A Consortium for the Advancement of Low Frequency Seismic Technologies

Measuring Two or More Octaves of Low Frequency Seismic Data and Achieving Full Benefits from Broadened Bandwidth

Proposal

A research consortium is proposed for the advancement of low frequency seismic technologies.

- The consortium will research and develop new technologies to advance low frequency seismic exploration two or more octaves beyond existing industry capabilities.
- The consortium will establish and document technical viability and usage specifications for its new technologies.
- Licensing will be available for commercial development and sale of applications, products, and services.

Benefits

An additional two or more octaves of low frequencies provides a cost-effective means for greater E&P performance and value. New seismic bandwidth for exploration and development activities leads to fewer dry holes and better placement of development wells and optimal field production. Inversion, resolution, imaging beneath complex geology, and imaging deep geology all benefit. New seismic equipment and services enable these enhancements.

Scope

The consortium will research and develop new technologies for step-change improvements in seismic acquisition of low frequencies, and best practices using the new bandwidth in imaging and inversion.

- Acquisition research issues include theory development, scaled experiments, full and/or application scale experiments including the design, construction, and testing of experimental prototypes.
- Imaging and inversion research issues include theory, algorithm and coding development, numerical testing, and test application to broadened bandwidth data. Leveraging other consortia may be possible where common interests exist.

The research consortium will develop recommendations and specifications for industrial use of successful technologies.

Deliverables

The consortium deliverables will include research results, access to students, and licensing for commercial use.

- Research results and reports will be available to members documenting:
    - <u>theory development and computer studies</u> –
        - theory and analytical developments, numerical analyses, and conclusions for practical applicability,
        - testable predictions of critical elements needing experimental validation,
    - <u>scaled experiments</u> –
        - experimental methods, procedures, and results,
        - conclusions on the validity or deficiencies in theory or experiment, and implications for full scale experiments,
    - <u>application scale prototypes and experiments</u> –
        - design and fabrication, device characterizations, experiments and results,
        - recommendations and specifications for industrial exploration applications,
    - <u>imaging/inversion algorithm development and testing</u>.
- Sponsors will have access to students working consortium projects.
- Sponsors will have access to licenses for intellectual property generated by the consortium, and background intellectual property needed to use consortium intellectual property, before non-members.

Start-up contributions

The ExxonMobil Upstream Research Company has licensed intellectual property, provided experimental prototype equipment, and released contractors/consultants in the following areas as contribution to a consortium start-up.

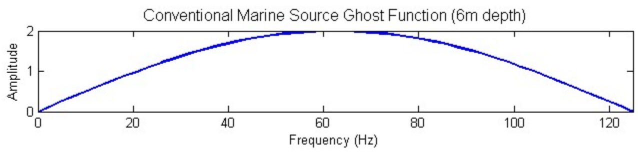
- <u>Marine dipole seismic source</u> –
  The marine dipole seismic source uses the reflective ocean surface to enhance low frequencies.
- <u>Counter rotating eccentric mass actuator</u> –
  Actuator provides large forces at low frequencies needed to enable marine dipole source and land acquisition.
- <u>Pressure gradient transducer</u> –
  A pressure gradient transducer insensitive to motion solves the noise problem in multicomponent streamers.

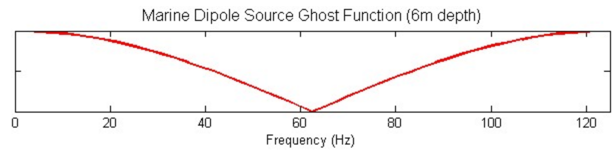
The Marine Dipole Seismic Source

Constructive Source Ghosting at Low Frequencies: Applications for Low Frequency Marine Seismic Sources and Source De-Ghosting

