ACOUSTIC PROPAGATION THROUGH THE ANTARCTIC CONVERGENCE ZONE – CALIBRATION TESTS FOR THE NUCLEAR TEST MONITORING SYSTEM

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ABSTRACT

We plan to carry out a series of calibration shots within and to the south of the Antarctic convergence zone (ACZ). The seagoing experiment will be one component of an already scheduled and funded multi-disciplinary expedition in the Southern Ocean. Hydrophone stations of the International Monitoring System (IMS) will record the calibration shots, and the observed source-receiver travel times will allow us to document the scale of the source location errors associated with hydroacoustic propagation through the strong oceanographic gradients of the convergence zone, and determine the transmission losses for sound crossing the convergence zone. In addition, apparent back azimuths to the source will be determined and, together with the travel times, compared to predictions of acoustic propagation models. Environmental parameters within the models will be varied systematically to assess how each change affects the predicted travel times, azimuths, and transmission loss. These findings will be related to our calibration shots specifically and will also be of general import, in terms of quantifying of the types of source characterization uncertainties that arise for hydroacoustic propagation across high oceanographic gradient zones. Physical parameters that will be considered include ocean temperature and salinity, seafloor variability (depth and sediment thickness), and sea surface roughness (waves) in the region where the sound channel breaches the surface.

The planned seagoing voyage departs Australia, crosses the ACZ along the way to the Davis Antarctic Station, and crosses the zone again on return to Hobart, Australia. We predict that the travel path between the calibration source site and at least one of the IMS receivers will be unblocked by seafloor topography along the entire ship track. We plan to use 4-lb US Navy signals underwater sound (SUS) charges, which generate broadband signals. These small explosive devices have been used for defense and research purposes in the ocean for several decades. Although other acoustic sources might be preferable, conditions in the Southern Ocean preclude the use of more sophisticated systems that require a calm-moderate sea state for safe operation.

Our experiment is designed as a one-time case. The calibration shots will be conducted along transects that each take about a week. Therefore, we will obtain essentially a snapshot of the ACZ and our signals will document the travel times and losses for the corresponding structure. The idea behind this type of experimental plan is that we can document the scale of the errors that arise due to uncertainty in ACZ structure. This will allow us to characterize how well an unknown event in the Southern Ocean could be located. The combination of our measurements with post-cruise modeling will allow us to assess the magnitude of various factors that contribute to the determined uncertainties. In summary, our experiment is designed to answer the following questions:

- *How does propagation through the ACZ affect travel times and apparent source-receiver azimuths?*

- *How does propagation through the ACZ affect the signal strength?* Parabolic equation modeling confirms that acoustic propagation is ducted north of the ACZ boundary, and surface-limited south of it. An unresolved question is whether acoustic energy is lost due to the strong gradient in ocean sound speeds at the ACZ boundary, or whether energy is lost due to scattering at the rough sea surface in the region south of the boundary.

- *How does source depth affect the transmission loss and travel times for source within the ACZ?* At a few sites, more than one charge will be deployed; trigger depths for successive charges will be varied between 200-100m below the sea surface so that variations due solely to source depth can be assessed.

OBJECTIVES

We have recently been funded to conduct a series of hydroacoustic calibration shots that will be used to compare observed signal propagation time and direction to that predicted by numerical models for paths crossing the (ACZ). A calibration experiment is needed because ocean temperature and salinity gradients across the ACZ are not sufficiently well characterized to predict how travel times may be affected by seasonal and annual variation in the structure of the zone, and propagation models are insufficient to fully handle the complexity of propagation across the ACZ. Our calibration signals will propagate to IMS hydrophones in the Indian Ocean from a series of Southern Ocean sites located along ship transects from 48°S-62°S. Comparison between the signal source locations determined using techniques that are standard for nuclear test monitoring and the known source locations will indicate the level of uncertainty in current methods. In addition, analysis of transmission loss between the sources and the receivers will be used to assess the influence of variation in oceanographic properties, sea surface conditions, and sea floor depth along the propagation paths.

