e^{-\alpha_{xy} d_{xy} \cos\phi}}{\sqrt{(1+R)\left(\left(\left(\frac{r_x}{r_x + d_{xy}}\right)^{n_{xy}} e^{-\alpha_{xy} d_{xy} \cos\phi}\right)^2 + R\right)}}$$

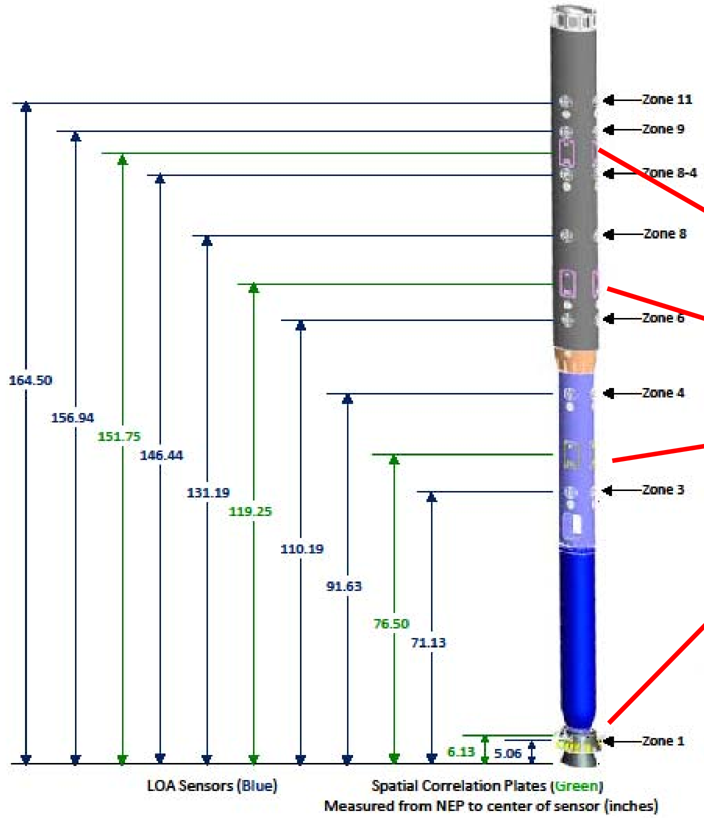
- **Relative phase between locations ('x' and 'y')**

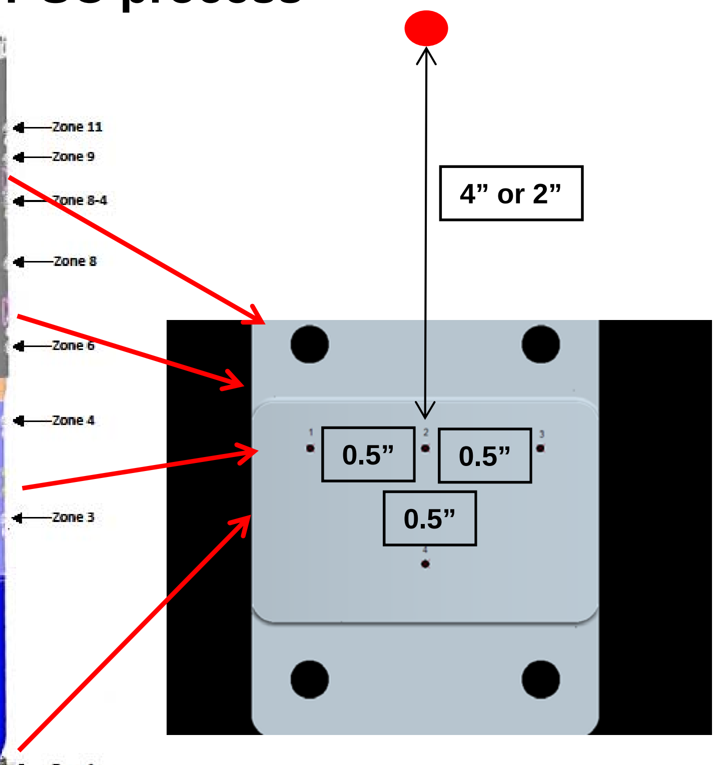
$$\theta_{xy}(f) = 2\pi f \tau_{xy} = \frac{2\pi f d \cos\phi}{c}$$



Spatial Correlation Plate Process Definition

- **ASMAT had spatial correlation (SC) plates distributed throughout the vehicle body**
  - Five pressure sensors per mounting plate
  - Spacing ranged from 0.5" to 4.5" apart
  - Phase synchronized specifically for spatial correlation assessments
  - Use linear coherence and relative phase relationships to determine SC parameters
- **Leverage ASMAT SC data to develop SLS / SMAT SC process**



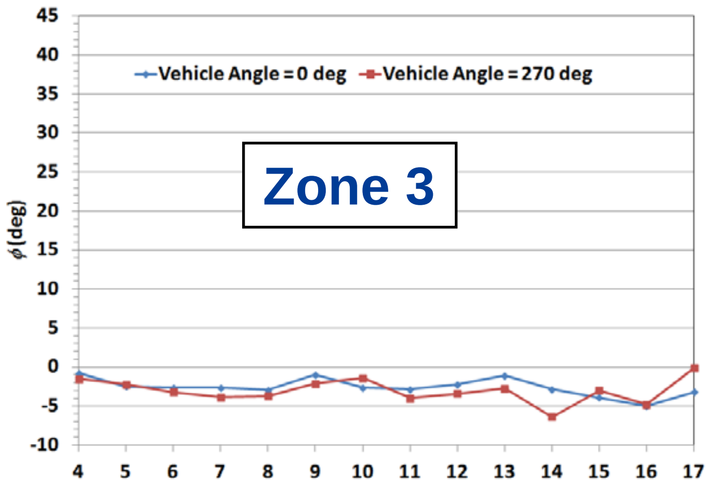


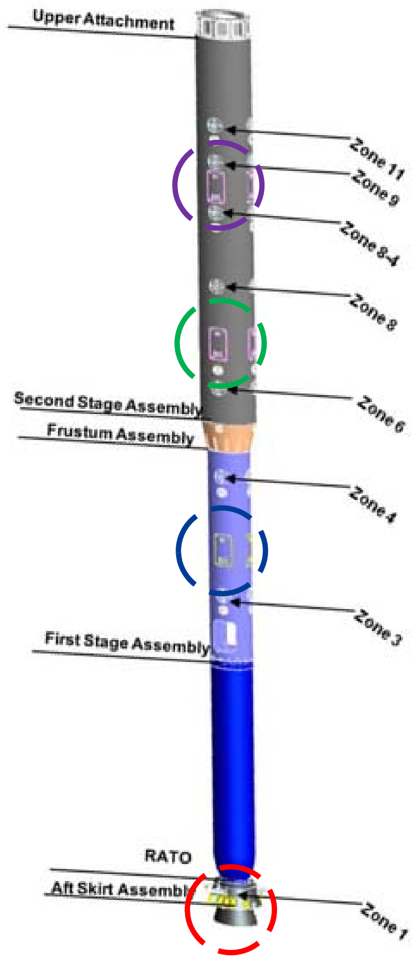
ASMAT SC Plate Parameter: Fitting Procedure