<u>The Technology Concept</u>

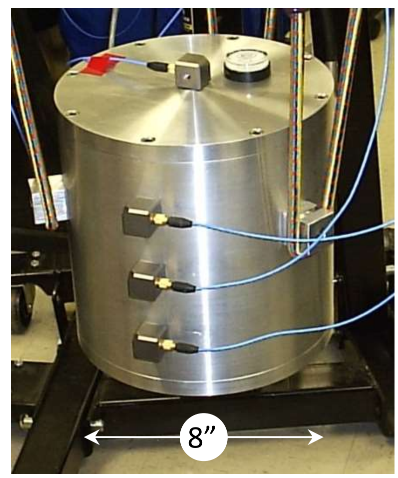
- Commercial marine seismic sources (e.g., airguns, marine vibrators) drive volumetric changes to excite seismic waves in a fluid medium. Their ghosting characteristics notch out the low frequencies.
- The marine dipole seismic source excites seismic waves by oscillating a fixed volume in the vertical direction. It's ghosting characteristic passes low frequencies.





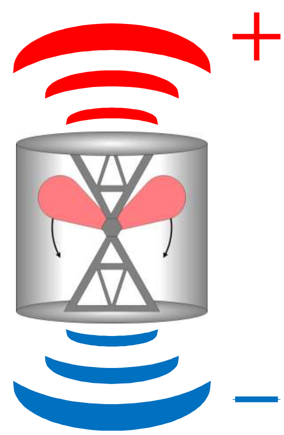
<u>Research and Development Status</u>

- From acoustics and fluid dynamics, theory was formulated to predict the dynamical behavior and radiated acoustic field for an oscillating rigid volume.
- A small scale, higher frequency marine dipole source has been demonstrated. The measured source behavior and wavefield characteristics agreed with predictions.
    - Confirmed far field radiation amplitudes at wavelengths orders larger than the rigid volume dimension,
    - Confirmed wavefields radiated on opposite sides of the source were opposite polarity from one another.
- From theory, the requirements for an experimental dipole marine source prototype capable of far-field radiation at low frequencies, including one hertz, have been predicted.
- An experimental marine dipole seismic source for low frequency radiation requires a large force, low frequency actuator, such as the CREM actuator (see Counter Rotating Eccentric Mass Actuator).



<u>Research and Development Plans</u>

- Design and build an experimental dipole seismic source prototype to demonstrate far field radiation in a marine environment at frequencies substantially below current technologies.
- Characterize experimental source performance and far-field radiation. Compare measurements with predictions. Quantify far-field signal-to-noise ratios in the operational frequency band.
- Develop specifications for a low frequency commercial prototype marine dipole source.



<u>Commercialization</u>

- Design and build commercial marine dipole seismic source prototype.
- Evaluate commercial performance.

<u>Patents and Publications</u>

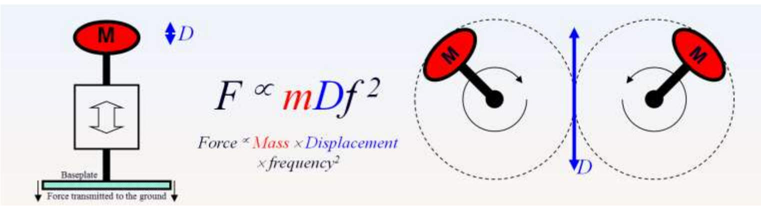
- Patent US 7,377,357: Marine seismic acquisition method and apparatus, Duren and Meier, May 27, 2008.
- Patent US 8,833,509: Two-component source seismic acquisition and source de-ghosting, Meier and Duren, September 16, 2014.
- Meier and Duren, “Theory for a low frequency marine dipole seismic source,” Journal of Seismic Exploration, 25, pp. 285-298, June 2016.

