Arctic Acoustics at MIT

Greg Duckworth

Dyer Symposium
14 June 2007
Preface

• 30 years since inception of the Arctic Program at MIT

• Changes
  – Arctic Ocean Basin has increased in size by 1-2 feet
  – Arctic ice cover has been dramatically changed by air and sea temperatures

• Arctic Acoustics Research
  – Scaled-back in mid-’90s due to fall of Soviet Union
  – Glimmers of new initiatives
    • International Polar year
    • Increased US Navy (surface?) operations may be needed—soon!
      – Much SHALLOW WATER → Ira is on the mark, as usual
Outline

• Review accomplishments of Arctic Acoustics work at MIT
  – ONR Sponsorship

• Subsequent work:
  – BBN/ONR AEAS Program Arctic Low-Frequency Active

• Show how it was done: a few pictures (if time permits)
  – Pre-GPS
  – Pre-Iridium/Globalstar
  – 1940’s Airframes
  – POST-DIGITAL!
MIT Arctic Program

• What I heard:
  – Dyer: We should do basin acoustics. The MED is a good basin.
  – ONR: Good idea, but we have another basin in mind…

• → Multi-facetated ONR Arctic Program:

<table>
<thead>
<tr>
<th>Acoustical Tools</th>
<th>Ice Science</th>
<th>Oceanography</th>
<th>Crustal Geophysics</th>
<th>SONAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Noise</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reverberation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Propagation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Seismic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Experimental Program

- CANBARX ('78)
- Fram II ('80)
- Fram IV ('82)
- MIZEX 83
- MIZEX 84
- PRUDEX 87
- CEAREX 89
- AREA 92
What is unique about the Arctic?

- It’s cold (for now)
- Surface Duct
- Frozen rough surface
- Very stable water column
- Ice cracking noise

FIG. 5. Central Arctic sound speed profile obtained from CTD measurement taken at the ZIRCON camp.
Fram II Camp Layout (& hazards)

- Cracks / Leads
- Horizontal 2-D array
- Science Hut
- Living / Mess
- Pressure Ridges
- Polar Bears
Ambient Noise: Ice Cracking

- **Goals**
  - Ambient noise statistics
  - Ambient noise understanding
    - Postulate and verify ice-cracking mechanisms and relation to sea-ice strength
    - Seismic noise from mid-ocean ridge

- **Methods**
  - Validate models for individual ice-crack events and aggregate spectral observations
  - Specific ice propagation studies with geophones and sources on the ice
  - Measure and localize earthquake events from the mid-ocean ridge

- **Results**

[Images of Ambient Spectrum, Horizontal Directivity, and Ice Stress Distribution]
• Precision Localization of earthquakes in Rift zone to within 5 km.
Propagation Stability

- **Goal**
  - Determine the stability of the multi-path Arctic propagation channel
- **Method**
  - Transmit LF CW tones over 300 km paths
  - Receive on array and beamform
  - Measure fluctuation statistics
- **Results**
  - Stability greater than measurable with available 25 dB SNR (15-40 Hz) and time windows

**Phase Variation**
- 0.2 cycles

**Amplitude Variation**
- < 1 dB

**Amplitude Distribution**
- Rician

**Doppler Spread**
- < 0.8 mHz
Basin Reverberation

• Goal
  – Probe the basin margins and everywhere in-between with a very-low-frequency active sonar → estimate backscatter strength

• Method
  – 8-10 Hz active sonar. 24 element 2-D logarithmic array (1 km aperture)
  – 440-1600 lbs TNT source at 800’ depth
  – > 1 hour listen time for 2500 km range

• Results: Backscatter strength + a new feature!