Precise source times and locations are critical for calibrating trans-ACZ travel times to the IMS hydrophone stations. While there are natural sources that yield acoustic signals generated south of ACZ that are observed at IMS stations, for example, icequakes (Talandier et.al., 2002) and earthquakes, their event times and locations must be inferred from model-dependent calculations; ground truth information on exact event time or location is not available. Furthermore, many of these naturally occurring events do not generate strong signals in the bandwidth of interest (30-100 Hz).

We are in the process of finalizing the seagoing plan; at this time it still looks likely that we will join one of the 05/06 field season voyages run by the Australian Antarctic Division (AAD). A candidate voyage track enroute to Davis Antarctic Station and back is shown in Figure 1. The path between the calibration source sites and at least one, preferably more, of the IMS receivers must not be blocked by sea floor topography. This is the case to the Cape Leeuwin and Diego Garcia IMS stations for much of the area 85°E-135°E; paths to the Crozet IMS station will include some loss during propagation over Kerguelen Plateau, for sources east of 80°E (Figure 1), but paths for sources further west will be unblocked.

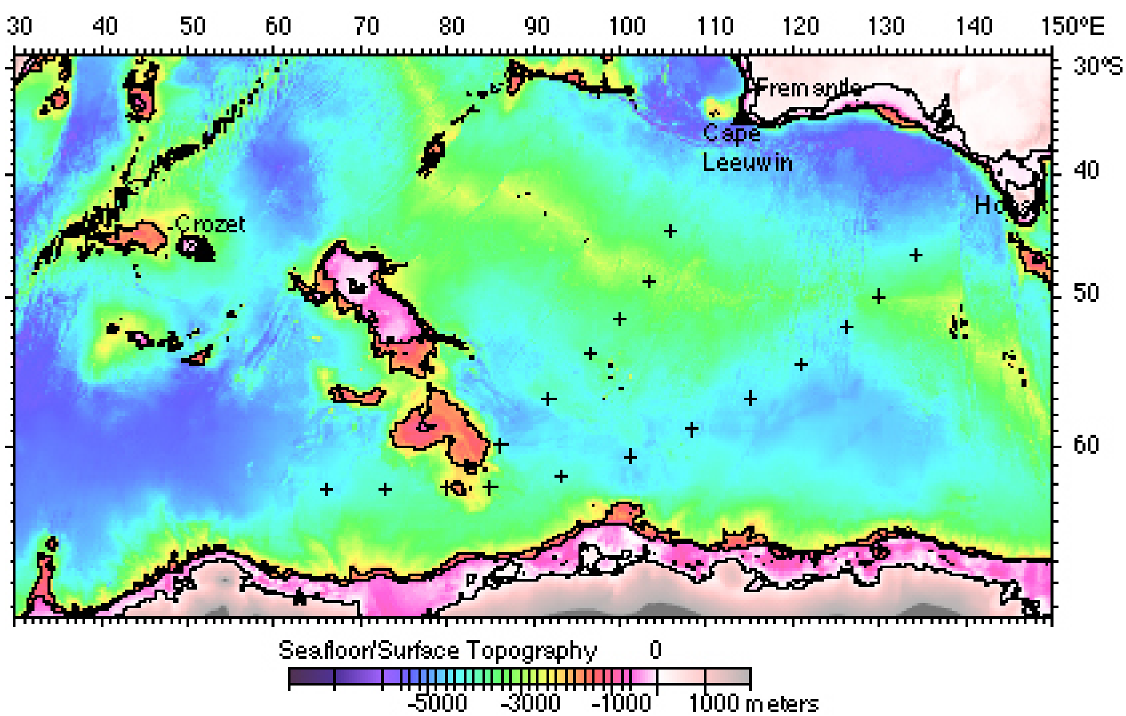

Figure 1 sketch of possible calibration source sites across the ACZ. Seafloor depth (color), IMS hydrophone stations (triangle; Diego Garcia off the map to the North), tentative source sites: +. The transects shown here correspond to Voyage 3 of the AAD field season for 05/06 austral summer.