The Counter Rotating Eccentric Mass Actuator

Forces to Four Hundred kilo-Newtons at Low Frequencies Including One Hertz: Applications for Land and Marine Seismic Sources

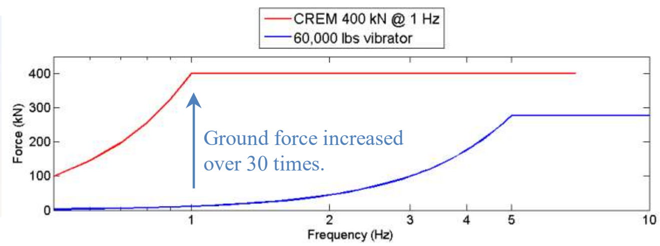
The Technology Concept

- Commercial seismic vibrators are displacement-limited, resulting in force output fall-off with frequency-squared. The force output at low frequencies is weak.
- The counter rotating eccentric mass (CREM) actuator displacements are far greater, enabling large forces at low frequencies.



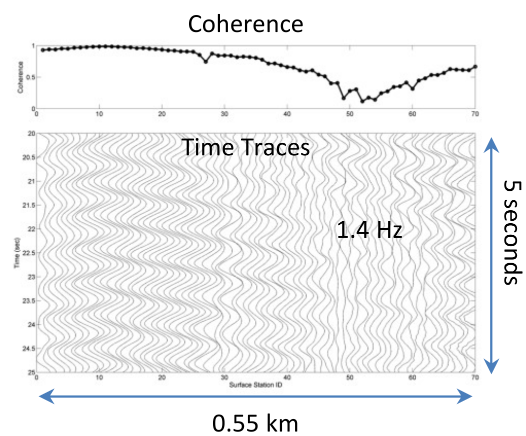
Conventional vibrator

CREM actuator



Research and Development Status

- A small scale CREM actuator has been demonstrated, and successfully coupled frequencies down to one hertz into the ground.
- A full scale experimental prototype (CREMV-XP) that can generate controlled sweeps with 400 kN of ground force from one to six hertz has been designed and fabricated.
- An experimental program has been designed and is being prepared for implementation.



Research and Development Plans

- Characterize the actuator and establish performance capabilities.
- Measure the earth response and quantitatively determine signal-to-noise ratios in the operational frequency band.
- Determine source performance needed to measure back-scatter down to one hertz.
- Develop specifications for a low frequency commercial prototype CREM seismic source.

Commercialization

- Design and build commercial prototype CREM seismic source.
- Evaluate commercial performance.

Patents and Publications

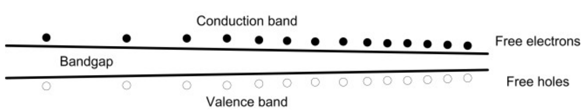
- Patent US 9,310,499 B2: Low frequency seismic acquisition using a counter rotating eccentric mass vibrator, Meier, Heiney, Tomic, Ibanez, Byrne, April 12, 2016.

The Pressure Gradient Transducer

A Motion Insensitive Transducer for Measuring Pressure Gradient in a Fluid Medium: Applications for Marine Seismic Acquisition

The Technology Concept

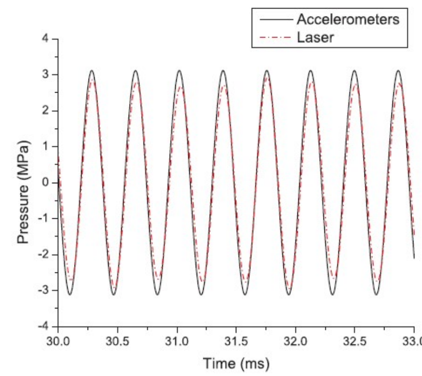
- Commercial multicomponent streamers use motion sensors. Measurements are assumed to represent the particle velocity (a proxy for pressure gradient) of passing seismic waves. However, many motions in fluid and streamers, not related to seismic waves, contaminate the measurement. Error overwhelms the measurement at frequencies near and below 20 hertz.
- Our pressure gradient transducer is insensitive to motion, and measures the pressure gradient in a fluid medium directly.