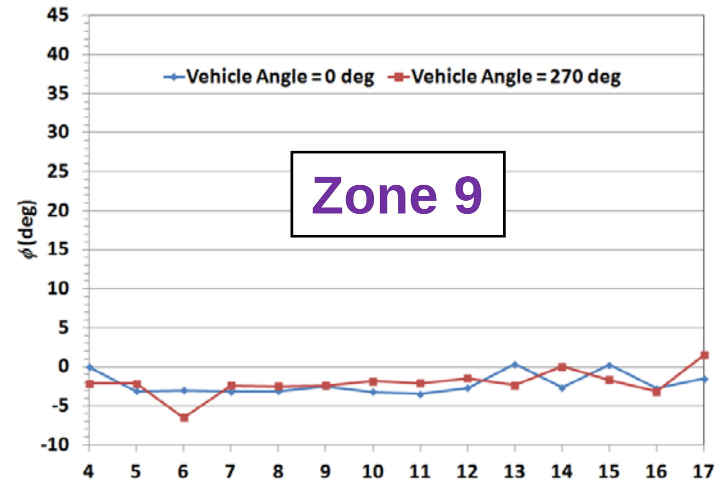
- **ASMAT program had 14 tests with SC plates installed (tests #4 - #17)**
- **For each spatial correlation plate installed, six sets of linear coherence and relative phase spectra were calculated per test**
  - Analysis window corresponds to established steady-state firing times of test
  - Frequency bandwidth was ~ 15 Hz, and number of averages was 55
  - Spectra was fit over 400 – 40,000 Hz model scale (~ 20 – 2000 Hz full scale)
- **Six sets of relative phase spectra were fit to determine average incident angle referenced to vehicle vertical axis**
  - Metrics determined where incidence angle was independent of frequency (propagating) and where values were non-viable (diffuse)
- **Six sets of linear coherence spectra were fit, versus frequency, to determine:**
  - R
  - n
  - α_{vert}
  - $\alpha_{azimuthal}$
- **Data results shown in next several slides:**
  - Average ϕ for vehicle zone locations and SC plate location for a given zone
  - Maximum n and R values seen over all frequency, for each SC plated and each test
  - R values seen versus frequency for multiple selected tests
  - α_{vert} values versus frequency for multiple selected tests

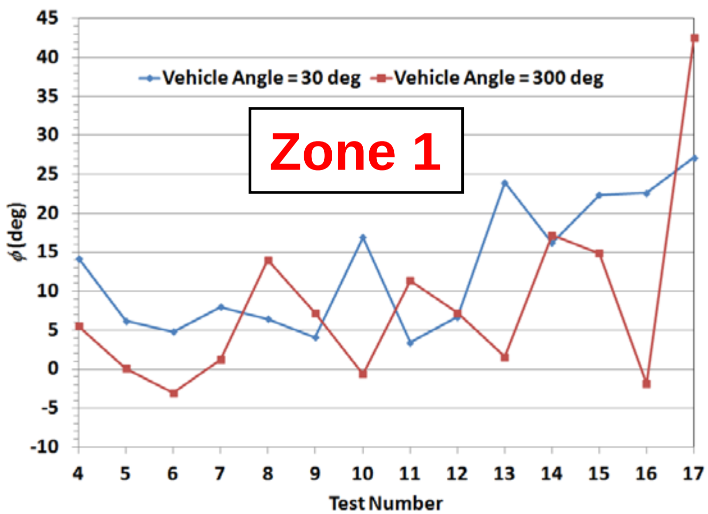
Acoustic Field Parameter: Incidence Angle

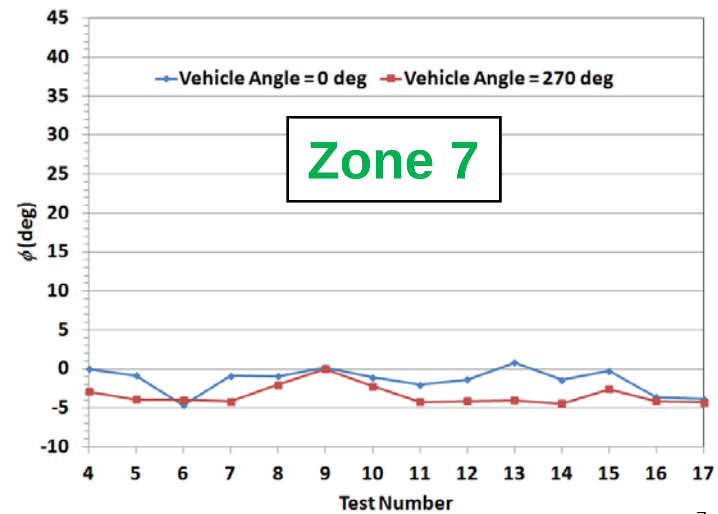
- Zone 1 shows most interesting variations test to test
- Higher zones all show evidence of propagating wave field coming nearly parallel to vehicle vertical axis





