Extending Low-Frequencies with a new seismic air source design

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Drivers for Low Frequencies – Extending Broadband

**LOW FREQUENCIES:**

**Broader amplitude spectrum**
- More octaves the better
- Lows reduce the side-lobes of the wavelet
- Smaller side-lobes improve the resolution

**Seismic Inversion**
- Inversion requires a flat spectrum from 0Hz
- Better lows improve the reliability of the inversion, less reliance on low-frequency models

**Full-waveform Inversion**
- Starting frequency can have a significant effect on the final result
Basic source design

- Amplitude is linearly proportional to the number of guns
- Amplitude is linearly proportional to the firing pressure
- Amplitude is proportional to the cube root of the volume
- Frequency output of an airgun is proportional to its volume

- More guns are better than big guns
- Big guns have better low frequency output
  - If two guns are near enough to each other, their bubbles coalesce
    - Output frequency is the same as if it was a single gun of the combined volume
    - Power output is up ~60% over a single gun
Classical airgun arrays

- We want to tune out the bubble effect – sharp spike
  - Bubbles oscillate with different frequency.
  - Bubble frequencies chosen for maximum destructive interference.
  - Gun distances chosen to ensure that the bubbles oscillate independently.

![Oscillating independently](image)

![Farfield signature](image)
Fundamental frequency of most classical arrays depends mainly on their biggest bubble size.

Rayleigh-Willis formula:

\[ f_0 = k \left(1 + \frac{d}{10}\right)^{5/6} \left(\frac{P}{V}\right)^{1/3} \]

- \( P \) = airgun firing pressure
- \( V \) = airgun fire chamber volume
- \( d \) = airgun depth
- \( k \) = empirical factor depending on gun type and volume
Ways to **change** the low frequency output

### Increase Total Volume
- More of the same
- Limited by compressor capacity
- **Lifts entire spectrum**

### Depth Changes
- Bubble frequency varies as the cube-root of effective volume.
- Tow deep and the hydrostatic pressure increases = small bubble = less lows
- .. but better zero notch
- Tow shallow, bigger bubble
- ... but operational constraints

### Increase Bubble Size
- Bubble frequency varies as the cube-root of effective volume.
- Larger guns – reliability trade off
- Clustering – limited # of guns in a cluster
- **Frequency locking** ¹

¹ Laws, Hatton and Haartsen, 1990
Bubble Interaction Changes the Oscillation Frequency

Single airgun

Clumped airguns

Harmony

Standard source
Single elements/clusters do not interact through pressure field

Bubble Interaction Changes the Oscillation Frequency

Frequency Locking
No bubble interaction
Pressure fields interact and “lock”\(^1\)

\(^1\) Laws, Hatton and Haartsen, 1990
Atlantic Deep Water Test

- Endurance testing
- Full source deployment
Test objectives

Reliability testing
Refill times
Different cluster configurations
Normal source QC over time
Test for frequency locking
Bubble Period estimates NFH2 only (peak to peak pick) 06/07/2021

Refill test
Partial Frequency Locking Increments on Raw NFH Bubble Period

- Single gun
- Single cluster
- Two mildly interacting clusters
- Two stronger interacting clusters
- Three stronger interacting clusters

Data points:
- 4.0 Hz
- 4.5 Hz
- 5.0 Hz
- 6.0 Hz
- 7.0 Hz

Median of data points:
- x 1.07
- x 1.18
- x 1.26
Johan Sverdrop Test

- Endurance testing
- Full source deployment
Johan Sverdrop Test configuration

Both sources at 8m depth
CoS separation 16m

Co-located sources, 25m flip-flip acquisition
Harmony Spectra

- Farfield signatures computed from nearfield hydrophones

  ~uplift approx. 10dB @4Hz

- Spectra from common shots, permanent reservoir monitoring nodes

Reference high-output source
5085cuin, 3 sub-arrays, 24 elements
Shot gathers
Full Bandwidth
PRM system
Max offset ~20km
Harmony Flexible by Design

- **Design**
  - Uses equipment suitable for fleet-wide deployment
  - Harmony occupies a single sub-array position (+hot spare if required)
  - Field tested for endurance and reliability

- **Standalone broadband source**

OR

- **Incorporate with standard sources**
Summary

- Low-frequency rich source
- Enabled by frequency locking
- One sub-array design – flexible options