We plan to use 4-lb US Navy SUS charges for our acoustic source. Although other acoustic sources might be preferable, conditions in the Southern Ocean preclude the use of more sophisticated systems that require calm-moderate sea state for safe operation. Source trigger depths will be varied between 200 and 1000 m below the sea surface. The SUS signal is broadband and the output level of a 4-lb charge is listed as 276 dB re 1 µPa. The energy density flux is estimated to be about 6 dB greater than that for the 1.8 lb charges used for our prior work (Urick, 1983). At a few sites, more than one charge will be deployed; trigger depths for successive charges will be varied so that path effects are constant and variations due solely to source depth can be assessed.

The calibration shots will be conducted along transects through the ACZ that each take about a week and are separated by up to a few weeks (while other scientific activities are completed near the Antarctic station). Therefore, we will obtain essentially two snapshots of the ACZ and our signals will document the travel times and losses for the corresponding structure.

RESEARCH ACCOMPLISHED

We have analyzed transmission paths to the IMS receivers. For most paths, there is some ridge or plateau that projects at least partly into the oceanic sound channel and will probably strip away the highest order modes. Sites will therefore be selected prior to the cruise based on predictions of optimal signal to noise ratios at each IMS station. An example is shown in Figures 2 and 3. Figure 2 shows the environmental models from a potential site near 60°S, 101°E to each IMS hydrophone at which we anticipate signals can be detected. The axis of the sound channel shoals significantly toward the polar ocean and the upper part of the waveguide breaches the surface. Thus, even for relatively unblocked paths, part of the transmission would be surface limited (that is rays would be reflected from the sea surface) for sources within the ACZ. Propagation to H04W is at least partially blocked by the Kerguelen plateau, and would furthermore be surface limited for the entire path.

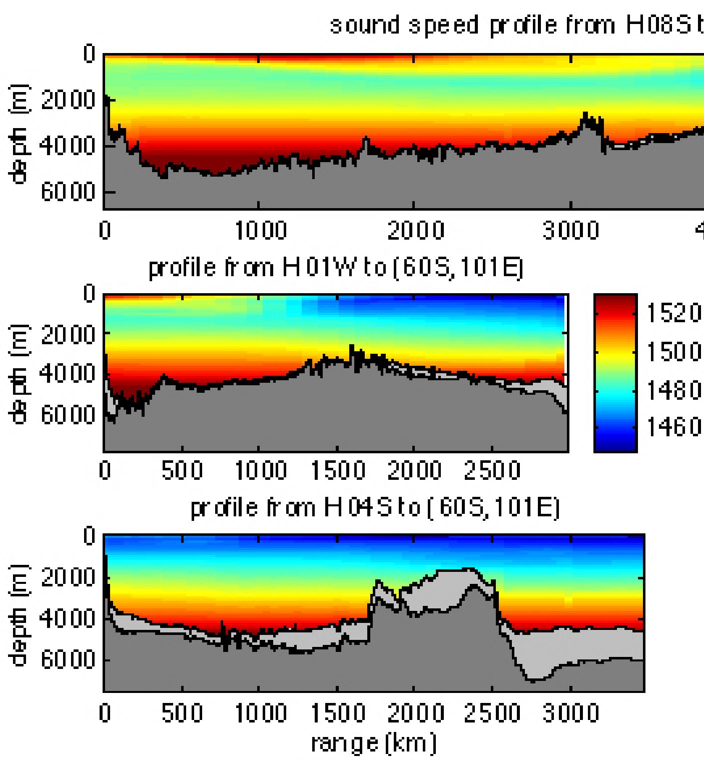

Figure 2. Ocean sound speed (m/s) profiles for paths between a potential source site (at 60.5°S, 101° E) and three IMS hydrophone stations. Dark gray is hard (basement) rock, light gray is a sediment layer (thicknesses from www.ngdc.noaa.gov/mgg/sedthick/sedthick.html). Sea floor characteristics affect transmission loss (TL) computations as sound mainly reflects from basement rock but is absorbed and attenuated by sediments.