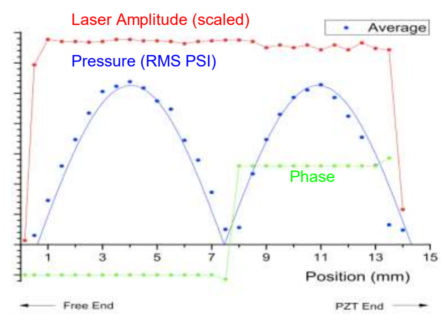


The energy band gap in some materials is sensitive to pressure. A gradient in pressure causes a gradient in the energy band gap; causing a gradient in free charge carriers, which can be exploited for an electrical response and transducer effect.

Research and Development Status

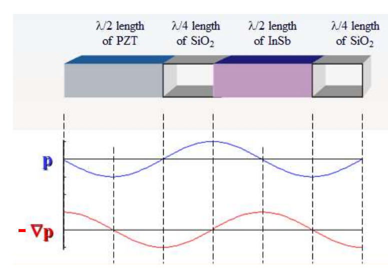
- Semiconductor and solid state plasma theory was examined and the plausibility of a measurable response from seismic waves with frequencies down to one hertz and amplitudes down to SS0 noise floor was determined.
- An experimental program to verify the transducer effect was designed and implemented. High frequencies and large signals are used to simplify verification.
  - A laser diagnostic has been developed to independently measure the free charge carrier concentration in our preferred semiconductor material.
  - Bulk pressure modulations were excited in a semiconductor sample and corresponding dynamics in free charge carrier population were observed using a laser diagnostic.
  - Pressure gradient modulations were excited in an acoustically resonant semiconductor sample with length equal to one wavelength, and corresponding dynamics in pressure and pressure gradient were confirmed using the laser diagnostic.
  - Magnetic field apparatus was fabricated to test for diamagnetic current from transducer effect.
  - The pressure gradient transducer effect was experimentally verified.





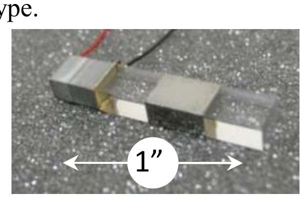
Research and Development Plans

- Design experiments to verify diffusion current from transducer effect.
- Proceed with engineering-research phase to confirm fluid coupling, and the sensitivities, dynamic range, and other characteristics needed for seismic applications are achievable.
- Package the transducer and manufacture sufficient count to instrument a streamer section for field trials.
- Develop specifications for a full streamer commercial prototype.



Commercialization

- Design and build a full commercial prototype multicomponent streamer incorporating the transducer.
- Evaluate commercial performance.



Patents and Publications

- Patent US 7,295,494: Diamagnetic current response transducer for sensing pressure gradient in a fluid medium, Meier, November 13, 2007.
- Patent US 8,681,586: Free charge carrier diffusion response transducer for sensing gradients, Hallock and Meier, March 25, 2014.
- Hallock and Meier, “Low frequency pressure modulation of indium antimonide,” Rev. Sci. Instrum. 83, 073906 (2012); doi: 10.1063/1.4737142.
- Hallock and Meier, “Density modulation of a solid-state plasma using acoustic pressure,” IEEE Pulsed Power & Plasma Science Conference Proceedings, 2013.
- Hallock and Meier, “Resonant transducers for solid-state plasma density modulation,” Rev. Sci. Instrum. 87, 044902 (2016); doi: 10.1063/1.4947507.
- Hallock and Meier, “Diamagnetic current measurements in a solid-state plasma,” Rev. Sci. Instrum. 89, 083505 (2018); doi: 10.1063/1.5029356.
- H. Salehi Najafabadi, “Carrier Transport Response and Behavior of Semiconductors Having a Gradational Energy Band Gap Due to Gradients in Pressure or Other Physical Properties ”, Ph. D. Dissertation (2020), University of Houston.