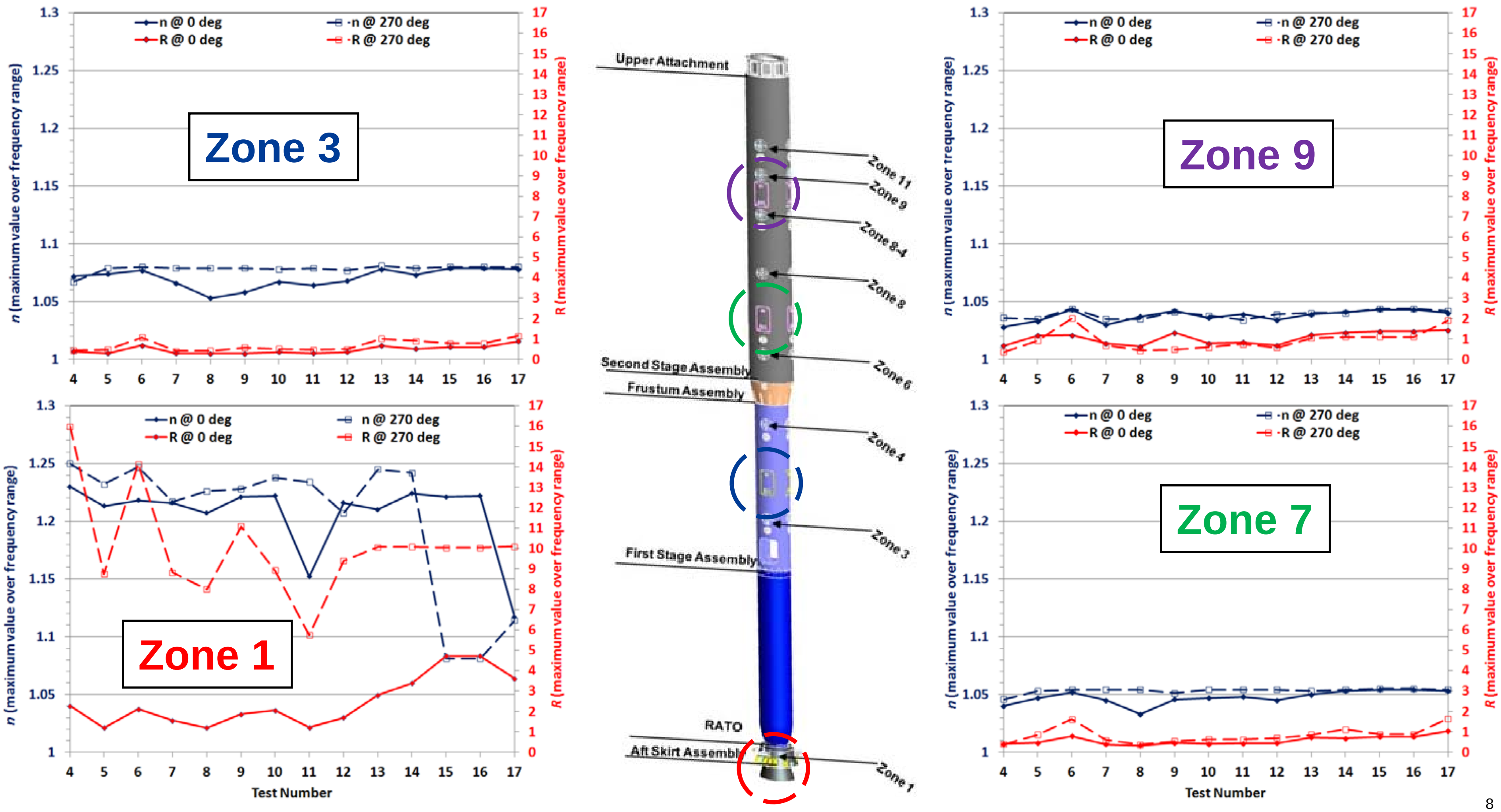






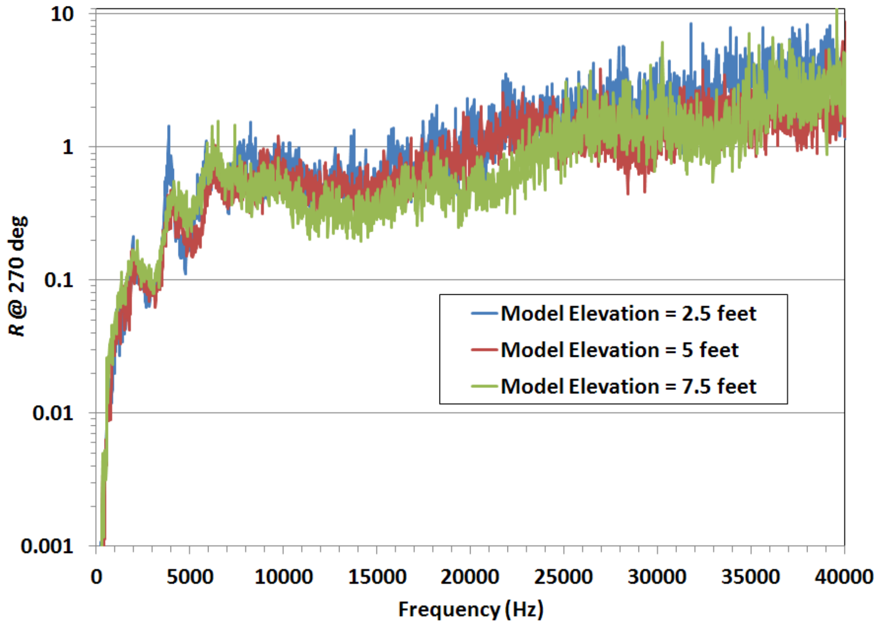
Acoustic Field Parameter: Maximum R and n

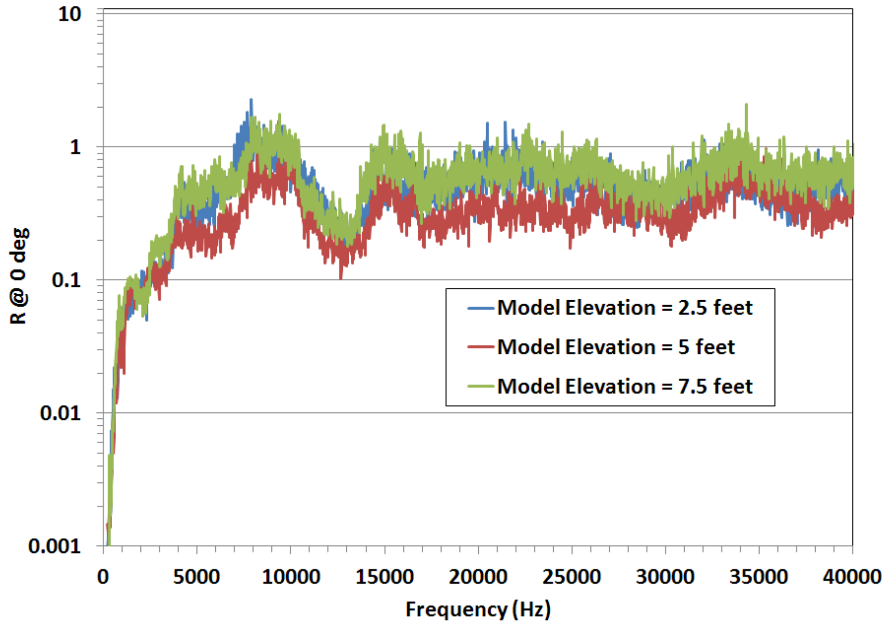
- Zone 1 shows most interesting variations test to test
- Higher zones all show evidence of significant propagating wave field component with spherical geometric decay