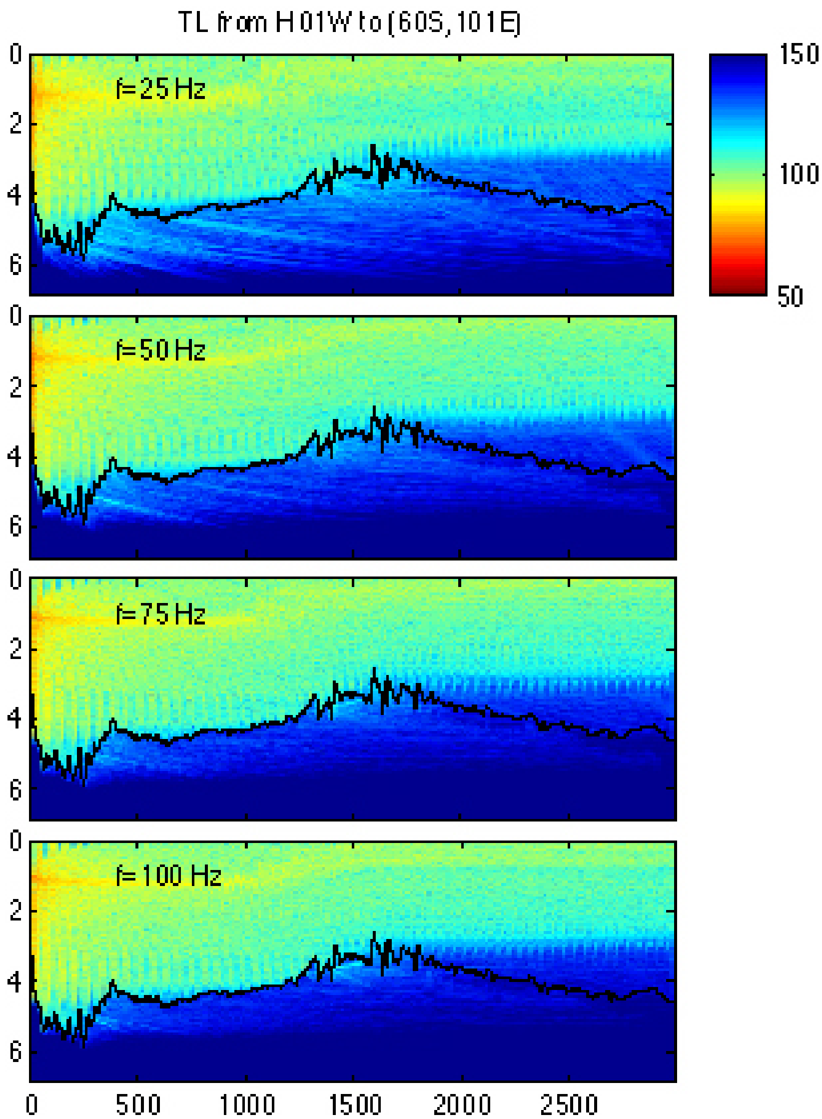

Figure 3. Predicted TL (dB) between the hypothetical source site and H01. Source and receiver are switched, so a series of trial trigger depths can be estimated using a single calculation per frequency. Propagation is surface limited where sound channel breaches the surface. Most the energy is confined within about 2.5 km of the surface, about the minimum seafloor depth along the travel path.

Figure 3 shows predicted acoustic transmission losses (TL) along a path from a H01W hydrophone to the potential site location near 60°S, 101°E, for several frequencies. These were computed using the acoustic parabolic equation (PE) modeling algorithm described in (Collins, 1993). By reciprocity, the source and receiver locations may be interchanged. Therefore, by computing acoustic transmission losses for a source at the hydrophone position, we only need to run the algorithm once in order to estimate the losses for a series of trial shot depths. For example, Figure 3 shows the expected transmission loss for a sweep of ranges (along profile) and depths (vertical axis) for a source located at the H01W hydrophone, near Cape Leeuwin. By reciprocity, a source fired at any point along the profiles would yield the identical transmission loss at H01W. Thus Figure 3 implies that any source fired within approximately 2000 m of the sea surface would yield relatively low transmission losses at the H01W hydrophone; deeper sources would be much more severely attenuated. It is worth noting that the shots fired in the Heard Island experiment (Heaney et al*.*, 1991; Munk et al., 1988) had even longer propagation paths through the Antarctic Convergence zone, and were detected at Bermuda on unfiltered records; thus even with our much smaller shots, we might be able to detect signals with careful processing.

