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SOUND RAY STABILITY IN THE FRAM-STRAIT

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In the research program ``Acoustic Monitoring of the Ocean Climate in the Arctic" (AMOC), the objective is to assess the possibility of using acoustic methods to monitor any long term changes in temperature and ice thickness in the Arctic. The main influx/efflux of water (and heat) to the Arctic Ocean is through the Fram-Strait. Thus, monitoring the temperature distribution and water flux in the Fram-Strait is an important issue in this respect. In this presentation we focus on certain aspects of acoustic thermometry using ray tracing. In order to apply acoustic means for monitoring temperature and flux of water masses it is essential that it is possible to identify arrival of individual rays at the receiver location, while the environment undergoes seasonal and shorter time scale variations. The present study is based on ray simulations using environmental data for the period 1950-1990 in terms of decadal means. In addition a detailed map of one passing meso scale eddy was used. The main conclusion is that some rays may be identified most of the time, even during passing eddies.

1. FRAM-STRAIT ENVIRONMENT

The environmental data used in this project is prepared from the "Joint US-Russian Arctic Oceanography Atlas CDs "[1] and is gridded for the Fram-Strait in 9 stations separated by about 2.8 degrees along the 79° N latitude, covering the longitude 11° W to 11° E. About 200 km of the 600 km wide Fram-Strait between Greenland and Spitzbergen at 79°N is more than 2000m deep. The bathymetry of the strait is shown in Fig. 1, with a color map of the mean sound speed for the summer seasons 1950-1989. The width of the strait allows inflow of warm water to the Arctic Ocean and outflow of cold water and ice to be separated horizontally, with the warm water flowing northwards on the Spitzbergen side and cold water flowing southwards on the Greenland side, which is ice covered almost all year round. This results in strong horizontal sound speed gradients in addition to vertical, as clearly seen in Fig. 1. Here Greenland is to the left and Spitzbergen at the right hand side, and the origin is placed at 11° W. The seasonal variations occur mostly in the upper 600 m of the water column. From an acoustical point of view the Fram-Strait is an extremely difficult environment to monitor because of the two opposing currents which is displaced horizontally. In this study we have therefore focussed on placing the sound source in the middle of the strait, and having a receiver array on the the eastern flank near Spitzbergen. In the examples shown the source is located at 250 km, and the receiver at 410 km. Because of the the sound ducts which appear in the upper layers it is necessary to lower the source to 300 - 500m depth - in the examples shown 500m.

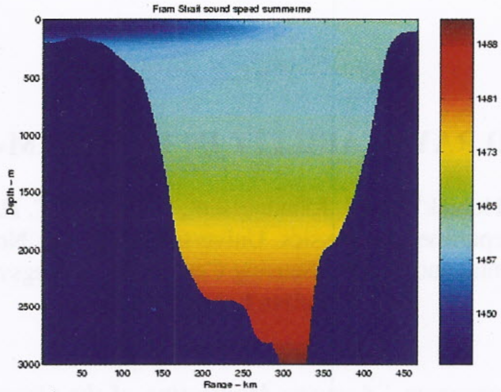

Figure 1. Bathymetry and summer mean sound speed map of the Fram-Strait.

2. RAY FANS

A preliminary study was made by using the ray tracing code "RAY" [2] to search for "eigenrays" between the source and a receiver at 300m depth. For the different seasons and decades the number of eigenrays varied between 2 and 14. A study of the eigenray signatures, determined by launch angle, number of top and bottom bounces and angle at receiver, revealed a marked difference between summer and winter seasons, and a rather confusing pattern emerged. In order to investigate this further a different approach was taken. Instead of searching for eigenrays a large number of rays was launched within a narrow angle interval about the horizontal (ray fan), and the depth and travel time at the receiver range was recorded. A plot of the ray fan for summer 50s is shown in Fig. 2 a) as ray depth at receiver against source angle (negative angles point downwards), and b) as depth against arrival time.

Each ray arrival is plotted as a circle, and the density of these represent the intensity of the sound. The horizontal line indicates a receiver at 300m depth. It's intersections with the curve identify the eigenrays for this receiver. The eigenray algorithm found 5 eigenrays, corresponding to the densest intersections. Do observe that in the "depth against arrival time" plot the deepest rays are the last to arrive! This is found to be the case in general (with only one exception), and is contrary to ordinary sound channel behavior. The fastest rays - in most cases a narrow ray fan launched almost horizontally (in Fig.2a -1° to +0.5°) - propagate in a narrow, undulating band about an almost straight line from the source to the receiver, which is reached at depths varying from 800 m to 50 m. Thus, these rays seem to follow the range dependent sound channel axis. The reason why they are the first to arrive must be due to the path length being as much shorter than for the deeper rays that it compensate for the lower sound speed.

Ray fans plotted as in Fig. 2a are helpful for investigating stability of eigenrays. A generic plot of this type, obtained for example by disregarding range dependence (using the sound speed profile at the source) is rather symmetric about zero source angle, and shows 3 undulations to each side. These are narrowly peaked at the top and wide at the deep end. The outer flanks fall off steeply towards depths about 1 km. As seasons vary both amplitudes and widths of these undulations fluctuate, in particular in the region ± 2° , and sometimes they are severely deformed in Fig. 2a the rightmost undulation is actually No 2, not 3). The pattern may be shifted upwards or downwards, and some undulations may merge (the central ones) or split. The trend emerging from such analysis is that the rays belonging to the outer flanks are the ones most likely to be recognizable at all times, while those launched more horizontally are less reliable. Also, since the stablest rays are also the deepest, they are the most promising candidates for acoustical thermometry in the Fram-Strait. For convenience these eigenrays are labeled "a,b"and "g,h", where a and h are on the outermost flanks, and b and g on the inner side of the outer undulations (in Fig. 2 only eigenray "b" is present, near -4^0 source angle). In Fig. 3 is shown traces of these eigenrays for all seasons (source depth 500m, receiver depth 300m). They cover the water column down to 1 km and more, and thus the dominating part of the West Spitsbergen Current.