Acoustic Field Parameter: Zone 1 *R* Spectra Model Elevation Comparisons

- No significant effects of elevation; tower side has more diffuse field content





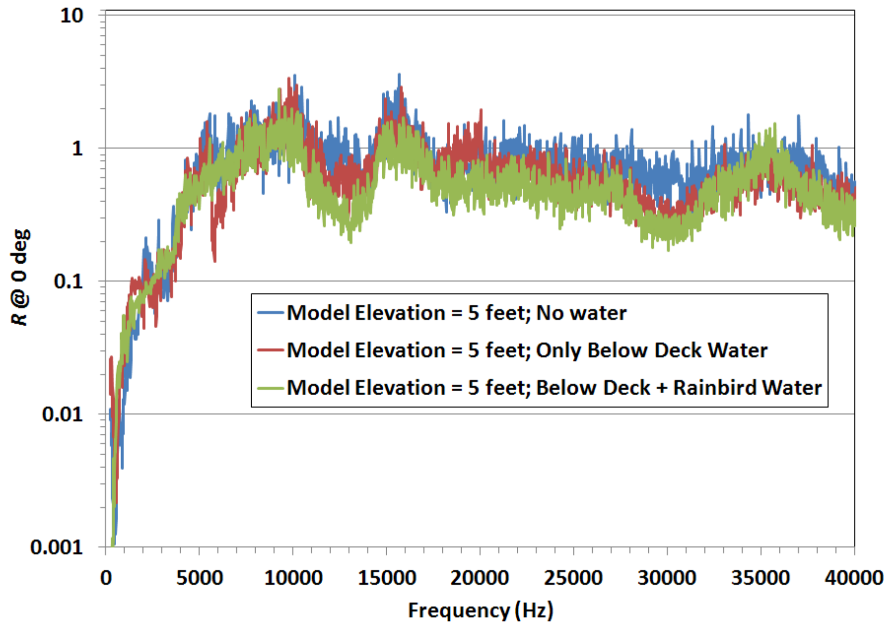
2.5 feet

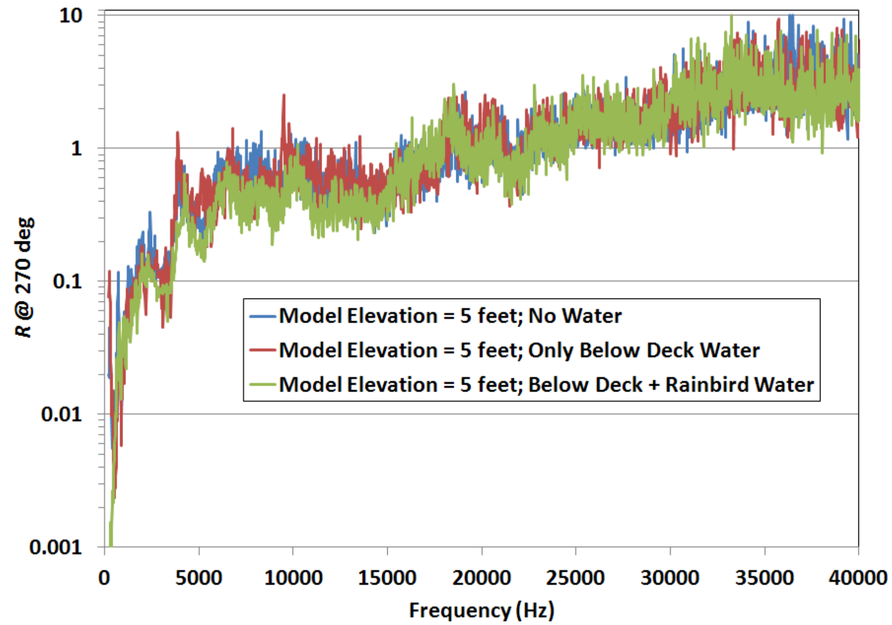
5.0 feet

7.5 feet

Acoustic Field Parameter: Zone 1 *R* Spectra Model Water Effect Comparisons

- No significant effects of water; tower side has more diffuse field content





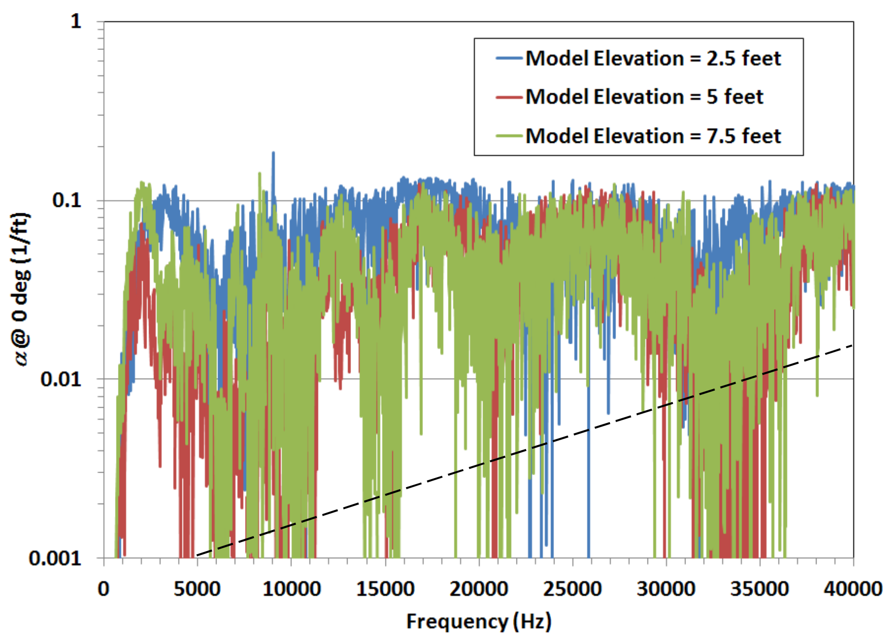
Rainbird Water

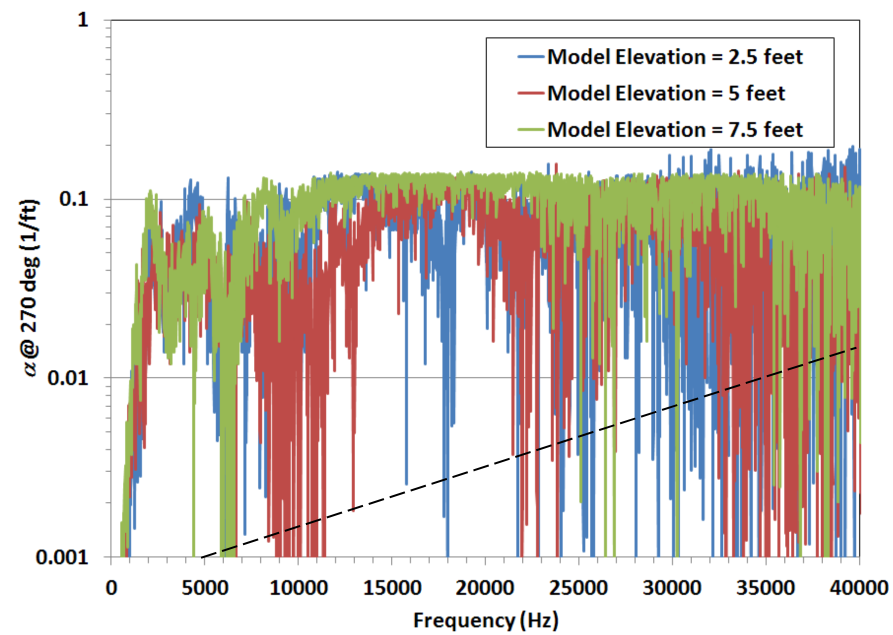
Below Deck Water: ML

Below Deck Water: Trench

Acoustic Field Parameter: Zone 1 α_{vert} Spectra Model Elevation Comparisons

- Relatively constant levels over frequency; higher than atmospheric absorption





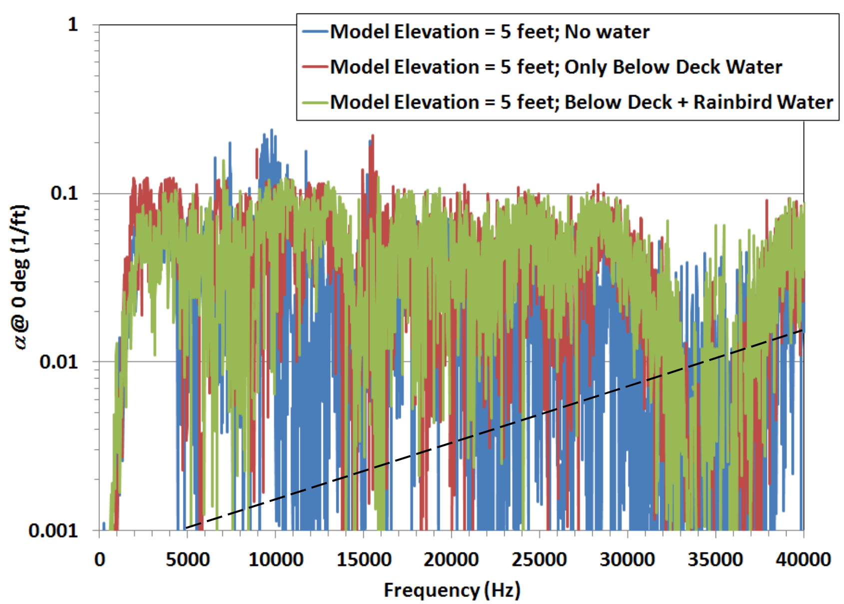
2.5 feet

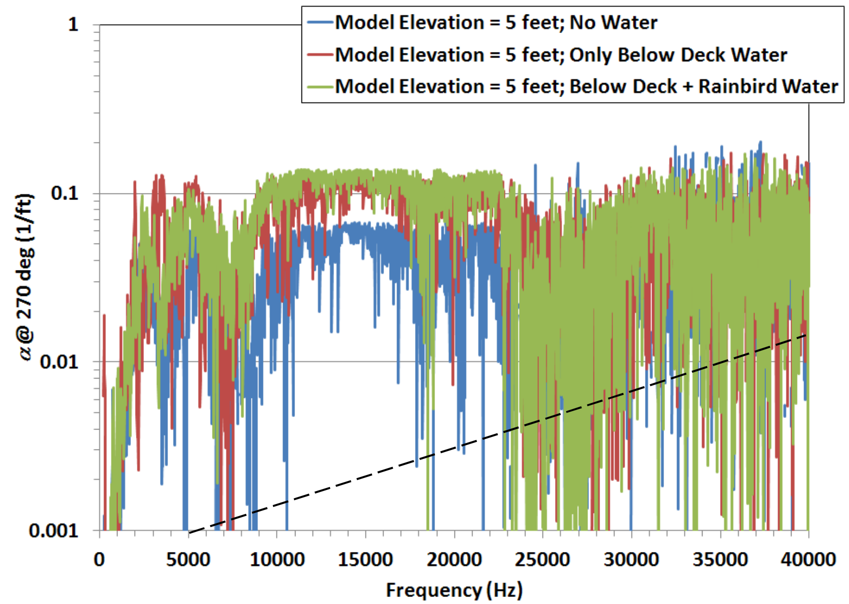
5.0 feet

7.5 feet

Acoustic Field Parameter: Zone 1 α_{vert} Spectra Model Water Effect Comparisons

- Water appears to increase decay values on tower side





Rainbird Water

Below Deck Water: ML

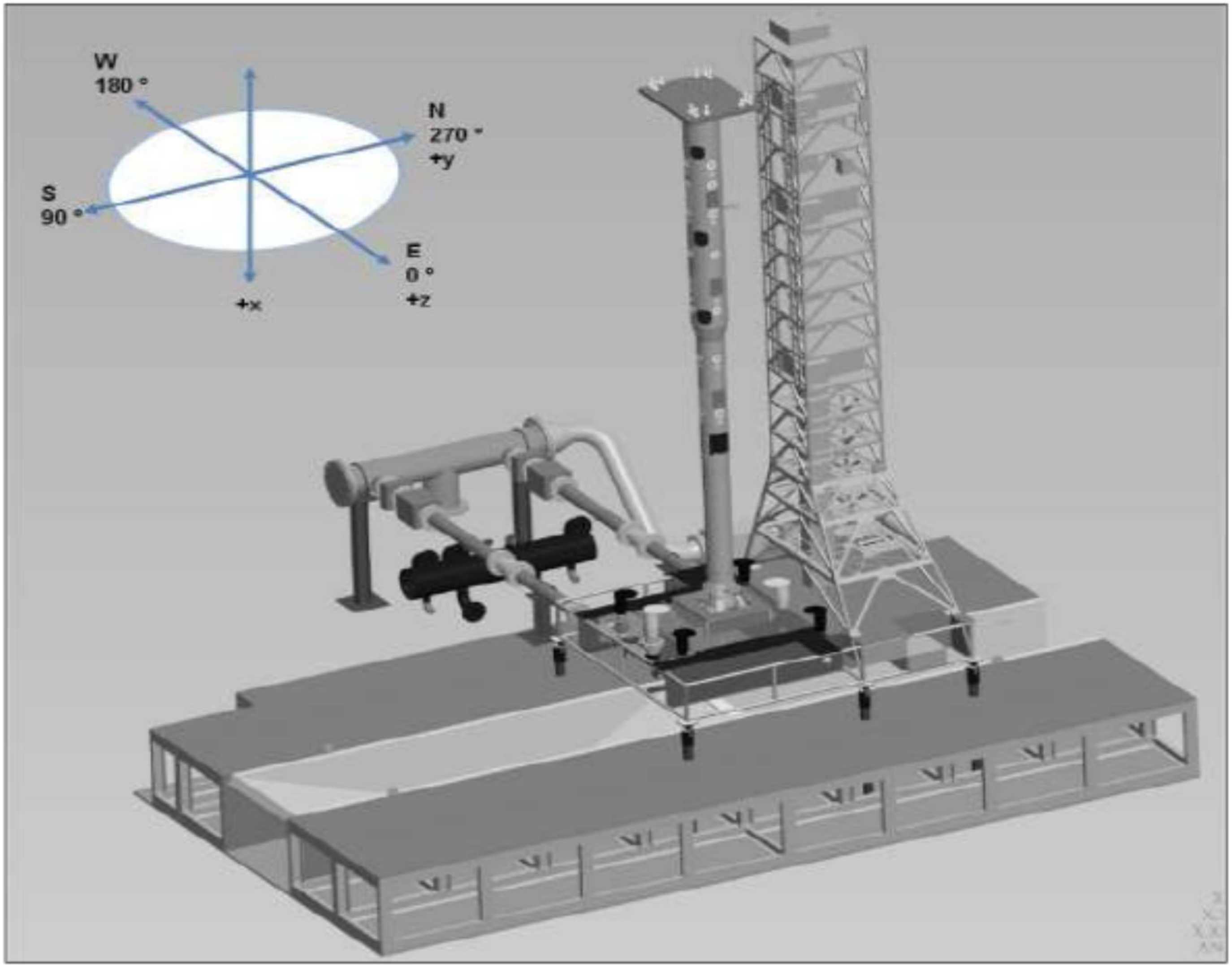
Below Deck Water: Trench

Conclusions and Forward Work

- **MSFC improving how 'design-to' acoustic environments are defined**
  - Inclusive of spatial correlation information to aid in refined vibroacoustic measurements
- **SLS acoustic model testing will include spatial correlation plates**
  - Number of sensors per plate = 5 – 7
  - Placed multiple areas along vehicle
- **ASMAT spatial correlation data used to help develop acoustic environment definition process**
  - Good measurements and variety help with refining approach
- **Results show that mixed field considerations are needed for aft skirt region, but less so for higher zones**
  - Important to define spatial parameters versus frequency to better capture range of possibilities.