Note that the transmission losses computed above represent best-case scenarios because the propagation modeling assumes a mirror-flat sea surface, which reflects, with phase reversed, all in-coming hydroacoustic energy. Furthermore, the PE equation modeling does not take into account back-scatter at the ACZ transition zone. More realistically, when acoustic propagation is surface limited the transmission is adversely affected by sea surface roughness, which scatters incoming energy. Sea surface roughness depends strongly on weather conditions along the travel path and throughout the Southern Ocean. The faster the wind, the longer it blows in one direction, and the greater the fetch, the bigger the waves. The contribution of sea surface roughness to transmission loss should therefore be seasonally and storm dependent. Wave height information derived from satellite data will allow us to assess the contribution of sea surface roughness to losses for each source-receiver path. Figure 4 (from https://www.fnmoc.navy.mil/ PUBLIC/) is a map of wave height and wind direction for the Indian Ocean, indicating a large storm moving across the region in which are shots will be fired. In general the sea surface roughness is greatest south of 40°S, especially in winter.

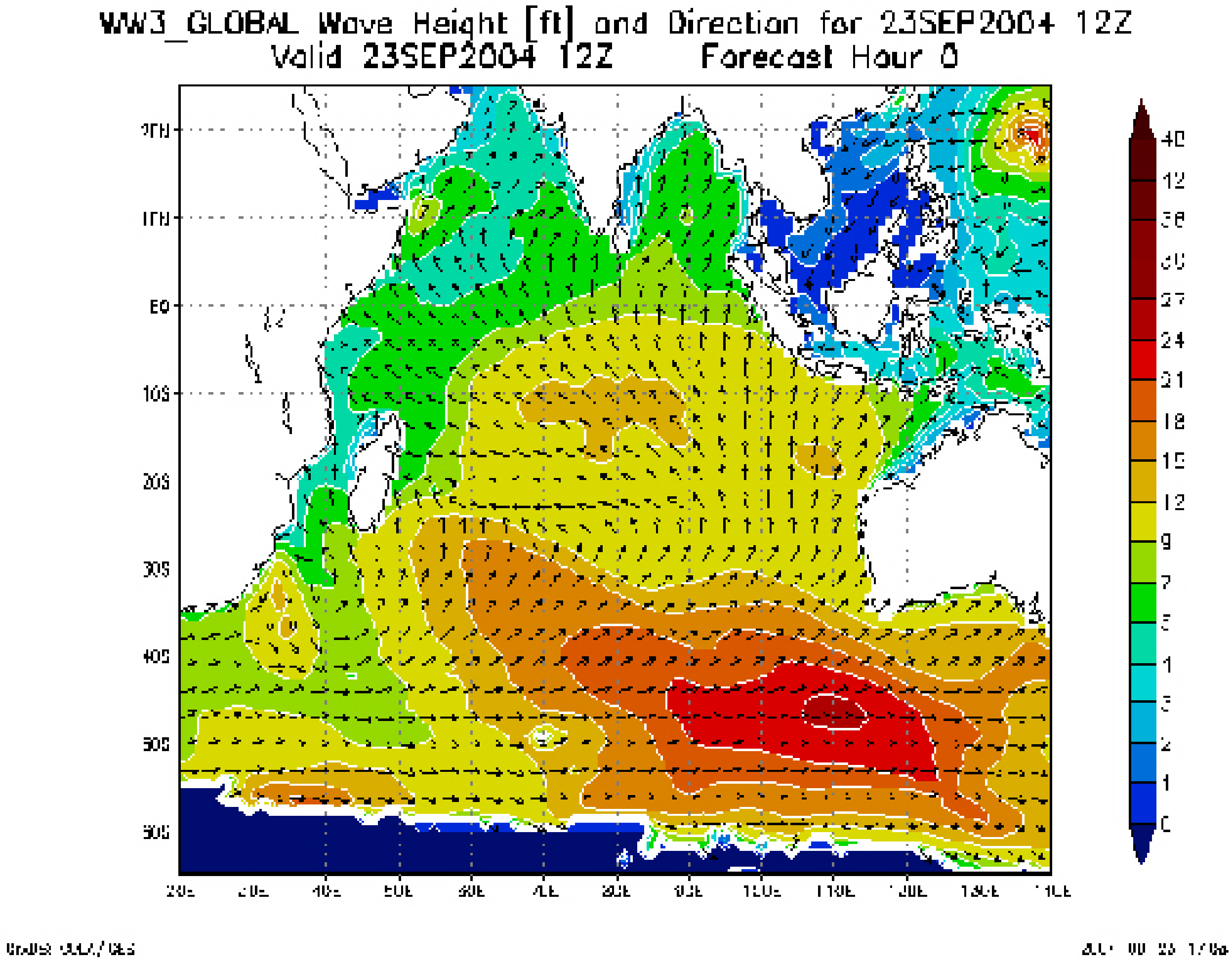

Figure 4. a) Wave height (0 to 50 ft, blue to brown) and wind direction (arrows), from www.fnmoc.navy.mil/ PUBLIC. These daily data will allow us to assess sea surface roughness along the propagation paths.

The effect of sea surface roughness is most pronounced at high frequencies. In Brekhovskikh and Lysanov (1991), it is shown that at a rough boundary, the modified reflection coefficient in the specular direction (ie the direction predicted by Snell's law) is given by

$$R' = R(\theta) \exp(-P^2/2),$$

where $$P = 2\, k\, \sigma \cos(\theta),$$