- Reverb Map
- Ice Camp
- Unexpected Return
Basin Reverberation

- Seamount “G. Leonard Johnson”
  - 73.2 N  139.0 W

Seismic Reflection / Refraction

- **Goal**
  - Understand the crustal structure of the Arctic basins down to the mantle

- **Method**
  - Reflection: Air gun / SUS
  - Refraction:
    - Fly transects away from array at camp with helicopter
    - Drop 25-100 kg charges @ 800’ depth
    - Velocity analysis and inversion
    - Exploit extensive multiple arrival structure

- **Results**
  - Well-constrained sediment / igneous crust velocities down to mantle
Seismic Refraction Results

Refraction Migrations

Compressional

Pole Abyssal Plain
Crustal Velocity Structure

Shear

Key: Invert all direct and multiple arrivals to make up for the sparse shooting geometry
Sediment Refraction

341 km shot geometry

Sediment Velocity Structure

Also inverted for sediment Q (loss factor) and surface scattering loss

22 Sediment Penetrating Multiples

Velocity Analysis → tau-p inversions

Fig. 6.15] The 16 Hz velocity spectrum of the data and the normal mode and WkId predictions. See the text for a discussion of this plot.
Post-MIT: Arctic LFA (Low Frequency Active)

• Goal
  – Design and Test LFA Sonar for the Arctic

• Method
  – Exploit Surface Ducted Energy
    • Low dispersion
    • Low backscatter (low grazing angle)
    • Continuous coverage (no CZs)

• Results
  – LFA Performance (classified)
  – Surface Backscatter model
  – Ice Deformation Tracking
  – Potential for coherent clutter subtraction demonstrated
Typical Camp Layout: ZIRCON (AREA-92)

VLA

HLA

Science Hut

Living / Mess

Shot Drop

WHOI Array Tracking Pingers

JACKPOT Echo-repeater camp

1 km
Reverberation Analysis

$$rl(t) = c_{sl} \sum_{\text{out}}^{m} \sum_{\text{in}}^{n} \left[ t_{g1_m}(r_{mn}(t)) \alpha_{mn} \gamma_{mn} t_{g2_n}(r_{mn}(t)) \right] + nl$$

$$\gamma_{mn} = \alpha (\sin \theta_m \sin \theta_n)^\gamma$$

Unknowns: $nl$, $\alpha$, $\gamma$

<table>
<thead>
<tr>
<th>Group</th>
<th>Grazing Angle at Surface (degrees)</th>
<th>Normal Modes Included</th>
<th>Group Speed (m/s)</th>
<th>Turning Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = Surface Duct</td>
<td>8.4 +/- 2</td>
<td>1-2</td>
<td>1442</td>
<td>210 +/- 100</td>
</tr>
<tr>
<td>2 = Mid Depth</td>
<td>12.5 +/- 1.3</td>
<td>3-17</td>
<td>1457 +/- 1.5</td>
<td>1527 +/- 506</td>
</tr>
<tr>
<td>3 = deep RSR</td>
<td>17.5 +/- 0.63</td>
<td>20-40</td>
<td>1465 +/- 1.4</td>
<td>3937 +/- 327</td>
</tr>
</tbody>
</table>
Backscatter Strength Results

\[ s_{mn} = \alpha (\sin \theta_m \sin \theta_n)^\gamma \]

- Inversion Results and 2-D elastic perturbation theory in reasonable (3 dB) agreement
Fun with acoustics: Ice Floe Tracking

- **Goal**
  - Examine the stability of ping-to-ping clutter returns
  - Determine potential for coherent clutter subtraction
- **Method**
  - Track Individual Scattering Patches using ping-to-ping / beam-to-beam coherence
- **Results**
  - Can measure the deformation of the ice sheet for a radius of 150-200 km
Ice Floe Tracking

- Floes can be tracked
- 4 hour strain shown
- Coherence threshold at 0.15 / 250 DOF

Uniform strain rate model
Exx = -.00015 /h   Eyy = 0.00013 /h
(-30m/h @ 200km  +25m/h @ 200km)
Conclusions

• Acoustics is a fundamental tool for Arctic Geophysics and Ice Science

• Sheds light (sound!) on all areas
  – Ice properties and kinematics
  – Oceanography
  – Crustal structure and seismicity

• MIT contributed greatly to this work
  – Techniques
  – Results

• I am eternally grateful that I was in the right place at the right time
  – I apologize for much great work not represented today, and for the cursory and simplistic presentations of much of what was represented!