- **Parameters show frequency dependency, but not much sensitivity on launch vehicle configuration**
  - Propagating wave field appears to be spherically spreading
  - Diffuse field content increases with frequency for aft skirt zone
  - Linear absorption decay values much higher than predicted by solely atmospheric absorption
    - Need to refine fitting process!
- **Will continue to refine parameter determination to prepare for SMAT testing results**
  - Scaling – more geometric parameters identified, the better
  - Dispersions – will use Monte Carlo approach to identify uncertainties
    - More sensor pairs will decrease uncertainty

BACKUP

ASMAT Coordinate System



Acoustic Field Definition of Propagating Wave

- **The propagating wave definition for the fluctuating pressure is:**

$$p_p(\vec{r},t) = \left(\frac{r_o}{\left|\vec{r}\right|}\right)^n P_o e^{-\alpha\vec{n}\cdot\vec{r}} e^{i\left(\vec{k}\cdot\vec{r}-\omega t\right)}$$

- **where:**
  - r = distance vector from the source center
  - r_o = source radius
  - P_o = source emitted pressure
  - α = linear attenuation coefficient
  - k = wavenumber vector
  - n = geometric spreading coefficient
    - $n = 0$: plane wave
    - $n = 0.5$: cylindrical wave
    - $n = 1$: spherical wave

Acoustic Field Definition
Mixed Field Autospectral Density

- **The mixed acoustic field definition for the autospectral density is the summation of the diffuse field and propagating field contributions for a given frequency:**

$$G(f) = G_p(f) + G_d(f) = G_p(f)(1+R)$$

- **where:**
  - G = autospectral density at frequency f
  - R = ratio of diffuse to propagating field autospectral densities

- ***G(f)* can be substituted into the sound pressure level definition to see the effect of *R* on relative decibel levels (*SPL*)**