$R(\theta)$ is the reflection coefficient for the equivalent smooth surface as a function of incidence angle θ, k is the wave number of the sound, θ is the angle of incidence of the sound wave at the boundary, and σ is the rms displacement of the rough surface from its average position. The reflection coefficient at a rough surface therefore depends on acoustic wavelength, and thus frequency. In Figure 5, the absolute value of the reflection coefficient is plotted as a function of frequency for several rms displacement values. For a perfectly smooth sea surface, the reflection coefficient has an absolute value of 1, that is, the energy is totally reflected in the specular direction. As the ratio of the roughness to the acoustic wavelength increases, more energy is scattered in the ocean channel. The dash-dot lines represent values for normal incidence at the sea surface and thus represent maximal scattering. More realistic values for the angle of incidence at the sea surface can be derived from the TL example shown in Figure 3. As indicated there, most of the rays have turning points within the top 2.5km. Using Snell's law, and the ocean sound speed profile data near (60S, 101E), we find that the angle of incidence at the sea surface would range from 80° to 76° for turning points from 1km to 2.5km depth. The solid lines in Figure 5 represent values for angles of incidence of 75°; the specular reflection coefficient increases significantly at grazing incidence. Using the result that, in a medium with a constant velocity gradient a ray path follows the arc of a circle, we can also find the approximate distance between surface reflections for the example shown in Figure 3. This distance varies from about 25km for a ray with a turning point at 1km depth, to about 40km for a ray that turns at 2.5km depth.