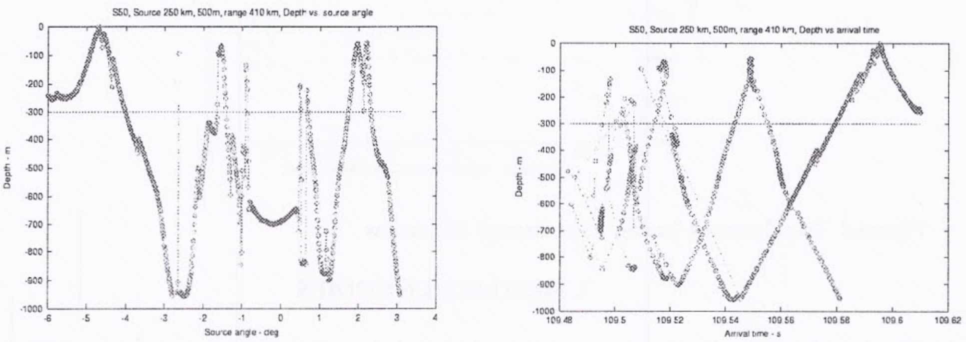

Figure 2. Ray fan results for summer 50s.
a)(left) Depth against source angle. b) (right) Depth against arrival time.

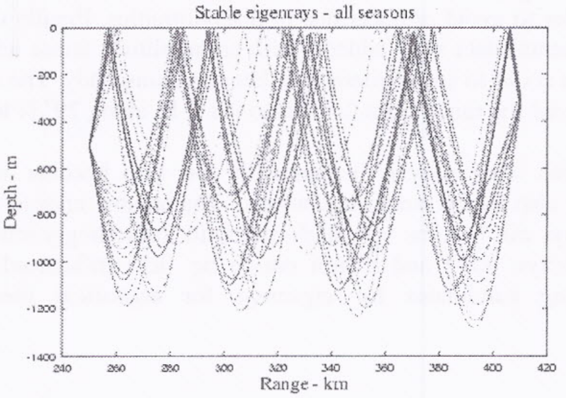

Figure 3. Trace of "stable" rays through all seasons

The ray fan plots also show that one should have receivers at several depths, in order to increase the probability of finding stable eigenrays - if they fail at one depth for a period there would be some at other depths, and *vice versa*.

In order to demonstrate the sensitivity of acoustic thermometry based on the stable rays the travel times of these rays are shown in Fig. 4. There is a marked difference between summer and winter seasons; typically about 100 ms faster in the summer. Therefore the seasons are separated in the figure. Note that ray h is missing in all summer seasons. The eigenrays show basically the same trend: Slightly decreasing travel times with time, and more pronounced at the later decades. The change is small, however: Winter rays arrive 31± 2 ms earlier in 1980s than in 1959s, corresponding to an increase in sound speed 0.42 ± 0.03 m/s, or an increase in temperature of roughly 0.09°C. Inversion based on details of the ray paths has not yet been performed.

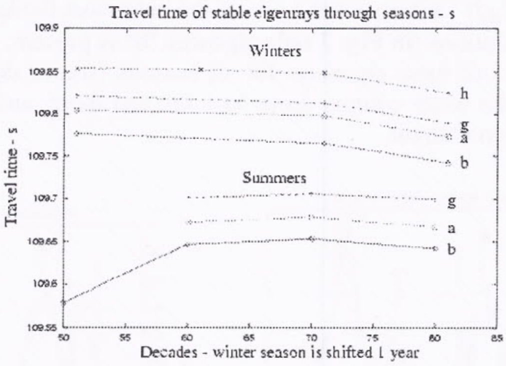

Figure 4. Travel time of "stable" rays through all seasons

3. MESO SCALE EDDIES

Meso scale eddy data were incorporated into the environmental data in the following way. First sound speed data taken by the 1997 AOGC expedition [3] was interpolated on a regular grid horizontally and vertically in terms of sound speed differences (global mean = zero). Secondly, margins were added to both sides and bottom with tapered sound speed differences, in order to avoid artifacts due to discontinuities. Finally the data set was merged onto the environmental data sets (added), with an amplitude factor adjustable between 0 and 1. In this way one could to some extent simulate a passing eddy. The original meso scale data (SEASOAR) covered the range from 2.45° E to 9.15° E, along 79° N longitude, and to a depth of 250m.

As the meso scale eddy is increased the ray fans become distorted, first near zero source angle, later also on the outer undulations. The pattern tends to become chaotic, and the number of eigenrays can become very high, but with forbiddingly low amplitude. However, the "stable" eigenrays, a,b,g and h turn out to be less influenced than the rest, and are therefore promising candidates for eigenrays for acoustical thermometry in a future experiment.

REFERENCES

1. The Joint US-Russian Atlas of the Arctic Ocean is available from: User Services, National Snow and Ice Data Center, University of Colorado, Campus Box 449, Boulder, CO 80309-0449, USA. URL: http://www-nsidc.colorado.edu.
2. J.B. Bowlin, J.L. Spiesberger, T.F. Duda and L.F. Freitag, "Ocean Acoustical Ray-Tracing Software RAY", Tech. Rep. WHOI-93-10, Woods Hole Oceanographic Institution, Woods Hole, Mass. USA, 1992, 49 pp.
3. O.M. Johannessen, V.J. Haugen, "AMOC 1997. Seasoar and CTD data in the Fram-Strait". NERSC special report no 62.