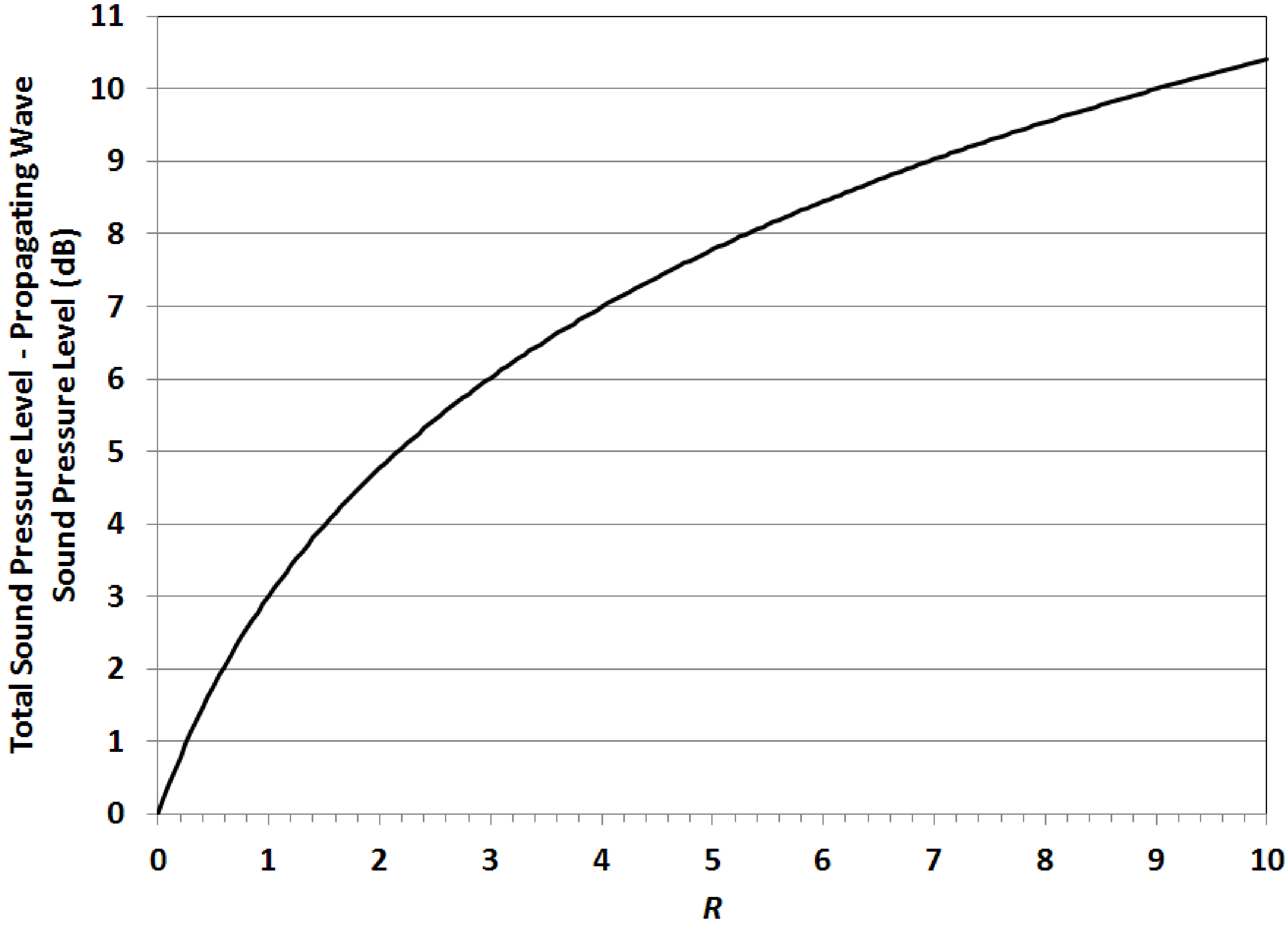
Diffuse field contribution at *f*

$$SPL(f) = SPL_p(f) + 10\log(1+R)$$

Total sound pressure level at *f*

Propagating sound pressure level at *f*

Sound Pressure Level Dependence on R



Acoustic Field Definitions and Relationships to Spatial Correlation – Mixed Field

- **The propagating field, *$G_p(f)$*, has defined cross-spectral properties measured between two locations ('x' and 'y') within the field:**
  - Cross-spectrum

$$G_{xy}(f) = G_p(f)\left(\frac{r_x}{r_y}\right)^{n_{xy}} e^{-\alpha_{xy} d \cos\phi} e^{-i2\pi f \tau_{xy}} + G_d(f)\frac{\sin(2\pi f d/c)}{2\pi f d/c}$$

  - Linear coherence

$$|\gamma_{xy}(f)| = \frac{\left(\frac{r_x}{r_x + d}\right)^{n_{xy}} e^{-\alpha_{xy} d \cos\phi}}{\sqrt{(1+R)\left(\left(\left(\frac{r_x}{r_x + d}\right)^{n_{xy}} e^{-\alpha_{xy} d \cos\phi}\right)^2 + R\right)}}$$

  - Relative phase

$$\theta_{xy}(f) = 2\pi f \tau_{xy} = \frac{2\pi f d \cos\phi}{c}$$

Acoustic Field Definitions and Relationships to Spatial Correlation - Diffuse

- **The diffuse field, $G_d(f)$, has defined cross-spectral properties measured between two locations ('x' and 'y') within the diffuse field:**
  - Cross-spectrum

$$G_{d\_xy}(f) = G_d(f)\frac{\sin(2\pi fd/c)}{2\pi fd/c}$$

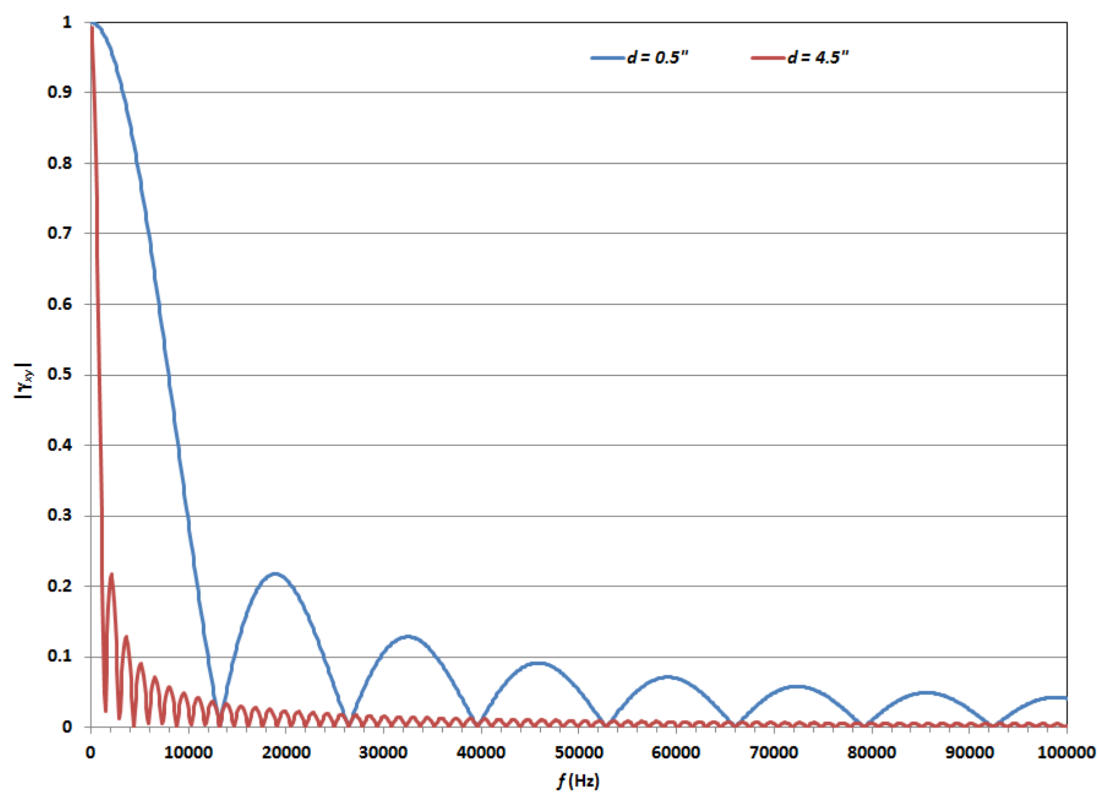
  - Linear coherence

$$|\gamma_{d\_xy}(f)| = \left|\frac{\sin(2\pi fd/c)}{2\pi fd/c}\right|$$

  - Relative phase

$$\theta_{d\_xy}(f) = 0$$

  - where:
    - d = distance between locations
    - c = ambient sound speed



Acoustic Field Definitions and Relationships to Spatial Correlation - Propagating

- **The propagting field, $G_p(f)$, has defined cross-spectral properties measured between two locations ('x' and 'y') within the field:**
  - Cross-spectrum

$$G_{p\_xy}(f) = G_p(f)\left(\frac{r_x}{r_y}\right)^{n_{xy}} e^{-\alpha_{xy} d \cos\phi} e^{-i2\pi f \tau_{xy}}$$