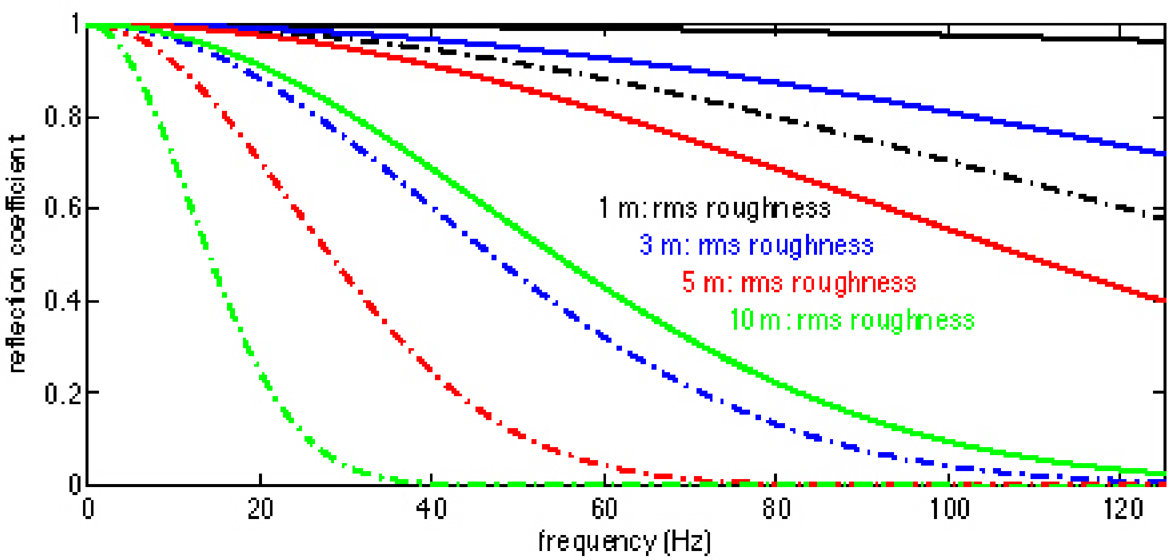

Figure 5. Specular reflection coefficients as a function of frequency at a rough seasurface. The values are shown for several sea states: black indicates 1m rms roughness (calm seas), blue indicates 3m rms roughness (a moderate seastate), red indicates heavy seas (5m rms roughness) and green indicates very heavy seas (10m rms roughness). The dash-dot lines are the values for normal incidence on the sea surface, which correlates to maximum scattering. The solid lines are the reflection coefficients for a 75° angle of incidence, which is a more realistic value as discussed in the text.

Given the number of surface reflections for a particular path and the specular reflection coefficients shown in Figure 5, it might seem straightforward to compute the additional transmission losses that result from scattering at the rough sea surface. However, it should be noted that much of the energy scattered at the rough surface may end up propagating to the receiver anyway; scattering mainly results in dispersing the energy out into a broader beam about the specular direction. Acoustic energy is lost if it is scattered downward into the sea floor, or into a direction away from the receiver. The amount of transmission loss attributable to sea surface roughness is thus not easily predicted; our experimental design will allow us to place observational constraints on acoustic transmission losses due to sea surface scattering.

The rest of our work in this first period of the study has been in experimental planning. We have completed the initial review stages for joining an Australian Antarctic Division voyage. The final stage of environmental review is currently underway, with preliminary assessment indicating that we will not be required to file for a permit (which would probably delay the experiment 1 year). We are working with the expedition leader to determine whether we can join the ship in Hobart or Fremantle, and have cleared most of the SUS shipment/handling issues for the latter.

The voyages under consideration would provide source signals in either late October/November 2005 or late February/early March 2006.

CONCLUSIONS AND RECOMMENDATIONS

We have designed a relatively inexpensive, logistically feasible experiment that will allow us to determine source-receiver travel time and azimuth errors that are characteristic of autumn (or summer) conditions across a range of polar front acoustic propagation paths. This is the type of information required to assess the location capabilities of the IMS for possible Southern Ocean nuclear tests. The main results that we will obtain are:

- Quantify travel-time errors associated with limited accuracy in ACZ characterization.
- Compute location uncertainties for Southern Ocean events, based on these errors.
- Assess the scale at which various physical parameters contribute to this uncertainty.

One-season results will document the scale of such errors. Given this knowledge it will be possible to address whether additional efforts are justified to more fully document, for example, early versus late season, annual, or source-receiver path differences that could be developed into a database for events from specific time/space regions for the Southern Ocean.

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