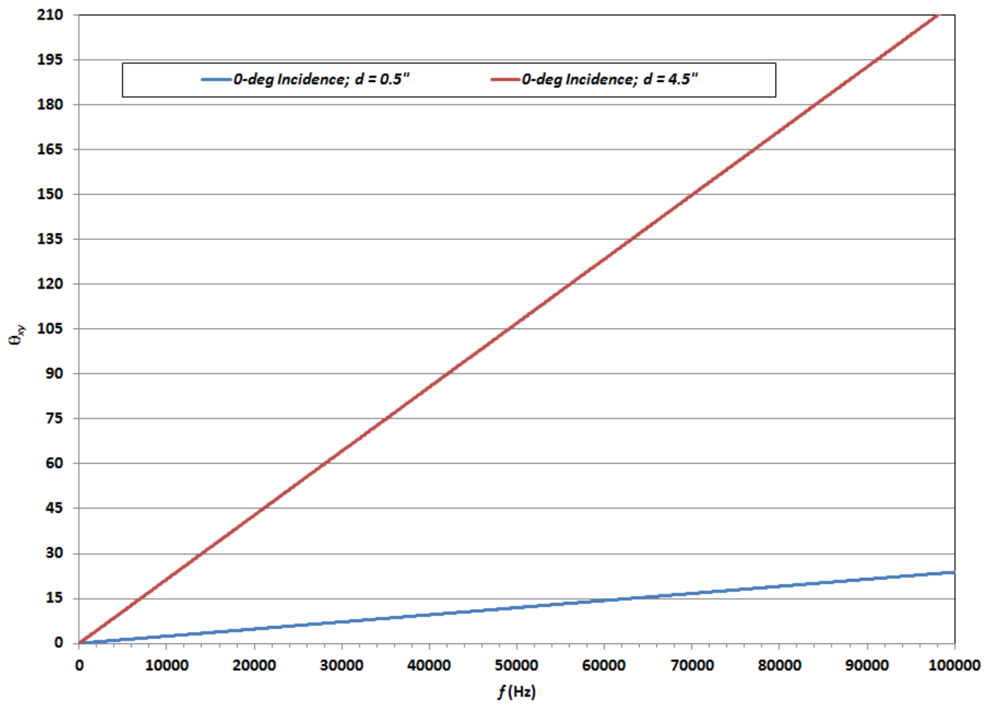
  - Linear coherence

$$|\gamma_{p\_xy}(f)| = 1$$

  - Relative phase

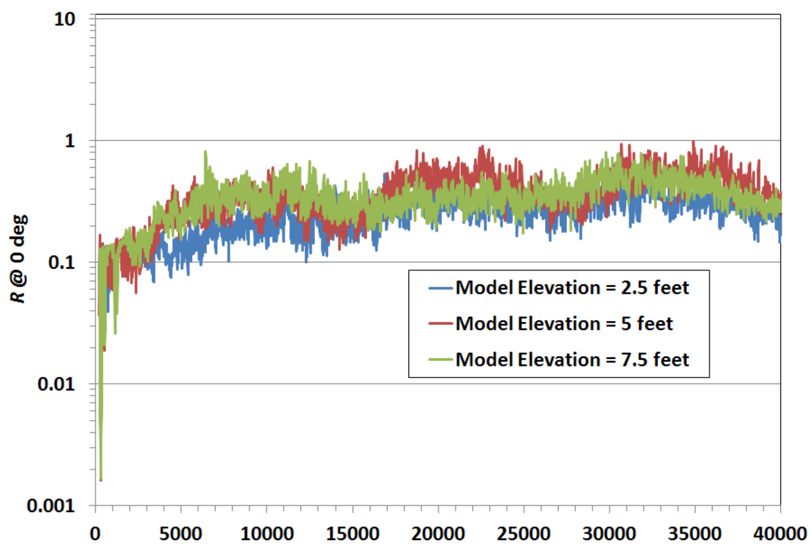
$$\theta_{d\_xy}(f) = 2\pi f \tau_{xy} = \frac{2\pi f d \cos\phi}{c}$$

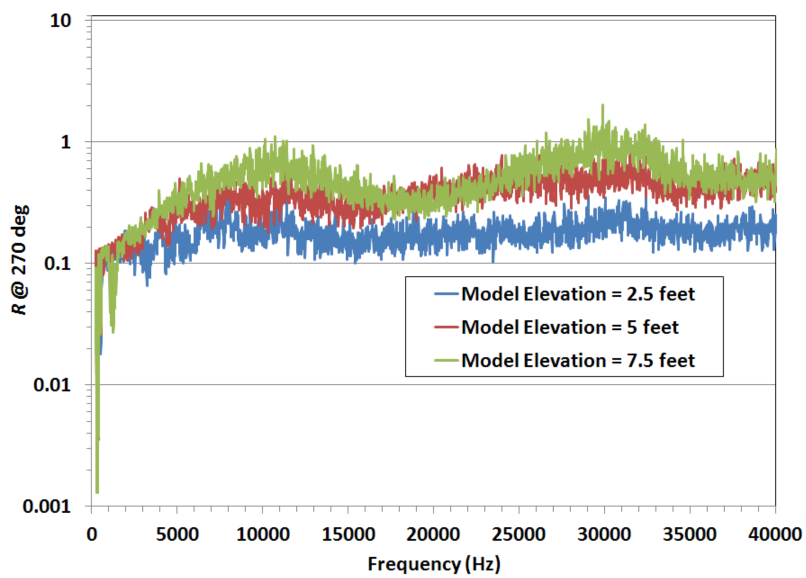
  - where:
    - ϕ = incidence angle
    - r_i = distance from source to measurement location 'i'
    - n_{xy} = geometric decay coefficient (n = 0; plane wave, n = 1; spherical wave)
    - α_{xy} = absorption decay coefficient



Acoustic Field Parameter: Zone 9 *R* Spectra Model Elevation Comparisons

- Higher elevations show more diffuse field content on tower side





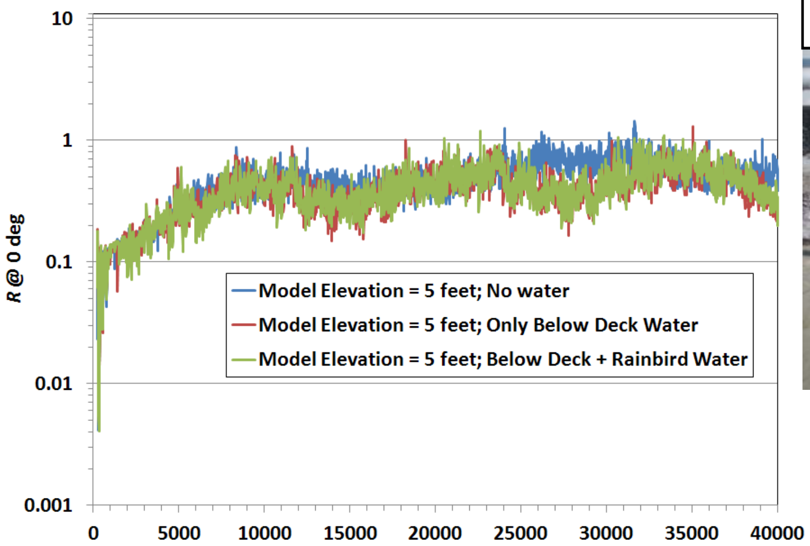
2.5 feet

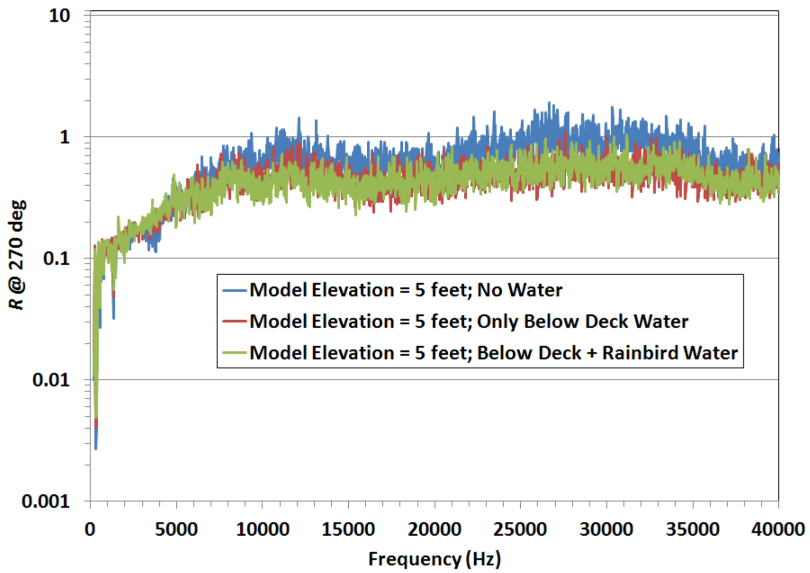
5 feet

7.5 feet

Acoustic Field Parameter: Zone 9 *R* Spectra Model Water Effect Comparisons

- No significant effects of water





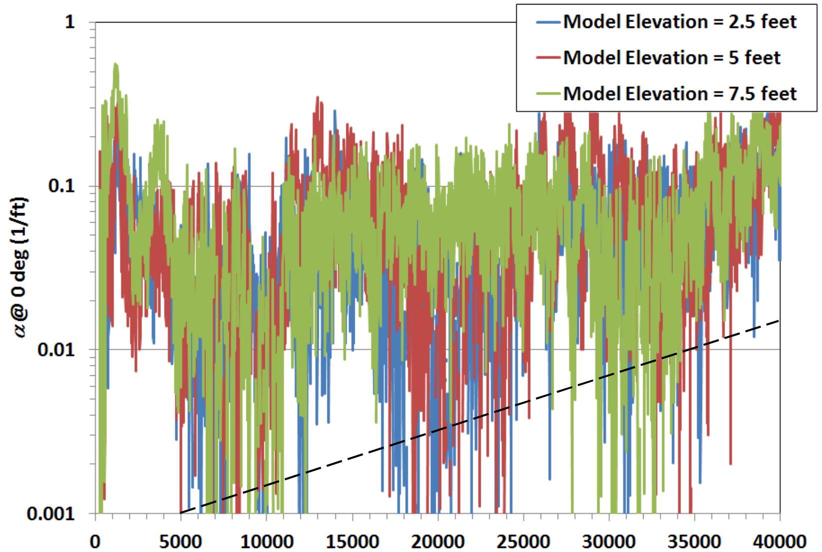
Below Deck Water: Trench

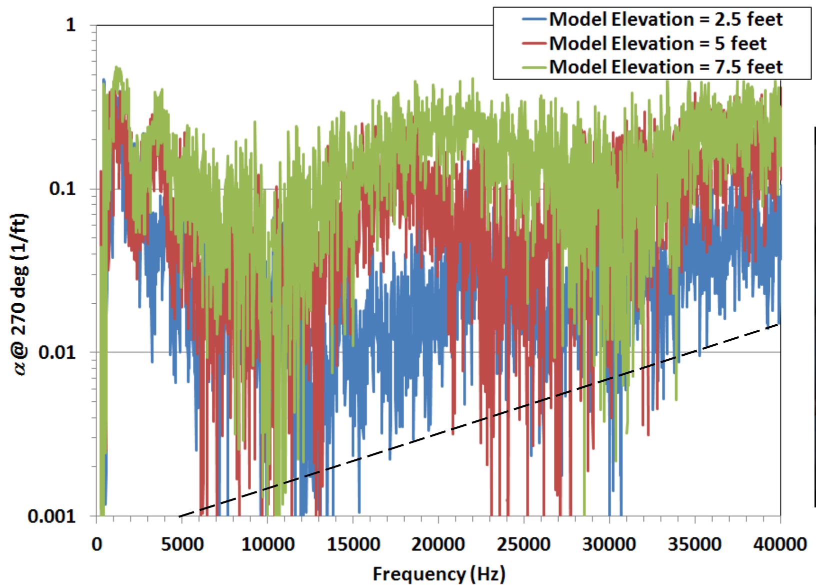
Below Deck Water: ML

Rainbird Water

Acoustic Field Parameter: Zone 9 α_{vert} Spectra Model Elevation Comparisons

- Relatively constant levels over frequency; higher than atmospheric absorption





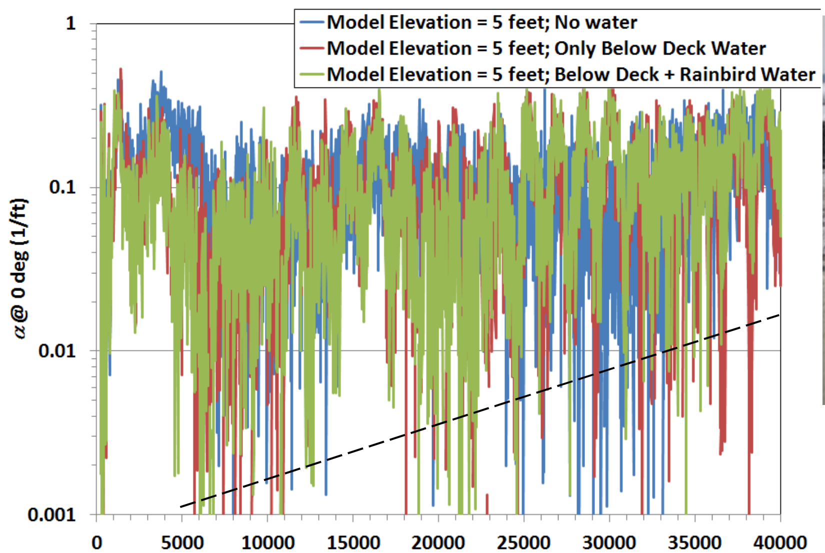
2.5 feet

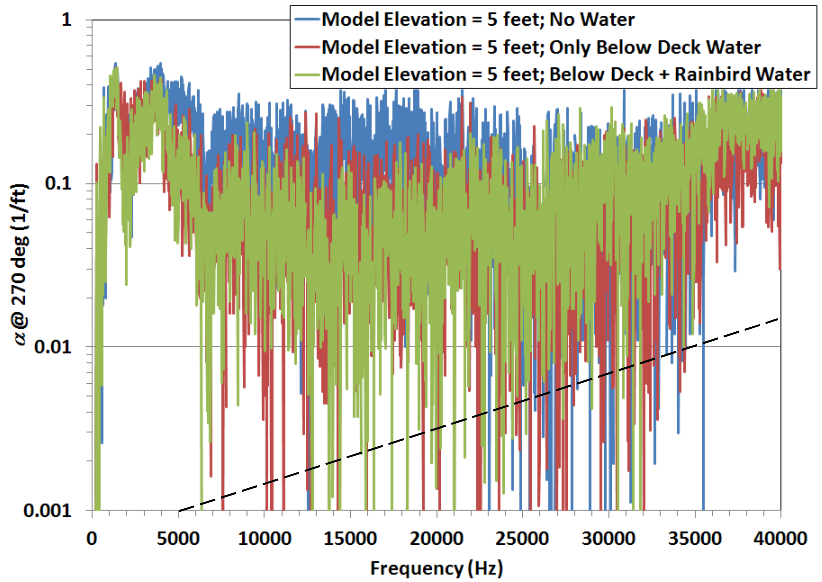
5 feet

7.5 feet

Acoustic Field Parameter: Zone 9 α_{vert} Spectra Model Water Effect Comparisons

- No real differences between levels





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